Pattern Recognition in Astrophysics and the Anthropic Principle

Daniel W. Darg

Physics Department and New College, Oxford

A thesis submitted for the degree of Doctor of Philosophy
in the University of Oxford.

Trinity Term 2011

Declaration

I declare that no part of this thesis has been accepted, or is currently being submitted, for any degree or diploma or certificate or any other qualification in this University or elsewhere. Except where explicit reference is made to the work of others, the work contained in this thesis is my own, and is not the outcome of work done in collaboration.

Daniel W. Darg

(October 2011)

Acknowledgements

There many to whom my sincerest gratitude is owed in coming to this point. I firstly thank the John Templeton Foundation for the main three-year grant for the DPhil and the Oxford Scatcherd study-abroad program for six months of funding for my work in Paris. I thank Khalil Chamcham for his work in arranging the grant and for his amicable support throughout the thesis including his review of most of my essays. I thank my supervisor Joe Silk for all he did in making this grant possible, for help and advice in all the projects I undertook, and for allowing me the freedom to follow the path that I thought was most pertinent to the philosophy of cosmology. I thank Julian Barbour, Bernard d'Espagnat, Kelly James Clark, Richard Swinburne, Ard Louis, Andrew Briggs, Don Page, Pierrick Bourrat and Robin Collins for many interesting conversations and for reviewing some of my philosophical essays.

On the physics side I owe a special thanks to Sugata Kaviraj and Chris Lintott for all their help and close collaboration. In similar regard I thank Kevin Schawinski, Sadegh Khochfar, Sebastien Peirani, Marc Sarzi, Sam Geen, Alfredo Carpineti, Stephen Bamford, Bob Nichol and all the others with whom I have collaborated or gone to for advice. The astrophysics department at Oxford makes for a very pleasant environment to work in and I would like to thank the community at large for helping make my DPhil an overall enjoyable experience.

Most importantly, I wish to thank my family - mother, father, brother and sister-in-law - for their love and support throughout my life. In the big things and the small, they've always been there for me. I also thank Ken Barnes and Ted Barham for their friendship. Finally, I thank my wonderful wife who, in these first few months of marriage, has been so supportive and understanding in the final lead up to the thesis and who, for the majority of my graduate education, has had to put up with a trans-Atlantic relationship. I hope it was worth the wait - it certainly was for me. Oh, and thank you Skype.

In memory of Alexei Chernyakov

Publications

This thesis is the result of various research activities carried out during my DPhil candidature between 2007 and 2011 that lead or contributed to the following publications.[1]

First-Author Publications in Physics

Galaxy Zoo: the fraction of merging galaxies in the SDSS and their morphologies,
D. W. Darg, S. Kaviraj, C. J. Lintott, K. Schawinski, M. Sarzi, S. Bamford, J. Silk, R. Proctor, D. Andreescu, P. Murray, R. C. Nichol, M. J. Raddick, A. Slosar, A. S. Szalay, D. Thomas and J. Vandenberg, 2010, MNRAS, 401, 1043

Galaxy Zoo: the properties of merging galaxies in the nearby Universe - local environments, colours, masses, star formation rates and AGN activity,
D. W. Darg, S. Kaviraj, C. J. Lintott, K. Schawinski, M. Sarzi, S. Bamford, J. Silk, D. Andreescu, P. Murray, R. C. Nichol, M. J. Raddick, A. Slosar, A. S. Szalay, D. Thomas and J. Vandenberg, 2010, MNRAS, 401, 1552

Galaxy Zoo: multimergers and the Millennium Simulation,
D. W. Darg, S. Kaviraj, C. J. Lintott, K. Schawinski, J. Silk, S. Lynn, S. Bamford and R. C. Nichol, 2011, MNRAS, 416, 1745

All the Minor and Major Mergers in SDSS ($z < 0.1$),
D. W. Darg, S. Kaviraj, C. J. Lintott, F. I. Lumb, J. Wood, J. Silk, K. Schawinski, 2011, MNRAS, *in preparation*

Is Lambda Optimal for Life?,
D. W. Darg, S. Khochfar, J. Silk, S. Kaviraj, 2011, *in preparation*

CO in merging-spirals at the transition mass of galaxy bi-modality,
D. W. Darg, C. J. Lintott, K. Schawinski, S. Kaviraj, J. Silk, 2011, MNRAS, *in preparation*

First-Author Publications in Philosophy

Cosmic If Statements,[2]
D. W. Darg, 2012, in *God and Physics - Exploring the work of John Polkinghorne*, ed. C. Knight, Ashgate Publishers, *forthcoming*

The Fine-Tuning of Consciousness,
D. W. Darg, 2011, *in preparation*

---

[1] Materials can be found here: `http://www-astro.physics.ox.ac.uk/~ddarg/shtml/thesis.html`

[2] This essay was awarded first prize in the Polkinghorne international essay competition, ISSR.

Contributing-Author Publications in Physics

Tidal dwarf galaxies in the nearby Universe,
S. Kaviraj, D. W. Darg, C. J. Lintott, K. Schawinski, J. Silk, 2012, MNRAS, 419, 70

Spheroidal post-mergers in the local Universe,
A. Carpineti, S. Kaviraj, D. W. Darg, C. J. Lintott, K. Schawinski, 2011, MNRAS, *under review*

Galaxy Zoo: Building the low-mass end of the red sequence with local post-starburst galaxies,
O. I. Wong, K. Schawinski, S. Kaviraj, K. L. Masters, R. C. Nichol, C. J. Lintott, W. C. Keel, D. W. Darg, S. P. Bamford, D. Andreescu, P. Murray, M. J. Raddick, A. Szalay, D. Thomas and J. VandenBerg, 2011, MNRAS, *under review*

Preface

Background and Development of Thesis

The mind wants to discover by reasoning what exists in the infinity of space that lies out there, beyond the ramparts of this world - that region into which the intellect longs to peer and into which the free projection of the mind does actually extend its flight. – Lucretius[3]

This work has been made possible by a grant from the John Templeton Foundation falling within the category of ‘Science and the Big Questions.’ This is just one of several initiatives supported by the Foundation to promote cross-disciplinary research in both cosmological physics and philosophy. Another such initiative was a conference I helped run in September 2009 in honour of George Ellis titled “philosophy of cosmology: Characterising Science and Beyond.”[4] It was intended to launch, in the words of Joe Silk, “a serious dialogue between active cosmologists and philosophers of science with the hope of catalysing scholarship in the philosophy of cosmology.” This is due in large part to the remarkable shift in the last decade towards a ‘Multiverse cosmology’ where anthropic reasoning plays a central role. Some are calling this a “deep change of paradigm”[5] or “new zeitgeist”[6] in cosmology and particle physics, prompting interest from far afield. These are exciting times in the fields of astrophysics, cosmology and philosophy and it has been a privilege and a pleasure becoming involved at such a monumental period in human discovery.

My own interest in this field began many years ago after reading Paul Davies’ *The Mind of*

---

[3] *de rerum*, Book II.

[4] `http://astroweb1.physics.ox.ac.uk/~philcosmo2009/home`

[5] Barrau 2007.

[6] Wilczek 2007a.

God. That book, more than any other, created within me a sense of curiosity and open-mindedness about the world that I believe has remained with me to this day. It is what brought me to Oxford and the undertaking of this thesis on the ‘Big Questions.’ There is no other subject I would rather have worked on.

This DPhil has been something of an experiment in the still-developing field of the philosophy of cosmology. It was proposed that the work be divided into $\sim 1/3$ philosophy and $\sim 2/3$ astrophysics, which is roughly how it worked out. By its experimental nature, the exact outcome was unknown and so I shall take the opportunity now to offer a report on the overall experience.

Research-level philosophy is difficult and distinctive amongst academic subjects. Just about everything there is to say in philosophy has already been said and, with mounting contributions from each generation of deep thinkers, it is ever harder to find something new and worthwhile to talk about. As Alfred Whitehead once remarked, “The safest general characterisation of the European philosophical tradition is that it consists of a series of footnotes to Plato” (Whitehead 1929, p.53).

This is not to say that there is no room left for a philosophy of cosmology. On the contrary, new *specific* questions arise all the time spawned by genuine discoveries in cosmology, both empirical and theoretical (see §3.1), that are distinctively philosophical in nature (Ellis 2008). Often, however, it is not the case that nothing like these questions has ever been conceived. The history and depth of philosophy is so vast that we need not recreate the wheel for the most part but, rather, relate these new specific questions arising out of cosmology to those in the same class that have already been studied in other areas of scholarship. For example, with the rapid acceptance of anthropic reasoning in cosmology in the last decade, cosmologists have, somewhat unexpectedly, found themselves having to analyse what exactly is meant by an ‘observer.’ This, of course, has been the conundrum of quantum physics for almost a century now and has thus provided much ground work for cosmologists to appropriate within their context.

Relating the new questions arising in cosmology to the wider history and philosophy of science as well as metaphysics and epistemology (*viz.* the nature of ‘evidence,’ ‘explanation,’ ‘rational inference,’ etc.) requires a tremendous breadth of knowledge, the surface of which few can scratch.

Going about this within an astrophysics department makes an already difficult task all the more so. This is not because physicists are not willing philosophers but, as one might expect, they tend to focus on one kind of philosophy - what you might call the “scientific kind.”[7]

I do not say this as a criticism; astrophysicists have a job to do and this requires a pragmatic mind-set in order to get results and make progress. There is never a shortage of new and exciting problems to work on in an astrophysics department. This further adds to the difficulty of performing philosophical research in an environment where the urge to join in with ‘down-to-earth’ projects with ‘real data’ and an assortment of interesting puzzles can be very alluring.[8]

As I was free to spend $\sim 2/3$ of my time working on more mainstream astrophysics in connection with the Anthropic Principle, I decided to work towards issues on galactic habitability since, as shall be seen, I am unconvinced that there is much utility to be gained from theories purporting to describe an alleged reality that, *even in principle*, can never be observed (*viz.* the Multiverse).[9] Galactic dynamics, on the other hand, are more amenable to the ‘classical’ scientific method, being open to testability and falsifiability and thus provided a welcome counter-balance to the non down-to-earth ideas that I knew I would end up studying (namely the current ‘buzz-topics’ of parallel worlds, Boltzmann Brains, infinite copies of ‘us,’ etc.).

For this reason, I was more than happy to get involved in the Galaxy Zoo project[10] when presented with the opportunity. Not only did it offer me the chance to get involved in something ‘real,’ ‘solvable,’ ‘grounded,’ etc., but the whole concept of employing the internet to do pattern recognition as a giant ‘neural net’ of sorts intrigued me, fitting in with my interest in the philosophy of mind. Moreover, having witnessed so many powerful internet ventures spring up in my lifetime, I was keen to get involved in what possibly could be the next big thing. Indeed, over the last three or four years the Galaxy Zoo project has grown tremendously and spread out into numerous other

---

[7] I do not wish to go into detail at this early stage as to what I mean by that term. Speaking informally, I might describe it as the view that any problem in philosophy can be solved using Bayes’ theorem.

[8] C.f. (Kuhn, 1996, Ch.IV) “Normal Science as Puzzle-solving.”

[9] I would add several caveats to this sentence if it were not too early to get pedantic.

[10] The Galaxy Zoo project was established to perform morphological classifications of galaxies from the Sloan Digital Sky Survey using a web interface and the volunteer work of hundreds of thousands of users from around the world. It is a prime example of ‘Citizen Science’ - a form of crowd sourcing - in action. See `http://zoo1.galaxyzoo.org/`

‘Citizen Science’ projects including some outside of science.[11]

One of these projects is the fruition of an idea stemming from my past as a humanities student. I proposed that the web-interface technique could be used to help transcribe ancient manuscripts and built the first prototype.[12] Like with galaxy images, there are far too many manuscript fragments around the world for experts to sift through[13] and degraded papyrii written over by numerous hands is far too difficult a pattern-recognition problem for computers to handle. Three years later, in August 2011, the ‘Ancient Lives’[14] project was launched thanks mostly to Chris Lintott for obtaining funding and making it a reality.

In the meanwhile, the core projects in astrophysics focussing on galaxy-images continued and evolved significantly. My role was to work on galaxy mergers specifically and, after much grappling with interfaces, I developed what I believe is the best method to date for overcoming the very difficult pattern-recognition problem of identifying mergers in large telescopic surveys. These projects allowed me to acquire the background experience required to do astrophysics at research-level quite generally with issues of galactic habitability as my overarching goal in order to connect up with the philosophical component of the thesis.

The philosophical side of my research developed gradually for the first half of my DPhil candidature. When I joined the astrophysics department I had already had a fair dose of philosophy and was still wavering between realism and anti-realism and, having not made up my mind, would probably have described myself as a phenomenologist.[15] As is common in philosophy, my opin-

---

[11] `http://www.zooniverse.org/`

[12] `http://www-astro.physics.ox.ac.uk/~ddarg/shtml/greek.html`

[13] There are millions of ancient Greek fragments in the Sackler library in Oxford alone, mostly from Oxyrhynchus in Egypt. Over the century in which they have been there, only a small portion have been published but include many important documents lost to antiquity (unknown Gospels, philosophical works, astronomical fragments) and the project promises much in the way of future discovery.

[14] `http://ancientlives.org/`

[15] Phenomenologists are conservative philosophers who tend to think that we don’t ultimately ‘explain’ anything, we merely ‘describe’ what we see, hence the ‘phenomena’ in the name. It differs from empiricism in that phenomenologists (in the philosophical sense) are more focussed on sense-data, seeing the terminus of that which ultimately ‘exists’ in mechanical instruments as somewhat arbitrary. Entities beyond what are observable, Kant’s ‘noumena,’ may well exist (hence it is not as assertive as idealism), but then we just don’t know anything about them other than the affects they confer on the phenomena, so the phenomenologist reserves the designation of ‘existence’ for sense-data and mental life alone. It is primarily associated with Continental philosophy and is not to be confused with the ‘phenomenalism’ of the Analytic tradition - a theory of epistemology that was popular with Ernst Mach, Bertrand Russell and the logical-positivists A. J. Ayer and Rudolph Carnap. My original aim for the philosophical part of the thesis was to give a ‘phenomenological interpretation’ of the Fine-Tuning of the Universe and, though eventually abandoned, vestiges of

ions developed and changed over the course of my DPhil candidature. Nowadays I think my position is closer to what philosophers would term ‘epistemic structural realism’ and, since this is the time my thesis is due, this is the position I will defend in evaluating the Anthropic Principle.

The most intensive part of the philosophical research came about during six months of studying abroad in Paris that I arranged in order to work with Bernard d’Espagnat (who was kind enough to lend me his time). This was a wonderful experience and the change of scene and solitude was very helpful at a time when much hard thinking was required. I would highly recommend a similar course of action to any future dual-topic candidate.

In the end, after much difficult reading and pondering which, by its very nature, is apt to frustrate and bewilder the mind, I am personally extremely pleased with the philosophical conclusions I reached as well as the outcomes of the astrophysical projects - though many are still on going. The Big Questions remain of course, as they always will, but hopefully I will have succeeded in saying something interesting about them that, as far as I can tell, few else have noticed before.

That said, the task of now articulating thoughts on matters so close to edge of communicability is most exacting. To accomplish this I think it will be helpful to the reader to first acquire an overview of the thesis and how it fits into the progressing field of the philosophy of cosmology.

Overview of the Thesis

There is something like a Puritan’s restraint in the scientist who seeks truth:
he keeps away from everything voluntaristic or emotional. – Albert Einstein[16]

The grand totality of the world - the Cosmos - has always stood near the forefront of philosophical enquiry. Although the ancients had only the visible stars and planets to guide their thinking, some still managed to survey an impressive range of philosophical possibilities regarding their nature and origins. The Greeks in particular, from whom modern astronomy has inherited so many terms and concepts, partook in sophisticated discussions that continue today (more or less) in de-

---

this original aim can be found in §2.3.3.

[16] Einstein archives, 1-160.

bates over scientific realism versus empiricism. As described by Duhem in great detail,[17] the classical schools divided the study of the heavens into two disciplines: ‘astronomy’ and ‘physics,’ what today we would call physics and metaphysics respectively. Astronomy was considered a branch of mathematics and sought to represent the movements of the planets (the ‘wandering stars’) through geometric models as pioneered by Plato’s students Eudoxus and Callippus.[18] Aristotle, by contrast, was less interested in describing the movements mathematically and more interested in the question of their essence and causation, that is, their φυσις.

Up until the scientific revolution, it is safe to say that European scholarship gave far more regard to the philosophical project of Aristotle. The Greeks knew that their geometric models were underdetermined - that various configurations of spheres in different relative motions could be used to describe the same movements of planets - and so, the ancient physicists argued, the only way to decide which configuration of spheres truly corresponded to ‘reality’ must be a question of nature and essence, not mathematics.

The debate was rekindled when the gravitational model of Newton, that consisted of formulae, challenged that of Descartes’ vortex theory, a description of substance. As we know, Newton won out and ever since physics has become increasingly abstract, focussing on mathematical relations, whilst declining to address questions of ‘nature’ and ‘substance.’ Thanks to this choice of methodology, our description of the world has reached a point of breath-taking scale and detail epitomised by the standard models of particles and cosmology. With regards to the latter we have been privileged in this past decade to witness the detection of the vacuum energy of space, to see the quantum ripples of the early Universe fossilised in the CMB and to have found hundreds of new solar systems that resemble our own.

Given the unquestionable impressiveness of these achievements, it is tempting to think that we are finally in a position to answer the philosophical questions of old, to be the first to break out of

---

[17] C.f. *Sauver les apparences. Sur la Notion de Théorie physique*.

[18] Plato famously posed the problem to his mathematical contemporaries: “what are the uniform, perfectly regular, circular movements of the planets that are suitable to take for hypotheses to enable the phenomena to be saved?” (Duhem 2003, p.14; my translation.) Eudoxus and Callippus took up the challenge and developed models of the solar system with 27 and 34 concentric spheres respectively. These were later supplemented with epicycles by Apollonius of Perga and Hipparchus of Rhodes and formed the basis of the Ptolemaic system that lasted in Europe until the Copernican revolution.

Plato's cave and see reality as it is 'in itself.' There is great public interest in claims that modern physics implies the existence of an infinite Multiverse, that the law of gravity brings the world into existence "from nothing" and has thus rendered God "unnecessary."[19] But something seems amiss here, as though we've suddenly reverted back to the Aristotelian project. Is the modern scientific method, in virtue of its restriction to mathematical representation, capable of establishing such metaphysical inferences? Surely modern science has taught us *something* philosophical about the nature of reality, but what?

Let us consider wherein our privileged outlook is supposed to lie. Is it that we have more data than the ancients - a bigger list of numbers? All astrophysical images are grids of numbers. The CMB data is just a grid of numbers. The spectra of Type 1a supernovae can be printed out as a long lists of numbers. Is that it? Is our possession of more numbers all that separates us from the belief systems of old? One might say that it's not *just* that we have these numbers at our disposal, it's also that we *understand* them - where they come from and what they *mean*. This seems right; 'understanding' and 'meaning' must have something to do it, but much philosophical ambiguity can arise through blind deference to these terms, so we must be careful. Two considerations are worth noting.

Firstly, we can only ever push the origin of numbers down a level. Only numbers beget numbers. We can always posit a mathematical relation that maps one number to another, and this law might prove useful in describing observations, but we can always ask: why *this* relation and why *this* numerical domain rather than many others that we can imagine? How does the postulation of relations help understand how it is that numbers - those seemingly immaterial constructs and conventions of the mind - manage to get instantiated in the world, to 'exist' (if indeed that term is appropriate) 'out there' in the first place?

Secondly, to speak of the *meaning* or *understanding* of numbers is to make tacit reference to some cognitive process. The human brain is, no doubt, a highly adept 'pattern-recognition' machine. It receives inputs (photons, sound waves, etc. - all characterised by numbers) and produces

---

[19] "Because there is a law such as gravity, the universe can and will create itself from nothing. Spontaneous creation is the reason there is something rather than nothing, why the universe exists, why we exist. It is not necessary to invoke God to light the blue touch paper and set the universe going," Hawking & Mlodinow (2010).

outputs (more sound waves, mechanical impulses through limbs, etc. - all characterised by numbers). The relation between these inputs (e.g. the image of a tiger) and outputs (e.g. running) needs to be very specific if the brain is to last long enough to reproduce itself. Perhaps then 'to understand' simply is to be equipped with something like a neural net so-configured as to allow one to survive effectively.

But survival is not the only input-output relation exhibited by humans. The typical human brain has $\sim 10^{11}$ neurons and these provide ample scope[20] with which we could construe *all* of life's activities as a machine processing numerical inputs and outputs - eating, recreation, philosophical musing, etc. This would include the astrophysicist in the act of interpreting, say, the latest CMB data. Patterns of light enter the neural net that is the physicists's brain and eventually result in a specific sequence of mechanical impulses acting on a keyboard (the typing of a publication to an astrophysical journal). These patterns are encoded into electronic signals that are sent around the world-wide web allowing certain other brains, that have been 'trained' to process such patterns in a similar way (i.e. other physicists), to undergo modifications to their neural pathways. These newly configured nets then carry forward these patterns (a 'scientific paradigm') and can be made subject to new data inputs. And so science advances.

Some consider this to be an 'elegant' view of the world expunged of mystery wherein numbers and relations between numbers exclusively constitute the fabric of reality. But, in my opinion, something has been left out in this picture. Although I *feel* like I understand this scenario as I've described it so far, if I now put *myself* in the position of the aforementioned astrophysicist - a brain processing inputs and outputs - I no longer see any role for *feeling* whatsoever. This creates a conundrum of sorts: how can number-processing give rise to qualitative *sensations* and how can qualitative sensations end up undergirding *every* conclusion one can arrive at as to the interpretation of numbers?

Perhaps that last statement needs expansion. When the physicist is asked why she thinks the CMB data imply a particular conclusion, she does not reply, "because my brain-state was charac-

---

[20] If each neuron can take just two states (an underestimate) then the total number of possible brain states is $2^{10^{11}} \sim 10^{30000000000}$.

terised by the list of numbers $\{1.0929, 23.45, 27.0 + i35.22, ...\}$ at the time of my analysis." Rather, she replies, "because it *feels* like the simplest option" or "it *seems* like the most plausible interpretation." But what do *feelings* have to do with reality? Unless there is some fundamental connection between the way the world 'is' and how it 'appears' to our minds in the form of qualitative sensation, it just seems immaterial what one 'feels' about the data. We therefore must believe there to be a connection between 'feelings' and 'reality' if we are to be realists and this brings us to the 'problem of knowledge': how can we infer anything about reality when we are forced to deal not with 'the thing in itself', Kant's 'noumena,' but with the world of appearances, the 'phenomena'?

Where does this fit into the philosophy of cosmology? Firstly, if we are to interpret the numbers and mathematics in the way that some cosmologists would like, for instance, to infer that an infinity of other worlds (where everything that can happen will happen) are "unquestionably real" (Vilenkin & Garriga 2011),[21] we must surely ask whether our minds are up to the task in the first place. This, like most things in philosophy, is controversial, but a significant few think that evolution lends little case for confidence in our capacity to do metaphysics.[22]

Secondly, and more obviously, questions of epistemology are relevant to the philosophy of cosmology due to the centrality of anthropic reasoning in Multiverse scenarios. As I shall argue herein the Anthropic Principle - a famous misnomer - can be recast as a *mind principle* or, as I have called it elsewhere the "Noological Principle" (see Darg 2012b). The Anthropic Principle simply states that one can only observe oneself to be in a place where all the necessary and sufficient conditions for observers to exist are met. The philosophical ramifications that that entails will thus depend on what understands by the term 'observer,' which will depend in turn on one's position within the philosophy of mind. Is there something special about the human mind as, for example,

---

[21] Claims of such certitude are not rare in the popular literature. For example, that the cold spot in the CMB is "the unmistakable imprint of another universe beyond the edge of our own" (Mersini-Houghton 2007) or that "[t]he Multiverse is forced upon us by observation" (Tipler 2007, p.15; this claim is based on the many-worlds interpretation of quantum mechanics).

[22] Some examples are Eugene Wigner: "We have no right to expect that our intellect can formulate perfect concepts for the full understanding of inanimate nature's phenomena" Wigner (1950); Briane Greene: "Our brains evolved so that we could survive out there in the jungle. Why in the world should a brain develop for the purpose of being at all good at grasping the true underlying nature of reality?" quote from Kruglinski (2004); Patricia Churchland "Boiled down to essentials, a nervous system enables the organism to succeed in the four F's: feeding, fleeing, fighting and reproducing. The principal chore of nervous systems is to get the body parts where they should be in order that the organism may survive... Truth, whatever that is, definitely takes the hindmost" Churchland (1987).

Roger Penrose believes (Penrose 1999)? Does a photographic plate count as ‘an observer’? I will pay brief attention to the notion that an ‘observer’ is an entity capable of performing pattern-recognition, i.e. to have the capacity to extract patterns from the surrounding environment and utilise this information to its own advantage. This is, in many ways, an interesting and useful view and highly amenable to the scientific method (hence why it is strongly favoured by philosophers of mind known as ‘eliminitavists’ such as Paul Churchland; see Churchland 2000). However, I shall suggest that this view of an observer is ultimately vague and that it unsuccessfully attempts to side-step the elephant in the room: consciousness.

My eventual conclusion will be that, although the urge to shift paradigms to include anthropic reasoning is *a priori* understandable given the fine-tuning of the Universe for intelligent life (FTL), cosmologists who go down this path will, ultimately, end up with far more metaphysical baggage than they originally bargained for. In that sense, the philosophical component of this thesis will resemble Davies’ critique of the Multiverse (Davies 2007).

Now, to those who are *not* adverse to metaphysics, myself included, this is does *not* mean that Multiverse theories are not fascinating ideas. In fact, I fully concur with its proponents in reporting a sense of *elegance* about the notion that, say, our Universe is part of a giant fractal of sorts, exponentially growing with each passing moment in a single, unimaginably large space-time. I also find the String-Landscape proposal rather *attractive* in its generation of $\sim 10^{500}$ values of the cosmological constant. Where I *do* differ from exuberant proponents of the Multiverse scenario is in the significance attached to reports of mental sensations (“elegance,” “attractive,” etc.) that it conjures up within one’s mind. Since, as shall be argued, the Multiverse does little or nothing to aid in the taxonomy of the physical Universe - the algorithmic compression of the phenomena - the idea that the existence of an infinite space-time is to be epistemically grounded in a ‘feeling’ alone sounds far from scientific and, according to George Ellis, it “does not belong fully in the scientific fold” (Ellis 2011, p.295). This concerns the ‘demarcation problem’ in the philosophy (and sociology) of science (on what basis does one distinguish ‘science’ from ‘non-science’), which this thesis will touch on.

These philosophical considerations lead into more familiar astrophysics once we turn to the

Principle of Mediocrity (PoM). The idea that, roughly, “we should expect to find ourselves in the largest reference class of observers” is philosophically contentious but is the closest one comes to a ‘test’ of the Multiverse. Although I am personally sceptical that any strong conclusions can be drawn from the principle it is, nonetheless, an intrinsically interesting question whether or not our habitable zone is optimal for life in the local parameter space of fundamental ‘constants.’

To investigate this, I use a cosmic-scale, semi-analytic model of galaxy formation to test whether variations in the cosmological constant lead to more or less disc-dominated galaxies - what I term a ‘second-order’ proxy for life. These models are tuned to *real* physics in *our* Universe and will instigate, I believe, a fascinating series of future investigations. Although our model probably relies on too many caveats at the present time to draw firm conclusions, it (i) highlights the many complex processes and feed-back mechanisms on which life depends and (ii) gives new incentive to the improvement of physical simulations. Only when we are *extremely* confident that our models capture observables (e.g. the galaxy luminosity function) in a near-unique way (breaking degeneracies in the tuning of independent parameters), will we be able to vary fundamental constants, such as the cosmological constant, to see what would happen in other universes with regards to life.

What our model does tell us though with good confidence is that the effects on the mass function of the Universe upon changes to the vacuum energy are non-negligible. In other words, mergers are important with respect to the abundance of life in the Universe and *understanding mergers*, in particular the effect they have in transforming ‘discs’ to ‘bulges’, is therefore a key ingredient in answering the aforementioned question: is our Universe optimal for life?

This brings us full-circle: in order to find and study merging galaxies we need to be *highly* adept at pattern recognition (as shall be discussed in some detail) and this requires us to be in a part of the Universe conducive to the evolution of such neural networks. Perhaps then, even if this Universe is not optimal for ‘life’ per se, perhaps it is optimal for the study of cosmology, since we would not be asking these questions if we were cognitively incapable of doing cosmology (as no other animal on the planet is). This also requires us to have a specific value of the vacuum energy at an epoch where $\Omega_m \sim \Omega_\Lambda$.

In the last few chapters I detail how the Galaxy Zoo project, by using the internet, allows us to combine the collective capacities of human pattern recognition, necessitated by natural selection, to find mergers efficiently. We produce the largest homogenous catalogue of binary mergers to date and study their fraction and properties (colours, stellar-masses, environment, star-formation rates and AGN signatures) for the local universe. We also study the fraction and properties of multiply-merging galaxies (i.e. small clusters) and compare them, as well as those of the binary-mergers, to the semi-analytic models of the Millennium Simulation.

I review the strengths and weaknesses of the Galaxy Zoo technique in comparison with other pattern-recognition techniques and develop a new, refined interface to find mergers and separate their photometries. Unlike the first mergers study, this improved approach allows for the study of minor-mergers - which are also important in galaxy evolution - in a virtually complete manner.

These studies are important in understanding the galaxy-transition mass of $3 \times 10^{10}\mathrm{M}_{\odot}$ that marks the split in the bimodal distribution of galaxy properties (between disc/late-type and bulge/early-type galaxies). We discuss the possible role that mergers play in the origin of this transition mass and conclude that, plausibly, they accentuate the disc-bulge bimodality around this mass since, on average, galaxies at this stellar mass no longer have sufficiently large gas fractions to reform discs. Plausibly then, too many mergers hinder life by reducing the volume of galactic habitability zones in a given universe through disc-to-bulge conversion.

Final Notes

This thesis is not intended as a book - the activities undertaken have been far too varied. Rather, it summarises and attempts to connect as best as possible numerous research projects that have been carried out over the course of the DPhil candidature. Because the language and methodology of philosophy reads and feels different to mainstream astrophysics, the thesis has been divided into two parts roughly corresponding to whether or not the subject matter is primarily philosophical or mainstream astrophysical. Of course, this is not a strict divide as philosophy is informed by ideas from science and science is permeated with philosophy. This division is merely to help prepare the reader in choice of mind-set. Part I, the philosophical section is, as one might expect, more pedantic in many ways and requires more background explanation and justification as this thesis is written primarily for astrophysicists. By contrast, Part II requires much less background description (e.g. the meaning of terms such as ΛCDM can be assumed). Had this thesis been written primarily for philosophers, it would have been the other way around (where the meaning of 'epiphenomenalism' could be safely assumed). The effect of this is to inflate the natural volume of Part I and so, to save space and enhance the readability, I have put a large amount of clarifying remarks into the footnotes.

There are many topics and tangents I wish I could have covered but have not been able to in the preparation time and page-limits of this thesis. In particular, after much deliberation, I chose to remove a central section of the philosophical thesis I had developed on the topic of epiphenomenalism. What started as an article to be published in a journal quickly became book length and, since the thesis was running long and since it is written primarily for astrophysicists, I decided that that section was a bit 'too philosophical' in the sense that it might have required too much background familiarity with the field. The risk though is that it potentially undermines the case I had been building. For this reason, I make available here[23] the full essay *if* the reader so wishes to explore it. This link also puts into one place materials showing the various projects that I have been involved in. This includes several ongoing projects that have not been included here in due to space but the reader may find informative nonetheless.

Above all, I have tried to write *clearly* and I would prefer that the reader understand what has been argued and disagree, rather than end up confused. The philosophical work is, like all matters philosophical, bound to prove controversial. It is very difficult to say anything interesting in philosophy that is not controversial. My primary aim is not to be purposefully controversial, but to say something interesting.

I use the convention of a capital 'U' for our Universe domain, that is, the finite volume within our horizon, which may or may not be part of a wider Multiverse, and small 'u' for a generic, putative universe domain. Below are some abbreviations used in the paper.

---

[23] `http://www-astro.physics.ox.ac.uk/~ddarg/shtml/thesis.html`

AP - the Anthropic Principle.

CAS - concentration, asymmetry, smoothness/clumpiness (system of galaxy-morphology parameterization).

CCD Chip - charge-coupled device chip.

CMB - the Cosmic Microwave Background.

GM$_{20}$ - Gini coefficient, second-order moment of the brightest 20% of a galaxyÕs light (system of galaxy-morphology parameterization).

DR6 - 6th Data Release of SDSS.

DWD - this author.

FTL - the fine-tuning of the Universe (laws, parameters, initial conditions, etc.) for the possibility of physical life forms as we know it.

GZ - the Galaxy Zoo project,

IDL - data analysis language; scripting language often used by astronomers.

IMF - initial mass function (of stars, galaxies, etc.).

MGS - Main Galaxy Spectral sample (of SDSS).

PoM - the Principle of Mediocrity.

SAM - semi-analytic model (of galaxy evolution).

SDSS - Sloan Digital Sky Survey (automated 2.5m telescope in NM, USA).

SED - spectral energy distribution.

SFR - star-formation rate.

ToE - Theory of Everything.

WW - Weinberg Window (see p. 72 for definition).

Contents

Appendices

Part I

Philosophical Investigations

Chapter 1

Introduction

1.1 Perennial Questions

I am reminded here of the aesthetic category of the sublime, as applied to the highest mountains, raging oceans, the night sky, the interiors of some cathedrals, and other things that are superhuman, awesome, limitless. No question is more sublime than why there is a Universe: why there is anything rather than nothing. – Derek Parfit[1]

Much was said by way of introduction in the preface. Here we aim to give an overview of the big philosophical issues connected with the Anthropic Principle and connect them with the specific questions that this thesis aims to address.

According to Leibniz, the first question of philosophy that "should rightly be asked" is "why is there something rather than nothing?" (Leibniz, 1951, p.527). This question is tightly bound to two more that follow from it and which, taken all together, neatly summarise the perennial questions of philosophy:

---

[1] Parfit (1998).

1. The Ontological Question: why does *anything* exist?
2. The Taxological Question: why does that which exists exhibit the *form* and *order* that it does?
3. The Axiological Question: why does that which exists and exhibits the form and order that it does *matter* to anyone?[2]

As stated, these questions seem to form a hierarchy; the second follows on from the first and the third from the second.[3] The common driving force behind all three questions is *conceivability*: we seem to be able to conceive of alternative outcomes to that which in fact obtains. We can make some sense of the Universe not existing, of it containing formless substance alone and of nothing whatsoever mattering to anyone (no 'good,' 'evil,' etc.). Not only that, but alternative outcomes to this world - or no outcome at all - seem to be simpler, more intuitive, more to have been expected, less mind-boggling, etc. than the very particular world that we in fact find ourselves in.[4]

With regards to the first question, the fact that something *does* exist is perhaps the single greatest violation of what Okham's Razor would have us expect.[5] For what could be 'simpler' than that nothing exist? Why, in the words of Hawking, does the Universe "go to all the bother of existing?" Yet, we know something exists, so one of the most widely-reported metaphysical intuitions – that we would expect nothing to exist – is completely wrong. This is not a promising start for metaphysics.

---

[2] My choice of term 'axiological' came after some deliberation. The first term that came to mind on the issue of 'mattering' and 'importance to the individual' was *existential*. However, the root meaning of this term is the same as ontological and breaks the trend of using Greek roots (as in the first two). Axiology, the study of 'good' and 'value' is to presuppose that something matters to at least *someone* in existence (to be discussed). I also considered calling this the 'noetic' question as the existence of 'mind' is a prerequisite to 'something mattering.'

[3] Many before me have noticed the similarities between these questions. As Marcelo Gleiser writes, "the question of "How come us?" is, in reality, not one but three questions of origins, intertwined and mutually dependent: "How come us?" implies the existence of (i) a universe capable of (ii) harboring life which, furthermore, is (iii) intelligent enough to ask about its origins. Thus, "How come us?" encompasses all three origins, of cosmos, life, and mind; they may be (and often are) treated separately, but they are part of an indivisible whole" Gleiser (2004, p.638).

[4] This sentiment is captured nicely by Wittgenstein who, according to his biographer Norman Malcolm, would often "have a certain experience" and then be "inclined to use such phrases as 'how extraordinary that anything should exist' or 'how extraordinary that the world should exist"' Malcolm (1958, p.56).

[5] Note: Okham's Razor is notoriously difficult to spell out formally (Sober 2008). One might complain that the principle is being misused here by construing it in 'too simple' a fashion (what other complaint could there be?); but if we need a more complicated construal of Okham's Razor then the principle is undermined all the more.

Similarly, why does the Universe exhibit the form and specificity that it does given an infinity of logically-possible alternatives? This, as we shall discuss, lies at the heart of the perplexity generated by the 'fine-tuning the Universe for intelligent life' (FTL). Finally, how is it that something manages to 'matter,' for there to be pleasure and pain and qualitative sensations when we can imagine an existent world like ours with complex, self-reproducing automata, but harbouring no mental life - no capacity for qualitative sensation - and thus no more the case for concern than a robot or computer (presuming that robots and computers do not have qualitative sensations)?

Contrast these mysteries with so-called 'Platonic' truths, such as the truth that 27 is divisible by 3. We might say that what *makes* this true is that there is no *conceivable* alternative; it belongs analytically to the very concept of numbers that 27 is divisible by 3. Statements of material existence, on the other hand, tend to be what philosophers in the tradition of Kant distinguish as 'synthetic' truths, that is, *a posteriori* truths discernible only by experience.

Although it seems unlikely that all three of these questions will ever be answered to our satisfaction, perhaps - given their interdependence - some can be shown to be redundant. As Barrow and Tipler noted in the opening of their seminal work on the Anthropic Principle (AP), the great idealistic philosophers regarded *mind* as fundamental, in which case existence and order must follow since these seem to be concomitants with (or what constituent) thinking. Cogito ergo sum. The primacy of mind is also the broad theological position expressed, in one way or another, by all the major religions, be it in describing God, the Deity or the Absolute. According to this view, Leibniz's first question is to be made subservient to our third, that is, existence is ultimately grounded in something like an axiological telos - an intended 'good' or 'value' (what Parfit calls the 'axiarchic' view).[6]

By contrast, naturalistic philosophers have long sought to show that order, complexity and mind are all emergent phenomena entailed by the potentiality of primitive, material existence. Nowhere else in science, which is methodologically materialistic, is this reductionistic goal expressed more poignantly than in the physicist's bid for a 'Theory of Everything' (ToE). Although

---

[6] Parfit (1992). An example of this view is represented by the philosopher and Neoplatonist John Leslie, who has written extensively on the AP. He thinks that the Universe exists because the "ethical need for a good universe or universes *is itself creatively responsible* for that universe or those universes" (Leslie 1996, p.126).

this phrase did not appear until the 1980's,[7] the modern notion can be traced back to the work of Roger Boscovich in the 18^{th}C, with clear expressions appearing by the end of the 19^{th}C, such as the following by William Hicks

> The ultimate aim of pure science is to be able to explain the most complicated phenomena of nature as flowing by the fewest possible laws from the simplest fundamental data... science will have reached its highest goal when it shall have reduced ultimate laws to one or two, the necessity of which lies outside the sphere of cognition. These ultimate laws - in the domain of physical science at least - will be the dynamical laws of the relations of matter to number, space and time... When these relations shall be known, all physical phenomena will be a branch of pure mathematics. Hicks (1895).

It will be helpful to this discussion to try and describe in more detail what the physicist has in mind by a ToE. As a first gloss, we can say that a future ToE would, in principle, be able to relate any measurement whatsoever that one might make back to a relatively small set of numbers with equations that have relatively few terms and few free parameters (the fewer, the better). To see why this would be such a desirable goal, it is helpful to adopt the modern picture of the Universe as a giant computer of sorts. (For parallel discussions see Davies 1993, ch.5; Lloyd 2010.)

One of the great insights that helped launch the scientific revolution was that the Universe somehow manages to keep track of a vast array of numbers and that these numbers can be accessed through the process of measurement. According to classical mechanics, the state of every particle can be given by just six numbers (the phase space of the Universe) and these could all be written out, in principle, as a giant list. The numbers in this list are not random variables but are related to each other by constraints that we call the laws of nature (and where there is a constraint, there is a symmetry).

The presence of these laws serves to *algorithmically compress* the length of the list of numbers that specify the phase-space of the Universe. One need not write out the whole list for every moment in time (what we might call the 'trivial representation of the Universe'), one only needs an initial slice plus the laws, and all future moments are calculable thereon (c.f. Laplace's demon).[8]

---

[7] A possible origin of the phrase is from Ellis (1986).

[8] This view could easily be extended to include classical fields which, forming a continuum, would need infinite

Although quantum mechanics might seem to spoil this view, the same overall principle remains (relating measurements to initial conditions and fundamental constants via mathematical algorithms), only we must exchange ‘deductive-nomological’ terms for their ‘statistical-inferential’ counterparts to be strictly general.[9] Although no single outcome of a quantum experiment can be predicted, the statistics of an ensemble can be.

With this view of the Universe as a computer of sorts, we can cast the vision of ToE proponents as the reduction of the trivial representation of the Universe to one using the fewest bits of information required to specify the initial conditions, fundamental constants and parameters within the laws themselves (e.g. the powers that feature in individual terms); i.e. to reduce the phase space of the Universe to a comparatively ‘simple’ representation. At first, this project seems daunting since the number of particles in the universe is $\sim 10^{80}$ and so (assuming particle conservation), the initial conditions at some arbitrary point in the past would require the same order of magnitude of free parameters.[10]

If left as it is, such large information content could hardly be called ‘simple.’ But we need to appreciate the role that randomness plays in such contexts. For example, while it is true that if we look out in any particular direction of space we will not be able to predict what the intensity of CMB radiation will be precisely, we do know that (i) it is likely to correspond very closely to 2.73 K (by the Universe’s large-scale isotropy) and (ii) if we take *enough* measurements in different directions we will find that, as a statistical ensemble, they can all be described very accurately by just a few parameters such as the spectral index governing the power law, n, of Gaussian inhomogeneities and their characteristic amplitude the Q parameter (see Tegmark et al. 2006). These parameters, n, Q, etc. are real numbers and so could, in principle, require an infinite number of decimal places. Nonetheless, going from $\sim 10^{80}$ real numbers to just a few is clearly progress in the reductionist project.

---

precision to specify in the trivial representation. Since we are only concerned with concepts at this point, we will ignore fields and speak only in terms of particles.

[9] Additionally, one can replace the classical ‘phase-space’ representation with the quantum ‘wave-function’ representation of the Universe; the key point is that in both cases the Universe is represented by a long list of numbers.

[10] Strictly speaking, this is an estimate of the number of baryons in the Universe and is simply figurative of the sort of numbers were dealing with when describing the classical phase-space of the Universe.

It is conceivable to then reduce this information content further. It could be that these real numbers, n, Q, etc. are related to, say, an inflationary potential parameterised by an integer power or two (whether or not this is the case is yet to be determined), thus reducing the required number of 'bits' from that of a real number to that of an integer. In other words, even $\sim 10^{80}$ real numbers[11] making up the initial conditions of the Universe, which at first seems like a tremendously complex information content for a theory to encapsulate, could in principle (if we allow the concept of 'intrinsic randomness'[12] to play a role in our explanatory framework) be reduced to just a few integers via some relatively short algorithms.

One might then hope that the inflationary potential takes the form it does because of some underlying theory of particle physics that would uniquely relate the parameters in the inflationary potential to, say, a fundamental constant (or a parameter that is the common progenitor of it and other fundamental constants). In this way, the giant list of numbers - perhaps infinitely long - that are the coordinates of the phase-space of the Universe could, conceivably, have the same Kolmogorov complexity as that found in a relatively short computer program and a few integers.[13] All of this is neatly summarised by Davies who writes,

> Although the Universe is complex, it is clearly not random. ... The existence of regularities may be expressed by saying that the world is *algorithmically compressible*... Given some data set, the job of the scientist is to find a suitable compression, which expresses the causal linkages involved (Davies 1995, p. 252, 49).[14]

If such a ToE were ever discovered, uniquely specifying our Universe, then it would be able

---

[11] Whether or not the precision of each real number in the coordinates of the phase-space of all the classical particles is infinite or not is a fascinating question. Some have suggested that there is a limit to the number of 'bits' of information that the Universe can store on its 'hard drive' based upon the number of plank volumes in the Hubble volume (presently $\sim 10^{122}$; see Lloyd 2002).

[12] The philosophical question as to whether or not there truly is 'intrinsic randomness' is beyond the scope of this thesis. I assume a common-sense understanding of the term.

[13] Kolmogorov complexity is a measure of the information contained within a string of characters or numbers in terms of the shortest algorithm required to generate it. A string of perfectly random numbers can not be reduced algorithmically at all, whereas an infinitely long number like π can be compressed algorithmically to a simple computational process. In this sense, the presence of 'naturally occurring' or 'geometric' numbers such as π and e can feature regularly in a ToE without doing too much to detract from its overall simplicity. See discussion p.16.

[14] Davies also points out in this article that the question as to what *language* we express the computations of the Universe in makes little difference to the overall scenario because all universal computers can simulate one another and that the extra program length needed is typically very small. He notes that, "The fact that the definition of machine complexity is machine-independent suggests that it captures a really existing quality of the system" Davies 1995, p. 252.

to predict *all* observations (statistically) in principle, relating them back to just a hand full of parameters, ideally, 2's and π's, etc. For example, if we were to ask what the galaxy luminosity function of our Universe would be at $z = 0$, such a theory would be able to predict it to arbitrary precision given enough computing power. Ideally still, the final ToE would also be such that 'it could not have been otherwise,' thus approximating 'platonic truths' such as why 27 is divisible by 3, etc. and thereby providing some sort of answer to Leibniz's first question.[15]

There are two very obvious reasons to be pessimistic over such a prospect. Firstly, even if the formalism of a ToE were ever worked out, it is hard to see how one's mental contemplation of the theory alone could ever address the question of its substantiation. What is it, as Hawking famously put it, that "breathes fire into the equations?" Secondly, it is very difficult to see how the ToE could ever be 'unique' since we can easily imagine *any* combination of numbers constituting the phase space of the Universe in the trivial representation. For this reason Weinberg thought that the best one could hope for would be an "isolated" ToE,

> The final theory would be like a piece of porcelain that cannot be warped without shattering. In this case, although we may still not know why the final theory is true, we would know on the basis of pure mathematics and logic why the truth is not slightly different. (Weinberg 1993, p. 189)

As the ToE is most closely associated with particle physics, it is not surprising that its practitioners in particular have been highly reluctant to admit anything anthropic (or the "A-word," see quote p.71) into their methodological framework. There are two key reasons why anthropic reasoning, if cogent, would undermine one's confidence in the future discovery of a ToE.

Firstly, as was argued in Darg (2012), it is plausible that our existence places 'anthropic constraints' on the complexity of the Universe, that is, on the extent to which the Universe's phase space can be algorithmically compressed. If the Universe were too simple, it would not be able to furnish the sort of complexity that our existence requires. A Newtonian world with two particles (and one free parameter) would be simple, and thus parsimonious in the way that proponents

---

[15] This hopeful prospect is neatly captured by the words of John Wheeler, "To my mind, there must be at the bottom of it all, not an utterly simple equation, but an utterly simple idea. And to me that idea, when we finally discover it, will be so compelling, and so inevitable, so beautiful, we will all say to each other, 'How could it have ever been otherwise?' (Wheeler 2004).

of a ToE would like it to be, but not life-permitting. Our presence *surely* requires some minimal number of independent parameters (just as a complex computer program does), of which there are presently several dozen,[16] that are required to specify our Universe. It could even be the case that we have already substantially achieved the maximum degree of 'compression' that is possible in the standard models of particle physics and cosmology (though it is methodologically pragmatic to assume this is not the case).

Secondly, it is widely accepted that these parameters turn out to be finely-tuned such that small changes to them (when expressed in a dimension-free manner) would render life as we know it impossible (or unlikely) for one reason or another (Carr & Rees 1979; Barrow & Tipler 1996; Rees 2003; Tegmark et al. 2006; see §2.1 and 3.1 for further discussion). For a discussion of the meaning and cogency of claims to FTL, see Appendix A.1. The increasingly popular position amongst physicists that would ostensibly "explain"[17] this fact is to combine the AP with a Multiverse containing a very large number of separate space-time domains where the fundamental parameters are allowed to vary. In this case the ToE - if there is such a thing - would have to govern the distribution of local 'by-laws' and values of 'constants' and would therefore be too general to describe our Universe uniquely. As a consequence, few or no predictions could be made regarding observables herein and our best theories would end up as they are now - semi-empirical prescriptions giving our local "address,"[18] so to speak, in the vast Multiverse.

The AP is no doubt also distasteful to physicists since, from its very inception, there has been an aura of 'mysticism' attached to it. Ambiguous and provocative choices of words are partly responsible for this, such as the 'Strong Anthropic Principle,' that states that the Universe *must* (whatever that means) be such as to eventually enable the presence of observers (Carter 1974). Additionally, theists have taken up the FTL and AP as a means to revitalise the teleological argu-

---

[16] For example, Scott (2006) counts there to be 26 free parameters in particle physics and 12 in cosmology; Tegmark et al. (2006) count there to be 26 in particle physics and at least 5 in cosmology though likely this will require about 6 more when observations are refined.

[17] Note that, what is meant by "explanation" is a philosophically contentious subject and shall be discussed throughout Chapter 2.

[18] I borrow this phrase from Tegmark; Wilczek expresses a similar thought, "According to the new zeitgeist, the real world of phenomena must be consulted after all, if only to position ourselves within a perfect, but inaccessible, multiverse" (Wilczek, 2007a, p.44).

ment (Stafford Betty & Cordell 1987; Holder 2004; Swinburne 2004; Collins 2009; Spitzer 2010). It is not surprising therefore that, for many, the AP is associated with extra-scientific discourse.

As understandable as the desire of the ToE proponent might therefore be to exclude the AP on methodological grounds, we note that it is, at rock bottom, a distinctively pragmatic *belief* that the Universe can be reduced to an arbitrarily simple representation by humans and that, arguably, it is implausible that this is the case. Not only does our existence seem to place a lower limit on the complexity of the Universe, such that *in principle* the Universe could not be reduced to an arbitrarily simple representation, there is also little reason to think that our cognitive capabilities are such as to be able to accomplish this. As Barrow explains, there could be a cognitive bias implanted in us to seek out patterns where none in fact obtain (or are discernible);

> the search for a single all-encompassing Theory of Everything [is] the ultimate expression of some scientists' deeply held faith that the essential structure of the Universe as a whole can be algorithmically compressed. But we recognize that the human mind plays a non-trivial role in this evaluation. Inextricably linked to the apparent algorithmic compressability of the world is the ability of the human mind to carry out compressions. Our minds have evolved out of the elements of the physical world and have been honed, at least partially, towards their present state by the perpetual process of natural selection. ... [because of evolutionary pressures] the brain would effect an algorithmic compression upon the Universe whether or not it were intrinsically so compressible. (Barrow 1991, p.232-3).

To asses the intrinsic worth (or lack thereof) of the AP, we must therefore think hard about the nature of human cognition. Unfortunately, this has been largely overlooked by working cosmologists since they, by the nature of their work, tend not to involve themselves in discussions on the philosophy of mind. In §2.1 it will be argued that there are surprising similarities between the key problems that cosmologists face today and what philosophers of mind have been trying to tackle for millennia.

Like physicists, philosophers of mind are in search of a "final theory" though there is little agreement on what that final theory would look like. The view most amenable to the scientific method is one in which the mind is viewed as a 'pattern-recognition' machine - an entity capable of extracting the patterns of nature and using these to create something like a simulation of the external world within the brain to help navigate one's way through life. It is regularly posited as a working proxy for ‘life’ in discussions on the AP (e.g. Hartle 2007 lists “information gathering and utilizing systems” as a candidate for a quantum cosmological selection-effect criterion).

From this perspective, the mind is a quantifiable input-output machine no different in principle from a computer, a thermostat or a windmill,[19] and ostensibly renders reference to everyday or “folk-psychological” concepts such as beliefs, perceptions, desires, etc. obsolete. This is the philosophical position of *eliminitavism*. It is the view that the wide-spread (hence “folk-”), common-sense assumption that such states as beliefs or desires are what constitute or chiefly affect the course of human cognition is, according to Churchland (1995, p.322), “probably mistaken” and therefore in need of elimination.

To illustrate this stance within the philosophy of mind, and to introduce the reader to the astrophysical projects that will feature in Part II, we can analyse the Galaxy Zoo project from the eliminitavist perspective. The Galaxy Zoo project is an initiative that originally sought to assess the morphologies of galaxies of $893,212$ photometric objects from the Sloan Digital Sky Survey (SDSS) using volunteers via the world-wide web. This is a pattern-recognition problem *par excellence*. The astrophysical motivations for precision evaluation of galaxy-morphology will be discussed in §4; for now, we will merely sketch out how Galaxy Zoo works. (The corresponding published description of the project is Lintott et al. 2008.)

Natural selection requires that humans navigate their environment in a manner that promotes survival. Over the course of time, the neural nets that constitute the human brain have come to be equipped with standard capacities such as the representation of 3D trajectories (the throwing and evasion of projectiles), the ability to form mental representations of the local environment and, in particular, acute facial recognition prowess (see Geary 1998, ch.8 and references therein). A large part of scientific discovery can be understood as spin-off effects of such adaptations (though we will not speculate on specifics in the fashion that is popular in the field of evolutionary psychology).

The human capacity for pattern-recongition lends well to galaxy-morphology studies - especially mergers - since the reconstruction of 3D trajectories, to mentally rotate discs, etc. allow one to assess the recent history of a galaxy to considerable accuracy (or at least, to much more

---

[19] C.f. Leibniz, *Monadology*, 17.

accuracy compared to a computer and relative to the processing times involved). Above all, the human brain is highly adaptable and can be readily inducted into new pattern recognition tasks not previously encountered by the individual. Before users of the Galaxy Zoo interface could participate, they had to have their 'neural nets' trained via an online tutorial, the principles of which are easily understood by *back-propagation* in neural net theory. (A user is shown a galaxy image and text that associates the pattern, say, "spiral" and a spiral shaped galaxy. If a user classifies a galaxy in disagreement with the pre-determined 'expert' opinion, then they are informed of this and their neural net back-propagates in such a way as to get it right next time; see Mackay 2009, ch. 39 for introduction.)

The volunteers then take a test which, if passed, enables their classifications to be officially registered. An image is sent via the web to the individual's computer screen to appear in the interface as shown in Figure 1.1. The image is transmitted via photons to the user's retina in a configuration that closely resembles the original photons incident on the 2048×2048 pixels of the CCD chip of the SDSS instrument. From there, the intricacies of the neural net take over that function, from the eliminitiavist perspective we are describing, deterministically. As a result of the image training undergone, the neural net of the individual is configured to fit the image to a template and this eventually results in the mechanical output on the computer mouse to click on the corresponding template (c.f. the spiral button) in the interface.

The grand effect of this is to produce something like a giant neural net via the world-wide web and hundreds of thousands of volunteers. Each image was viewed ~ 38 times allowing the extraction of a level of confidence for any given morphological fit. In particular, this study will concentrate on how the fraction of votes for the 'merger' category was used to produce a very powerful merger catalogue (see §4), and how this lead to the development of a new and improved technique for finding and studying mergers (§7).

The description given thus far required no folk-psychological terms in order to convey how, roughly speaking at least, the Galaxy Zoo project converts image arrays into morphological quantifiers. Indeed, this can be said of all processes in the external world; in particular, all human interactions can be analysed as the result of 'information processing' carried out by their in-built

Galaxy Analysis

Welcome to Galaxy Zoo's view of the Universe. If you're here you should already have seen the Tutorial, but feel free to go and remind yourself. There's no need to agonise for too long over any one image, just make your best guess in each case.

Galaxy Ref:
588010880371851294

Choose the Galaxy Profile by clicking the buttons below

Figure 1.1: The original Galaxy Zoo interface. Users had a choice of six morphological templates: elliptical, spiral edge-on, spiral clockwise-rotating, spiral anti-clockwise-rotating, star/error and merger. The major task carried out in §4 was to turn the clicks on the merger-button into something scientifically useful.

neural nets. Moreover, no distinction was apparent between the causal activity taking place in the internet, the computer, the telescope or the human brain: they were all part of the same overall ‘information-processing’ system.

This has ramifications when it comes to deciding what is meant by an ‘observer.’ If humans are indistinguishable from information-processing systems such as the internet, and humans are observers, then it is tempting to identify an observer as something that processes information. In which case the internet is an observer just as much as we are. And why stop there? Are the photons that travel across space “carrying information” also ‘observers’? As we can begin to see, as tempting as such a definition might be for an observer, ‘information’ is ultimately a vague criterion (see Barbour 2011 who notes that the term ‘information’ can be used in several different ways, often giving rise to ambiguity). Many systems exhibit input-output relations; even a rock that absorbs and subsequently emits radiation can be construed as an input-output ‘machine.’ Does the rock process information? Why is it different from a computer or the human brain?

This carries the discussion into the tricky subject area of ‘specified complexity,’ entropy and coarse-graining. The puzzling fact is that we have an intuitive sense in which the human is characteristically different from the rock, but it is extremely difficult to put one’s finger on exactly what - if anything - the distinguishing characteristics are without appearing anthropocentric. Consider the words of Penrose on describing entropy,

> It is important to realize, when we refer to the ‘specialness’ of a low entropy state, that we are referring to *manifest* specialness [e.g. an assembled glass full of water]. For, in a more subtle sense, the higher entropy state, in these situations [e.g. a smashed glass and spilled water], *is* just as ‘specially ordered’ as the lower entropy state, owing to the very precise coordination of the individual particles. (Penrose 1999, p. 399).

As Penrose recognises in the passages that follow, terms such as ‘special’ and ‘useless’ are somewhat vague and potentially anthropocentric; what does it mean for something to be ‘special’ or ‘useful’ independent of human convention? Yet physicists worry little about such nuances since the intuition that the brain is a very ‘special’ configuration (while the rock is not) is so strong that for all *practical matters*, their entropic calculations can be performed and applied without any need to worry. Unfortunately for us, we are not tackling a *practical* problem at this point but the *philosophical* problem as to what constitutes an observer. In a similar way, working physicists can operate using the quantum formalism of the Copenhagen interpretation and achieve their practical, technological aims without worrying about what constitutes a ‘measurement’ or an ‘observable’ in the philosophical sense (whereas *philosophers* of quantum mechanics, by contrast, require the pedanticism of Niels Bohr). It is not enough therefore to wave one’s hands and declare that there is a common-sense division between rocks and brains. Both are being viewed as material objects that interact with their environment, both are relatively low-entropy states. Appeals to ‘specified complexity’ or ‘specialness’ make tacit use of a privileged reference class, but which one and why? If ‘specialness’ makes ultimate reference to *us*, then this undermines the realist’s project of describing the world independently of human convention.

The lesson we shall draw at this point is that, as was found in quantum mechanics, ‘observerhood’ is a vague and controversial subject, and we cannot pretend to offer a definitive answer. The only conviction that can be put forward with any sort of force is that the notion that an observer is an ‘information-processing machine’ is an appealing one when doing science but it ultimately fails to offer much if any guidance as to how one demarcates observer from non-observer philosophically. Is a fly an observer? Is an amoeba an observer? Is a cell phone an observer? If not, why not?

These are questions we can leave to those of the eliminitavist stance that we have been considering (see Churchland 2000 for a hard-line take on the eliminitavist perspective). To others who perhaps agree that an ‘information-processing’ construal of ‘observerhood’ does lead to an impasse of sorts, a re-evaluation of the path that lead us to this point will seem worthwhile. That path was the denial of the first-person perspective in describing the contents and state of the world. To expel perceptions, beliefs, desires and the like from one’s philosophical outlook was always going to result in confusion for us, that it is, the individual contemplating such thoughts; for who else could be contemplating such thoughts apart from the individual?[20]

In the next chapter we shall bracket eliminitavism aside and take seriously the datum of consciousness in the context of the Multiverse scenario and AP. It will be shown that the Multiverse is such an all-encompassing concept that it can be used to “explain” absolutely everything - even problems as recondite as the mind-body problem. As a purely metaphysical proposal it can be adopted in regards to Leibniz’s first question but there is very little scientific utility in the proposal, if we understand science as the quest to render a positivistic account of natural phenomena.

---

[20] Our discussion thus far parallels d’Espagnat’s philosophical analysis of the observable and its inextricable link to the individual. He writes, “Up to this point, of course, a realist may consider that everything is still all right. We easily conceive of a Universe essentially independent of our own selves while some parts of it do act on us, and we find it reasonable to only talk about the latter. But on reflection we realize that we are faced with a serious question. If our universe of discourse is indeed limited and shaped up by our perceiving aptitudes, as we just considered must be the case, what guarantees have we that we do perceive facts and things as they really are “out there”? ... the idea seems to be to acknowledge the absolute primacy of the notion of possible observation (or experience) while simultaneously ignoring the ultimate reference to the fact of getting aware that the primacy in question normally implies [and] to try and make this view consistent by implicitly evoking some vague notion of some sort of impersonal, hence objective, “observation-per-se.” ... in their scientific acceptation, the notions “to observe” and “to experience” essentially imply selectively turning one’s attention to such and such particular. This is what distinguishes experimentation from just passively “looking around.” But then, may we really speak of the experience an instrument would have? Is there, in an instrument, something akin to selective attention? I mean, is, by itself, the position of its pointer more significant (for whom? for “it”?) than the one of any one of its constituting atoms, or of the fly that happened to graze its dial? ... when all is said and done, the very notion of some “observation-per-se,” taking place in a world completely composed of inanimate objects turns out to be self-contradictory.” (d’Espagnat 2006, p. 450-1).

Chapter 2

The Anthropic Principle and the Mind

2.1 A Surprising Connection

It is quite clear that experts in different disciplines of thought should communicate with each other more than they do. However, because human beings differ in their motivations, beliefs, and ways of thinking more than is apparent, it is always difficult to bridge the gaps between distinct fields. Incompatibilities between words and basic notions, differing conceptions of what strictness should consist of – these and other obstacles combine in making the task arduous indeed. Bernard d'Espagnat[1]

At a conference on the philosophy of cosmology in Oxford 2009, Martin Rees presented two conceivable forms that might characterise a final physical "Theory of Everything" (ToE), as discussed in §1, summarised versions of which are shown in Table 2.1.

These theories prompted the following exchange between Rees and three other cosmologists - George Ellis, Brian Greene and Raphael Bousso - that provides an excellent summary of the contemporary debate on fine-tuning and the Anthropic Principle.[2]

---

[1] d'Espagnat (1983, p. 1).

[2] The following transcript is taken from the video archive for the conference. I have chosen punctuation, elision and removal of pauses in a way that I believe remains faithful to the original intention of the participants. It can be found here `http://www-astro.physics.ox.ac.uk/\~ddarg/shtml/rees_talk.shtml` between $\sim 39:30-43:15$.

Table 2.1: Possible forms of a ‘Theory of Everything’ according to Rees.

ToE$_A$	**ToE$_B$**
1) All physical parameters are uniquely determined.	1) There are universes with several, or even an infinity of values, for some parameters, dependant on the outcome of symmetry breaking, compactification, etc.
2) (Therefore) there’s no role for anthropic reasoning.	2) The parameters in our “universe” should be typical of the anthropically allowed subset weighted by the (theory generated) prior probability distribution.

Ellis: What I don’t think people comment on enough [is that ToE$_A$] is more difficult to understand than [ToE$_B$] because then you’ve got your fundamental theory and it leads to a set of effective theories in the standard model of particle physics. . . [with] the parameters lying in one particular ‘spot.’ There is no reason why that fundamental theory should cause that ‘spot’ to lie in the anthropically allowed domain... so that introduces a much bigger puzzle and so [ToE$_B$] is a much less puzzling way of solving it than [ToE$_A$].

Rees: I completely agree that that is reason why, in ignorance of the detailed physics, many of us would not be surprised if we are forced towards [ToE$_B$] because, indeed, it does get round that problem.

Greene: I’m sorry, I don’t quite understand that. I mean, if you truly have a fundamental theory that determined all the parameters uniquely. . . what’s the issue? I mean, you can say ‘why *that* theory?’ . . .

Ellis: because... you could have ended up anywhere.

Greene: . . . yeah you could have, but you couldn’t, because it was uniquely determined, right? . . .

Ellis: . . . yes but there’s a subset there which allows life to exist and there’s no reason why $SU(10) \times U(5) \times O(3)$ - or whatever - must end you up with those values lying precisely where the strong-force-to-the-weak-force ratio is such as to allow life to exist. In that case the image of life would be written into $SU(10)$ in some sense so that is incredibly strange.

Greene: But if that’s how it is, that’s how it is. . .

Bousso: . . . this is just a comment on [Ellis’] and [Greene’s] exchange. String theory, I guess, [was long] believed to be one of those theories that will just spit everything out, you know, in terms of 2’s and π’s and so on and we’ll understand the electron mass and, back in the 80’s Schellekens, maybe others but certainly Schellekens, was worried about the fact that if this was true it would seem rather miraculous that at the same time, you know, all these incredibly Fine-Tuned things would come out just right because it's so obvious that if you just vary these parameters a little bit, suddenly you don't have complex structure. So it certainly was something that people did worry about, and I think with some reason…

Rees: …this is metaphysics …

Greene: …but what's the measure of the space of ideas for which we should be surprised? …I think that's the key thing that's driving the conversation.

Two important characteristics of the fine-tuning debate stand out in this discussion. Firstly, the question raised at the end of the exchange ("what's the measure of the space of ideas for which we should be surprised?")[3] is indicative of the widespread presumption of a functionalist account of mind amongst cosmologists.[4] This philosophical stance tends to go hand in hand with the common desire amongst cosmologists to "mathematize" literally everything in existence, even our 'ideas' (and leads them to take seriously the possibility that we might be living in a computer simulation).[5] This is philosophically contentious and extremely counter-intuitive, to say the least: surely we must consult our ideas *first* in order to assess whether our choice of mathematical representation is sensible, not the other way around.

This is connected with the problem of formalising our prior expectations in the Bayesian approach to anthropic reasoning given our lack of appropriate background knowledge in this metaphysical context. We can always write down *some* prior, but whether or not it is a 'sensible' choice

---

[3] Note, the participant might have intended this sentence to be metaphorical, meaning something like "but what is your background knowledge and why think that your sense of surprise is to be taken seriously?" Greene shows sensitivity to subtle issues regarding the philosophy of mind in his most recent book "The Hidden Reality," see Greene (2011, p. 281-306) for a good discussion on the philosophy of mind and its pertinence to the Multiverse hypothesis.

[4] Functionalism is the position that identifies consciousness with something like an information-processing system (e.g. a computer program). Many examples of this widespread presumption amongst cosmologists (and physicists generally) can be given, such as, "The human mind is a very complex yet special type of program. It is capable, in particular, of forming a model of itself as a subprogram, and studying this subprogram. This model-building and analyzing process is called consciousness." Barrow & Tipler (1996, p. 155). Also, "Computer scientists have made it plausible that the essence of mind is to be found in the operation of algorithms that in principle could be realized within radically different physical embodiments (cells, transistors, tinkertoys) and in no way rely on the detailed structure of physical law" (Wilczek 2007b, p. 151).

[5] Tipler (1994), Bostrom (2003b), Barrow (2007), Tegmark (2008), Greene (2011).

can only be decided by a strictly qualitative judgment.[6] I aim to show that some of the conceptual problems that characterise cosmological speculation (such as the Universe arising out of 'nothingness,' see §2.5.2) are due in part to a general lack of appreciation of the subtleties of the philosophy of mind and this leads to the 'over-reification' of mathematics. Until cosmologists start to think seriously about the nature of consciousness and its primacy in theory adjudication, certain confusions and points of contention (as seen in the above exchange) will continue on indefinitely. In short, cosmologists might benefit from interaction with philosophers of mind.[7]

Secondly, notice how difficult it is to articulate a sense of modality[8] that would appropriately depict 'why' the laws of physics take the form they do. On the one hand, it would seem like an absurd coincidence if the only possible form of ultimate physical theory were just right for life. On the other hand the very notion is paradoxical since, in some sense, there would be no 'coincidence' as it was 'unique' and therefore 'necessary' in the sense that an existing universe could not have been otherwise (hence Greene's aphoristic reply "you could have, but you couldn't").

Mainly owing to the strong intuitive sense in which it is in fact *not* necessary that our Universe be the only kind that can exist (for it is easy to imagine many other logically possible universes, see §2.2), cosmologists have largely turned to $\mathrm{ToE_B}$ and the anthropic reasoning it requires. So whereas the single-Universe hypothesis faced an awkward interplay between chance *or* necessity in light of fine-tuning, the Multiverse hypothesis (conjoined with the Anthropic Principle) offers a *prima facie* more satisfactory combination of chance *and* necessity.[9]

It is interesting to note that this question (why does the material world have the form it does?)

---

[6] Any series of mathematical symbols can be written down, but deciding whether or not (i) those symbols "mean" anything and (ii) whether those symbols have anything to do with "reality," requires a strictly qualitative judgment lest we end up with a regress *ad infinitum*. If my equation is deemed sensible because it can be mapped to some numerical proxy of "sensibleness," then we again have to decide whether that mapping is "sensible," and so on. This comes down to the fact that all human reasoning must boil down to statements of 'intuition' and 'naturalness.'

[7] Paul Davies seems to agree that there is something subtle and important about the nature of consciousness that is unduly overlooked in discussions on fine-tuning, "Humans… are more than mere observers. They also have the ability to *understand* the universe through logical reasoning and the scientific method. This remarkable fact, often taken for granted by scientists, cannot be explained by anthropic/multiverse reasoning." Davies (2007, p. 493-94).

[8] I.e. to say what is meant by 'necessary' or 'possible' in the given context.

[9] Suppose that the Multiverse exists in some 'necessary' sense (akin perhaps to how it used to be supposed the Universe existed 'necessarily' or 'brute-factly'). Then, no matter how rare ('chance-like') a biofriendly universe-domain might be in the space of *logical* possibility, if the Multiverse is sufficiently large and variegated it will inevitably generate one like ours. Then, because we can only observe the universe if it is suitable for life, our sense of surprised is removed (or so the argument goes). Hence an element of *both* 'chance' *and* 'necessity.'

has the same basic structure as that posed by philosophers of mind (why does consciousness exist and have the form it does?).[10] I aim to show that there are many intriguing parallels between these two questions. Unlike the cosmologists though, philosophers of mind continue to struggle with the traditional, restrictive modalities when it comes to 'explaining' how consciousness arises from matter and comes to take the particular form it does. Is it that it is somehow 'necessary' that matter give rise to consciousness (when we can conceive of logically possible alternatives) or is it to be construed as some play on 'chance'? It shall be shown that a very similar game can be played in the philosophy of mind as is currently played in cosmology, namely, that a Multiverse plus selection effects can be used to account for *absolutely everything* - even phenomenal, structurally coherent experience, that is, consciousness. Although this will be presented as an indirect criticism of infinite Multiverse hypotheses, it will likely intrigue philosophers of mind.

2.2 Historical Precedence of the Connection

Does this mean that understanding all the properties of our region of the universe will require, besides a knowledge of physics, a deep investigation of our own nature, perhaps even including the nature of our consciousness? This conclusion would certainly be one of the most unexpected that one could draw from the recent developments in inflationary cosmology.[11]
– Andre Linde

The teleological argument has had a rough ride since Paley. Few would now defend his design argument in academic circles where it is accepted that Darwinism offers a superior account of the origin of biological complexity. The last stand for the design argument, it would seem, therefore rests on 'wider teleology' such as the prerequisite FTL. However, Paley had a subtle rejoinder by way of the seemingly inexplicable correlation of consciousness with biological complexity (an argument he likely borrowed from Locke)[12] and, as shall be argued, this same basic rejoinder applies equally well to the modern day debate between theists and non-theists with regard to the

---

[10] The perennial problem philosophers of mind face is to find an appropriate modality to describe 'why' it is that matter gives rise to consciousness – an awkward interplay between 'chance' and 'necessity.'

[11] Linde (1994, p. 104).

[12] C.f. Locke, *Essay*, IV, iii, 28.

Multiverse and fine-tuning.

Let us begin by reviewing Paley's overall reasoning, which was subtler than many appreciate. This is in part because few are acquainted with Paley's work beyond his watchmaker analogy,[13] but also because Paley did not formalize his design argument via explicit premises, preferring to base his case solely on analogies.[14] It is therefore easy to read Paley and miss this much-neglected line of argumentation based on consciousness that Darwin was reluctant to address. Paley's design inference did not rely solely on there being complexity in nature (what we might label his eutaxological argument) but that it also coincided with the instantiation of pleasure and pain in living beings in an appropriate way (what we might label his teleological argument).[15] This extra focus is not surprising given his background.

Paley was not only a natural theologian but also a political philosopher and utilitarian.[16] The influence of this ethical-political stance on his natural theology is evident throughout his writings on the subject. Although Paley thought that material contrivance was sufficient evidence for a generic deity, it was phenomenal contrivance specifically that grounded his inference to theism. That is, it made no sense to say that the material contrivances of nature had a manifest *use* or *purpose* unless these terms made implicit reference to some occurrence of *utility* in nature in the phenomenal sense of the word – pleasure and pain in their qualitative aspect.

---

[13] In fact, the second half of Paley's Natural Theology focused precisely on proto fine-tuning arguments in astronomy and the laws of physics. Even when Darwinism took center-stage, its proponents were swift to recognize the wider-teleological implications of the theory as the whole ecological history of the world would have to have been "encoded" in the initial conditions of the Universe (or conditions going arbitrarily far-back in time). See, for example, the quote by Huxley, Barrow & Tipler (1996, p. 87).

[14] Paley was familiar enough with metaphysics to know that no knock-down argument could be given for the design inference that would overcome the extreme scepticism of pre-Darwinian thinkers like Hume. Thus "Paley sought to prove the existence of a Designer beyond reasonable doubt - knowing that deductive logical proof was not possible, but that while sceptical logic-choppers could never be silenced, they could be made to look absurd," Eddy & Knight (2008, p. xxi).

[15] It arguably belongs to the very concept of *telos* ($\tau\varepsilon\lambda o\varsigma$) that there not be just *any* sort of 'end,' but that the 'end' be of some *value* or *utility* to someone, the sort of end that an agent would in some way *desire*. In short, it is impossible to divorce the concept of teleology from utility. This is reflected in the very etymology of *telos*; as well as meaning 'end' or 'goal' the original Greek usage also denoted 'value,' 'price,' or 'tax.' The distinction drawn here between 'eutaxological' and 'teleological' arguments may be slightly idiosyncratic (where I emphasize the role that *qualitative utility* plays in demarcating the two concepts); for an alternative discussion of these two concepts, see Barrow & Tipler (1996, p. 29ff) who attribute the terminology to L. E. Hicks (1883).

[16] Paley was a key figure in the late 18th century movement 'Theological Utilitarianism.' It did not last long as most 19th century theists took exception to utilitarianism, reckoning it to be a secular system of ethics in competition with their own. Much of Victorian literature sought to discredit the philosophy by casting the antagonist (as Dickens so often did) as highly materialistic, cold, calculating, etc. See Cole (1991) for historical discussion of the movement.

Paley was thus explicit in the opinion that these two facets of nature are conceptually and metaphysically independent of each other: complexity is *not*, by itself, sufficient for the instantiation of the qualitative aspects of mental life, rather, the capacity to experience utility had been "superadded" to biological organisms that otherwise would have merely been complex automata.[17]

> The necessary purposes of hearing might have been answered without harmony; of smell, without fragrance; of vision, without beauty. Now [i]f the Deity had been indifferent about our happiness or misery, we must impute to our good fortune (as all design by this supposition is excluded) both the capacity of our senses to receive pleasure, and the supply of external objects fitted to excite it. Paley (2008, p. 252).[18]

There are thus two prongs to Paley's argument: the fitting of sensory organs (the eutaxological) and, separately, their 'capacity to receive pleasure' (the teleological). The one does not automatically entail the other, in Paley's opinion, and so the fact that physical states and mental states coincide in such a regular and appropriate manner would be entirely coincidental without design.[19]

Darwin's theory of evolution offered a radical alternative account for the first part of Paley's observations – the existence of biological complexity in nature – and in virtue of this alone came to displace the whole of Paley's design argument as the dominant intellectual paradigm. But despite deep familiarity with Paley's work, Darwin seems to have been extremely reluctant to grapple with the second, subtler prong of Paley's argument: why does nature bring forth the qualitative aspects of pleasure and pain? Why is there any conscious experience at all in nature? Darwin just seems to take it for granted that to account for complex behaviour automatically entails the instantiation of such things as qualia[20] (and thus utility). This is evidenced by his ambiguous intermixing of utility-

---

[17] "…the Deity has superadded *pleasure* to animal sensations, beyond what was necessary for any other purpose, or when the purpose, so far as it was necessary, might have been effected by the operation of pain." Paley (2008, p. 236) [Italics original]. In modern parlance, we could say that Paley took philosophical zombies to be both conceivable and metaphysically possible.

[18] He continues, "I allege these as two felicities, for they are different things, yet both necessary: the sense being formed, the objects, which were applied to it, might not have suited it; the objects being fixed, the sense might not have agreed with them. A coincidence is here required, which no accident can account for."

[19] To use Chalmers' paraphrase of Kripke (2001, p. 153-4), "When God created the world, after ensuring that the physical facts held, he had more work to do." (Chalmers (1996, p. 124).)

[20] Conveying to those unfamiliar with the term what is meant by (or referred to by) the word "qualia" is, in one sense, extremely difficult yet, in another sense, extremely easy. As a first gloss we can say that a *quale* (plural *qualia*; the term 'percept' is used in a similar regard in philosophical circles) is the distinctive, subjective quality that constitutes or

laden terms with mechanistic terminology and his gratuitous distinction between the ‘corporeal’ and ‘mental.’ For example,

> As natural selection works solely by and for the *good* of each being, all corporeal and mental endowments will tend to progress towards *perfection*. . . There is *grandeur* in this view of life. . . from so simple a beginning endless forms most *beautiful* and most *wonderful* have been, and are being, evolved.[21] [Emphasis added]

The obvious problem not addressed by Darwin’s purely mechanistic account of complexity – one that purports to expunge any form of *nous* (νους) from the creation account[22] – is the then anomalous appearance of *nous* in biological organisms. Why is there *any* ‘good,’ ‘wonder,’ ‘beauty,’ in nature rather “than blind pitiless indifference?” Certain key figures in the early Darwinian movement, such as Thomas Huxley, recognised the problem and sought to address it.[23]

---

characterises a mental experience. If this sounds rather untechnical and imprecise, there is a reason for that, namely, that it is impossible to precisely *define* something using words that mean or refer to other things that are not as intuitively immediate and accessible as the very thing you are trying to define. The claim is that the word qualia refers to those aspects of one’s mental life with which one is so intimately acquainted that we cannot really *define* what qualia are *per se*, we can only point them out through examples. Thus, it is common place to describe qualia through the phrase “the what-it-is-like to (experience something).” For example, if someone is asked “do you know what it is like to taste an orange?” or “do you know what it is like to see the colour red?” most people will reply, “of course.” It is in this sense that it is easy to grasp what is meant by qualia. When one is unconscious (say, in a dreamless sleep), one does not have any qualia. When one is awake and is visually experiencing the world, enjoying tastes, suffering pain, etc., one *does* have qualia. For an excellent further introduction to the concept, I recommend Frank Jackson’s famous thought experiment, “Mary in the black and white room” (`http://plato.stanford.edu/entries/qualia-knowledge/\#2`) Jackson (1982). (This thought experiment is also referred to as the ‘Knowledge Argument.’ My aim here is not to endorse Jackson’s conclusion, which he himself later repudiated, rather, I cite it as it is an excellent means to help the reader gain familiarity with the term.)

[21] Darwin (1998, p. 395-6). It is generally acknowledged that Darwin’s position on the philosophy of mind is difficult to pin down and that his opinions on the matter varied over his lifetime. On occasions he speaks of consciousness as something real and distinct from the biophysical system as when he writes, “A sensitive nerve when irritated transmits some influence to the nerve-cell... This involuntary transmission of nerve-force may or may not be accompanied by consciousness,” Darwin (1989, p. 53-4). Yet, most of his analysis of mind, principally in *The Descent of Man* and *Expression of the Emotions*, was strictly behaviourist and thus rendered phenomenal consciousness superfluous to his theory. Robert Richards surmises, “Darwin never really plumbed the philosophical depths of the mind-body problem. But he formed a fairly clear and simple idea of the relationship of thought to brain... For the Newtonian scientist (an ideal toward which Darwin aspired), the occult connections between matter and its powers did not need explanation, only description. So Darwin felt comfortable with the agnosticism expressed by Abercrombie as to the ultimate relation of mind and brain. In a passage Darwin marked, the Scots philosopher declared: “Matter and mind are known to us to be certain properties:- these properties are quite distinct from each other; but in regard to both, it is entirely out of reach of our faculties to advance a single step beyond the facts which are before us. Whether in their substratum or ultimate essence, they are the same, or whether they are different, we know not, and never can know in our present state of being.” To this passage, Darwin appended the Newtonian observation: “It is sufficient to point out the close relation of kind of thought & structure of brain.”” Richards (1987, p. 95). See also Richards (2005).

[22] This goes back to the Ionian philosophers. Anaxagoras. . .

[23] Huxley famously espoused a form of epiphenomenalism comparing conscious experience to the whistle on a steam locomotive - an effect of the engine with no causal feedback (Huxley 1874; quoted in James 1990, p. 86).

Alfred Russel Wallace, co-discoverer of natural selection, wrote,

> Neither natural selection, nor the more general theory of evolution can give any account whatever of the origin of sensational or conscious life. They may teach us how, by chemical, electrical, or higher natural laws, the organized body can be built up, can grow, can reproduce its like, but those laws and that growth, cannot be conceived as endowing the newly-arranged atoms with consciousness.[24]

Bracketing eliminativism for the time being, which simply denies there is conscious life or that it makes any sense to talk about it,[25] it seems clear that, unless one is a substance-dualist, "sensational" or "conscious life" must be an intrinsic property or potentiality built into the most fundamental layer of physical reality. On this view, the physical Universe is, in some strong sense, brute-factly utility-yielding, possessing properties or latencies in its very structure that bring forth pleasure and pain in their qualitative aspect.[26] This is, for those who contemplate it, an astonishing realization. Colin McGinn asks,

> How did evolution convert the water of biological tissue into the wine of consciousness? Consciousness seems like a radical novelty in the universe, not prefigured by the after-effects of the Big Bang; so how did it contrive to spring into being from what preceded it?[27]

McGinn's question is a loaded one for no naturalist will wish to accept that there was any "contrivance" *per se*, which connotes some overarching axiological telos in action, rather, they typically maintain that these properties or potentialities built into nature could not (in some metaphysical

---

[24] Wallace (1869, p. 391).

[25] I do not think it is difficult to speak meaningfully about consciousness. As John Searle writes, "There is a problem that is supposed to be difficult but does not seem very difficult to me, and that is the problem of defining "consciousness." It is supposed to be frightfully difficult to define the term. But if we distinguish between analytic definitions, which aim to analyze the underlying essence of a phenomenon, and common-sense definitions, which just identify what we are talking about, it does not seem to me at all difficult to give a common-sense definition of the term: "consciousness" refers to those states of sentience and awareness that typically begin when we awake from a dreamless sleep and continue until we go to sleep again, or fall into a coma or die or otherwise become "unconscious." . . . Consciousness so defined is an inner, first-person, qualitative phenomenon." Searle (1998, p. 5). See also the 'catalog of conscious experiences' compiled by Chalmers (1996, p. 6-11).

[26] Searle agrees on this point: "Only to conscious agents can there ever be a question of anything mattering or having any importance at all," Searle (1998, p. xiv).

[27] McGinn (1999, p. 13-4). He continues, "We have a good idea how the Big Bang led to the creation of stars and galaxies, principally by the force of gravity. But we know of no comparable force that might explain how ever-expanding lumps of matter might have developed an inner conscious life... A brain is a celestial object with more bizarre properties than any black hole or red dwarf or infinitely dense singularity." McGinn (1999, p. 15-6).

sense) have been otherwise *or* that they are a mere happenstance, an unintended by-product of the metaphysical dice that brought about our existence.[28]

These options seem exhaustive (though see §2.5.3 for an alternative 'Multiverse explanation'). Natural selection has no explanatory relevance here. To say that there is qualitative experience in nature because it is advantageous for organisms to have it is to miss the point completely. That would be as strange as supposing that electrons have charge because this is an advantage to organisms. The whole question is why it is that the Universe has any (potential for) qualitative experience *in the first place* upon which natural selection might act.[29]

To those acquainted with the debate on the FTL, these categorical terms (contrivance, necessity or chance) will sound quite familiar. The question has long been asked whether physical life[30] as we know it is common to the observable Universe ("necessary" given the underlying physics), an incredible fluke unlikely to be repeated again ("chance") or the result of intentional design ("contrivance").

Despite facing structurally similar problems, cosmologists and philosophers tend to prefer very different answers. Whereas many philosophers of mind end up accepting the emergence of consciousness from the underlying properties or potentialities built into nature as a mystery or a 'cosmic fluke' or as 'metaphysically necessary' - whatever such terms means - fewer physicists nowadays who work on the corresponding problem of fine-tuning in physics for the emergence of biological complexity are willing to accept *this* as a cosmic fluke or as metaphysically necessary, etc.

Why not? After all, physics is not complete and so, some have claimed, as we learn more

---

[28] For example, Davies (2003, p. 153) speaks of consciousness as "assured," whereas Gould (1987, p. 431) speaks of it as a "quirky evolutionary accident."

[29] McGinn continues, "It is important to see that Darwinian theory does *not* explain the existence of conscious minds. This is not because consciousness possesses a special type of design that cannot be explained by blind evolutionary natural selection. The problem is more fundamental. It is not especially difficult to see how matter can take on the attributes of design... Paley's argument was not that matter could not in principle be shaped into a complex organism... His argument was that design needs a designer, not that matter could not be configured into living organisms... But the problem with the conscious mind is that it is hard to see how *any* process – natural *or* divine – could possibly shape matter into mind... This seems impossible as a matter of principle." McGinn (1999, p. 81-2).

[30] As we shall see (§2.3.1) the term 'life' is used by different authors in different ways. Some treat it as a synonym for 'consciousness.' Here, by 'life,' I only mean the physical structures we call bodies and I leave open the possibility that they not be attended by qualitative experience (as in the philosophical zombie).

about the world we will eventually find that all of these fine-tuned laws, fundamental constants and boundary conditions will all be explained as part of a final and unique theory of everything. We would then see that what appeared to be "contrivances" turned out to be "necessary."

Few physicists find this plausible; for them, it is not satisfactory to declare a problem dissolved by merely asserting that an outcome was 'necessary.' We could say of any *prima facie* unlikely event that 'it came about, therefore, it came about necessarily – end of story.'[31] Consider the illustration given by John Leslie,

> Suppose that the words MADE BY GOD are found all over the world's granite. Their letters recur at regular intervals in this rock's crystal patterns. Two explanations suggest themselves. Perhaps God put the words there or perhaps very powerful visitors from Alpha Centauri are playing a practical joke. Both explanations might account for the facts fairly well, yet along comes a philosopher with the hypothesis that the only 'really possible' natural laws are ones which make granite carry such words. And in that case, says he, there is no need for anything to be 'fine-tuned' in order for there to be such words. Nothing else is genuinely possible! . . . Yes, there are countless logically possible natural laws, but the only *really possible* ones are the laws which yielded electrons, pebbles, stars, and MADE BY GOD. . . Surely this would be ingeniously idiotic.[32]

Unless we are to do away with "explanation" altogether,[33] the claim that the only "metaphysically-possible" physical universe *just is* (evidently) one fit for life is seen to be an empty response.[34] (Unless one supposes it is *life* itself that 'actualises' universes from the space of logical possibility; this is an interpretation of the Strong Anthropic Principle. This position does *not* 'explain away'

---

[31] Consider for example the question, "Why did the World Trade Centre collapse?" Few would accept the response, "because the probability of this happening was (evidently) one." Introducing the word 'necessarily' without any further information tells us nothing. Also, to say that our Universe alone is 'necessary' would, in a strong sense, profoundly violate the Copernican Principle by placing biofriendliness in the category of 'metaphysical necessity' which, to turn metaphorical, sounds like self-proclaimed deism.

[32] Leslie (1996, p. 16). Elsewhere Leslie comments, "The claim that blind necessity is involved - that universes whose laws or constants are slightly different "aren't real physical possibilities"... is in any case eroded by the various physical theories, particularly theories of random symmetry breaking, which show how a varied ensemble of universes might be generated." Leslie (1996, p. 202).

[33] This is not a facetious suggestion as the very concept of explanation is central to this discussion. In §2.4.1-2.4.3 we discuss its relevance and connection with 'algorithmic compressibility,' that is, the capacity of explanation to bring diverse observations under one common, mathematical/computational scheme.

[34] An alternate claim, though similar in character, is to suppose that just about any combination of physical parameters will lead to life. But this is as obviously false as is the claim life can be found anywhere in the observable universe (even the surface of the sun or in matter-free empty space). We can only live where the necessary and sufficient conditions for life are met. See quote by Wilczek p. 73.

FTL though, it merely elevates ‘life’ to a quasi-divine level of self-existence.) Carr and Rees concur,

> One day, we may have a more physical explanation for some of the [anthropic] relationships discussed here that now seem genuine coincidences. . . However, even if all apparently anthropic coincidences could be explained in this way, *it would still be remarkable* that the relationships dictated by physical theory happened also to be those propitious for life.[35] [Emphasis mine]

Smolin expresses the same thought rather poignantly,

> It strains credulity to imagine that mathematical consistency could be the sole reason for the parameters to have the extraordinarily unlikely values that result in a world with stars and life. If in the end mathematics alone wins us our one chance in 10^{229} we would have little choice but to become mystics. This would be an even purer mysticism than the anthropic principle because then even God would have had no choice in the creation of the world.[36]

The fact is, it is easy to conceive of logically possible universes that are not just life-prohibiting but, given the fine-tuning of our Universe, seem to be in a straight-forward sense much more probable than ours.[37] We can call this the Cosmological Conceivability Problem: what is it that picks *this* particular Universe (with the special feature of life) out of the space of conceivable universes and makes it ‘exist’?[38]

In a similar manner, the so-called “hard problem” of consciousness, to use Chalmers’ term, is essentially a conceivability problem. It is easy to conceive of a physical universe with com-

---

[35] Carr & Rees (1979, p. 612). Elsewhere Rees adds, “Maybe a fundamental set of equations, which some day will be written on T-shirts, fixes all key properties of our universe uniquely. It would then be an unassailable fact that these equations permitted the immensely complex evolution that led to our emergence. But I think there would still be something to wonder about. It is not guaranteed that simple equations guarantee complex consequences. . . Why should the fundamental equations encode something with such potential complexity, rather than the boring or sterile universe that many recipes lead to?” Rees (2007, p. 60).

[36] Smolin (1997, p. 45). The number 10^{229} is Smolin’s estimate for the random probability of finding the parameter values needed for stars to exist (p. 325).

[37] More probable *a priori*. If we choose a single random universe from the space of logical possibility, it seems extremely unlikely that it would be life-permitting. Roughly speaking, there are many more ways of combining physical laws and parameters that prohibit complex structures. If one objects that the probabilities of a logically possible universe being ‘actualised’ are not uniform, but peaked around life-permitting universes, then FTL has just been moved up one level: why does *this* probability distribution ‘exist’ over the space of logical possibilities?

[38] Some will complain that it is anthropomorphic to label this universe as more ‘special’ than, say, a de Sitter space sparsely filled with a blackbody distribution of low-temperature photons. This gets into the pragmatics of explanation (see §2.3.3) – *we are interested* in life precisely because it furnishes consciousness which is the *sine qua non* of there being any *interest* whatsoever and hence of there being *anything* ‘special.’

plex self-replicating machines[39] that are *not* accompanied by qualitative experience. Why then, if a causal account of the physical origin and functioning of biological entities can be given (the dominant view since Darwin), is there this extra something that we recognise and label by 'qualia,' 'consciousness,' 'self-awareness,' etc.? Moreover, why does qualitative experience correlate with the physical brain in such a regular and appropriate way, given that we can conceive of all sorts of random correlations that would not allow for a coherent mental life? We can summarize these parallel conceivability problems as follows:

1. Cosmological Conceivability Problem: Physical universes without complex, self-replicating machines are conceivable and common in the space of logically possible universes.[40] So why isn't *this* universe one of them?
2. Consciousness Conceivability Problem: Complex, self-replicating machines without qualitative experience (or with different psychophysical[41] correlations) are conceivable, causally accounted for (given Darwinism) and common in the space of logical possibility.[42] So why isn't *this* complex, self-replicating machine – the reader – one of them?[43]

The increasingly popular response of contemporary cosmologists to (1) is to appeal to a multi-universe scenario conjoined with the Anthropic Principle. That is, ours is *not* the only universe to exist, rather, *many* universes exist with varying physical laws and constants, most of which prohibit life. Only in those rare universes that allow for the existence of "observers" will there be anyone to make any such observations and so, according to this view, it is not surprising that the universe we find ourselves in is observer-permitting. This, in the opinion of most cosmologists, is a more

---

[39] Moreover, I think it is easy to conceive of philosophical zombies: beings that are physically identical to humans but not attended by qualitative experience (or, very different qualitative experience to what we experience). Again, if the reader disagrees that it is possible to conceive of a human being without consciousness then presumably they would disagree that it is possible to conceive of other universes.

[40] This is the premise of fine-tuning; i.e. there are far more values of physical constants that don't allow life than those that do, etc.

[41] The term 'psychophysical' is part of the standard vocabulary used by philosophers of mind, most often in reference to property dualism, the position that mental events and physical events are *sui generis*, that is, separate kinds of thing in the world, but that they are 'related' or 'correlated' through 'psychophysical relations/correlates.'

[42] The conceivability argument, like most things in philosophy, does find some opposition. For a discussion of the conceivability argument see Chalmers (1996, p. 65-9).

[43] Or, just as poignant is the question why aren't our mental states correlated with the physical *differently* to how they are in fact correlated? Not only are self-replicating machines without qualitative experience conceivable, it is also easy to conceive of many logically possible ways of correlating qualia and physical states differently to how they are in fact correlated. This would mean that our universe is *exceedingly* rare in the space of logical possibility.

satisfactory position to take in the fine-tuning debate than the empty response that FTL is, in some ill-defined sense, “necessary” or the one-off result of *extreme* chance.

Yet, philosophers of mind are reluctant to follow suit (explored in §2.5); they prefer to cling to the old categories, maintaining that consciousness is a “brute fact” or “necessary” feature of the physical world or even to deny that physical life without consciousness is conceivable.[44] These are the very sort of responses most physicists explicitly reject as an “explanation” to cosmological fine-tuning.

I suspect that this is probably because philosophers of mind do not regard consciousness as a ‘fine-tuning’ problem *per se* (just as, before cosmological fine-tuning was established, the Universe did not seem “contrived” to facilitate life and so its being a ‘brute fact’ was easier to accept psychologically).[45]

Before we delve into further details, it would be worth-while to further explore the interconnections between the fine-tuning debate (and fundamental physics generally) and the problem of consciousness.

2.3 Motivations for this Study

I shall briefly discuss some broad reasons why physicists in general and cosmologists dealing with metaphysics in particular cannot simply ignore the nature of consciousness and the role that it plays in shaping their conclusions. Unfortunately, there is such little dialogue between cosmologists and philosophers of mind that these issues rarely get raised.

---

[44] In a recent survey of philosophers of mind who are members of university faculties, 126/191 (=66.0%) of respondents “accept or lean towards” philosophical zombies (physical beings identical to humans but unaccompanied by qualitative experience) being “conceivable.” Significantly fewer (47/191=24.6%) thought that they are inconceivable (would these 47 philosophers also claim that physically different universes are likewise inconceivable?); 18/191 (=9.4%) said “other.” When philosophers of any subject were asked the same question, the fraction of those who “accept or lean toward” the inconceivability of zombies dropped to 149/931 (=16.0%), whereas 548/931 (=58.9%) “accept or lean toward” their being conceivable; 234/931 (=25.1%) said “other.” See Bourget & Chalmers (2009).

[45] Also, the fact that the universe was discovered not to be eternal, but must have had a “beginning” in the finite past helped overthrow the notion that the Universe is a ‘brute-fact.’ For example, Bertrand Russell famously declared (in the era before the establishment of the Big Bang) that “the universe is just there, and that’s all.” (From the BBC Russell-Copleston debate, 1948.)

2.3.1 Consciousness as a physics problem

Firstly, when cosmologists claim that the physical laws and boundary conditions of the universe are 'finely-tuned' they almost always state this in reference to some feature of the universe that they take to be *interesting* or *significant* (notice these are utility-laden terms) such as "complex chemistry," "life," "intelligent life," "conscious life," etc. The claim is that, were the Universe slightly different in its physical evolution, then the feature to which the fine-tuning made reference would not have obtained for one reason or another. This is often accompanied by the further (more philosophical) assertion that such coincidences are "surprising" and "require explanation."

There is a tacit assumption almost always at play in such discussions amongst scientists: if an explanation could be offered that would remove our sense of surprise regarding one finely-tuned feature of the Universe (e.g. "complex chemistry") then all the other referents to fine-tuning ("life," "intelligent life," "consciousness") would follow automatically. That is, in the context of fine-tuning, such referents as "life," "intelligent life," "complex chemistry" and "consciousness" are treated as virtual synonyms.

Undoubtedly at operation here is the pragmatic assumption that science can be compartmentalised: chemists get by using non-fundamental phenomenological "laws" that are assumed to be determinable, in principle, by the underlying physics of particles, etc. This assumption allows them to make "progress," especially technological, without the cumbersome task of making constant reference to the underlying fundamental laws (which are impossible, practically speaking, to solve for the vast majority of problems in science). *A fortiori*, physicists normally suppose that consciousness is the concern of brain-science and biology and is thus far removed from their domain of expertise *viz.* fundamental particles and the like. It is no more their task to resolve consciousness than to explicate the how other organs function in the body *even though*, in principle, physicists do suppose that this could be done.

The problem though is that many brain scientists and philosophers of mind are relying on physicists to help solve mind-body problem for them. A common position regarding this problem parallels our earlier discussion on fine-tuning: physics is incomplete and a future, unified rendition of the natural world will entail the emergence of qualitative phenomena. As William Lycan states,

> As microphysics continues to get weirder and weirder, it would indeed be idiotic to insist on a nineteenth-, twentieth-, or even twenty-first-century conception of ultimate matter; *it is hardly our place to second-guess the physicist.* For that reason, . . . by the time the mental is actually reduced to anything (if ever), physics may well be other than physics as conceived in the 2000s.[46] [Emphasis mine]

Yet, most physicists deny that this is their responsibility (or are simply oblivious to the onus being foisted upon them by philosophers). For example, in his presentation of the "Mathematical Multiverse" (which we shall examine in §2.5) Max Tegmark states,

> In my opinion. . . although understanding the detailed nature of human consciousness is an important challenge in its own right, it is not necessary for a fundamental theory of physics, which, in the case of us humans, corresponds to the mathematical description of our world found in physics textbooks. [47]

This passing of the buck between the different domains of science (that physicalists assume obey a causal/mereological hierarchy) can, in principle, go on indefinitely. But so long as it does, it simply begs the question regarding the presumption of physicalism as an 'ultimate explanation.'[48] To simply *assume* that physicalism does explain everything – including consciousness – prior to doing so is apt to beg the question.[49] So if, as physicalists claim, consciousness is a latent property of matter, then consciousness is just as much a problem for physicists to solve than for philosophers.

2.3.2 Epistemology and fundamental physics

Secondly, consciousness is relevant to physical theories in so far as they raise epistemological concerns. This is not just the trivial fact that epistemological problems potentially affect *all* areas of human thought. Rather, it is the special fact that cosmological physics has lead many to posit what are, on the face of it, such metaphysically extravagant entities (*viz.* an infinity of unobservable

---

[46] Lycan (2003, p.13).

[47] Tegmark (2008, p.109).

[48] As found in claims such as "[r]eductionist science is omnicompetent," Atkins (1995, p. 129).

[49] Especially since physicalism is often presented not just a methodological strategy, but a philosophical truth-claim enjoying 'epistemic justification.' This leads however to Hempel's dilemma: is our current conception of physics adequate to account for consciousness (this claim seems implausible) or is some ideal, future physics adequate to account for consciousness (this claim seems empty). See Hempel (1969, p. 180-3).

worlds in which *anything* that can happen will happen)[50] beyond the constraints of empirical adequacy that one might regard these consequences as a *reductio ad absurdum*. Given such claims, it is prudent and worthwhile to closely re-examine the intellectual path that lead us there. How did we, in just a few centuries, go from observing apples falling to positing the superluminal inflation of an infinite space-time? Are the epistemological foundations of science secure enough to bear the weight of an infinite ontology beyond the observable? It seems that a careful return to first principles of epistemology and scientific induction is required if we wish to rigorously assess the plausibility of extra-universe scenarios. But as epistemologists recognise, a return to 'first principles' immediately implicates consciousness into the discussion.[51]

A similar project took place with quantum mechanics. The 'physical' interpretation of the quantum formalism that made explicit reference to 'measurement' or 'observation' was so perplexing that its pioneers had to go right back to first principles of epistemology and philosophy of science. For Bohr instrumentalism was the only safe position one could adopt. For Wigner and von Neumann, it was consciousness itself that collapsed the wave function. For realists like Everett who wished to remove the observer completely, the formalism was taken to describe the branching off of infinitely many parallel worlds.

It is interesting to note that in both the science of the large and of the small - cosmology and quantum mechanics - the most popular realist interpretations to emerge in the modern day that purportedly remove the *observer* from our description of reality both involve the prodigious multiplication of reality beyond what we *observe*. Why not just stick with what we *know*, that is, with what we *observe*?[52] Does something "really exist" if its existence has no possible bearing on the evolution of our sense-data (which forms a key part of our mental life)? In a somewhat circular way of reasoning, multi-world proponents must respond, eventually, via reports of their

---

[50] Despite the objection that this position entails a *reductio ad absurdum* (Luke Skywalker *really did* blow up the Death Star a long time ago in a galaxy far far away), and Hilbert's argument against actual infinities, cosmologists commonly assert this to be the case, as any reader of New Scientist or Scientific American will know.

[51] As Daniel Robinson puts it, "Without pausing . . . to consider whether Descartes was on the right track in declaring himself to be a *res cogitans*, we can surely agree that our state of conscious awareness is a feature that trumps all others in the matter of epistemic authority." Robinson 2008, p. 18.

[52] The simple answer is that in the purest sense we only observe our sense-data and if we only stick with our sense-data, we end up embracing idealism. But as soon as we begin positing entities beyond our sense-data, that is, 'beyond what we observe,' we find no non-arbitrary terminus and this leads to one expression of 'ultimate plenitude' or another.

mental life: “because I find this theory beautiful,” “it seems natural,” “it strikes me as the simplest option,” “it’s marvellous, liberating, rich, exciting,” etc. But then, how can it be that physicists will put so much epistemic weight on the qualitative sensations - especially aesthetic - that accompany contemplation of their theories and then maintain that consciousness is not relevant to what they do?

Take for example the distinctive epistemological problem known as Boltzmann Brains - a problem that has lead some cosmologists to take seriously the nature of consciousness, ‘how’ it arises and ‘when’ it arises.[53]

The problem – which is uncannily reminiscent of the ‘brain-in-a-vat’ scenario that epistemologists are so fond of – goes as follows. In the late 19th Century, physicists tried to reconcile the fact that the observable Universe was in a low entropy state with its (supposedly) infinite age. The argument goes that since entropy is always increasing according to the second law of thermodynamics, the Universe would have reached thermal equilibrium an infinite amount of time ago if it had already existed for an infinite amount of time.

Boltzmann proposed that in a Universe of infinite age and spatial extent, random fluctuations can take place such that, very occasionally, a region of space will happen to find itself in a low entropy state just as, in an ideally isolated tub of water at room temperature, there is a non-zero albeit minuscule probability that the water collect itself into two regions of hot and cold. This does not violate energy conservation and so is permitted by the fundamental, classical laws of physics.[54]

---

[53] Consider the following passage of Linde amidst his discussion of chaotic inflation, “The standard assumption [in physics] is that consciousness, just like space-time before the invention of general relativity, plays a secondary, subservient role, being just a function of matter and a tool for the description of the truly existing material world. But let us remember that our knowledge of the world begins not with matter but with perceptions. I know for sure that my pain exists, my ‘green’ exists, and my ‘sweet’ exists. I do not need any proof of their existence, because these events are a part of me; everything else is a theory. Later we find out that our perceptions obey some laws, which can be most conveniently formulated if we assume that there is some underlying reality beyond our perceptions. This model of material world obeying laws of physics is so successful that soon we forget about our starting point and say that matter is the only reality, and perceptions are nothing but a useful tool for the description of matter. This assumption is almost as natural (and maybe as false) as our previous assumption that space is only a mathematical tool for the description of matter. We are substituting reality of our feelings by the successfully working theory of an independently existing material world. And the theory is so successful that we almost never think about its possible limitations. . . Will it not turn out, with the further development of science, that the study of the universe and the study of consciousness are inseparably linked, and that ultimate progress in the one will be impossible without progress in the other?” Linde (2004, p. 450-1)

[54] To envision how this is possible, imagine starting with this final state (a tub with the hot and cold water initially separated) specified by the positions and velocities of all the particles in the tub called the microstate, Φ_{final}. Now run

The problem though is that if our existence was due to a relatively rare occurrence of thermodynamic fluctuations, it is thought to be much more probable that the neural networks corresponding to our brains (equipped with our memories and contemplating this problem for a short duration) come about from these sorts of random fluctuations than a pocket region the size of the observable Universe lasting billions of years for brains to evolve.[55]

Boltzmann's original proposal assumed classical, time-reversible laws of physics, but the Universe is quantum mechanical and seems to be, with the collapse of the wave function, time-irreversible. Nonetheless, modified Boltzmann Brain problems are still a plague for infinite-universe hypotheses. According to quantum field theory interpreted with Copenhagen terminology, 'particles' are instantiated via 'measurements' of amplitudes of perturbations of scalar fields permeating all space and time.[56] As such, there is a non-zero, even if minuscule, probability of 'observing' a particle at any point in space. This implies that there is a non-zero probability of observing two particles bound together at any point in space, and so on. In short, the probability of observing *any* combination of particles in bound states – no matter how bizarre or ridiculous – has a non-zero, though inconceivably small, probability. According to this view, the 'reason' then

---

the clock so that the random collisions of the molecules eventually average out and the tub comes to be in thermal equilibrium (a higher entropy state), Φ_{initial}. Now run the system *backward* in time and, since the collisions all obey energy and momentum conservation, one will be able to trace everything back to the low entropy state of separated hot and cold, Φ_{final}. Now, according to the fundamental postulate of statistical mechanics all N possible microstates occur with equal probability. So if one instantiates N such tubs of water, chances are that that 1/N will be specified by the micro-state Φ_{initial}. But this causally entails the imminent separation of the water into hot and cold regions. The reason why we never see this happen is simply because N is an enormous number and there are *far* more microstates that don't result in any significant decrease of entropy within our lifetimes (or, indeed, within the age of the Universe). But in an infinite universe N microstates *are* realized and are realized an *infinite* number of times. Thus, in regions of space and time that are *greatly* separated, on average, one will find entropy decrease in the way described. By extension one can imagine, as Boltzmann did, that as the pocket fluctuation of low entropy that we call our Universe will eventually dissipate into a perfect fluid of thermal equilibrium, we can take *that state*, reverse the clock a few billion years and thereby account for the appearance of our low entropy region.

[55] To see this, imagine taking our adiabatically isolated tub of water at 100°C and putting a brain into it that is neurologically configured so as to instantiate the thoughts associated with this problem. Now run the clock forward (say a year) and one will find that the system has reached thermal equilibrium and the molecules associated with the brain are perfectly intermixed with the water. Now take *this state* (which at any moment has probability 1/N) and reverse the arrow of time – in a year the system will bring about a brain having such thoughts. The argument goes that the 'volume' of phase space corresponding to such a state of affairs is much larger than the volume of phase space corresponding to a universe that will last billions of years and allow brains to evolve therein. Hence such brains are more likely to occur (or so the argument goes), on average, as the result of 'spontaneous fluctuations' than on the 'normal' evolution-over-billions-of-years view.

[56] Not all particles are represented by scalar fields, but spinors also, which can be thought of as bundles of scalar fields that couple together in a specific way. Thus the electron and positron are components of one 'electron-positron-spin-up-spin-down field.'

why *we* never observe Luke Skywalker materialising out of the quantum vacuum is only due to its sheer improbability.

As Hawking and Israel put it this way in their discussion of quantum tunnelling from a Black Hole,

> It is possible for a black hole to emit a television set or Charles Darwin ... but the overwhelming probability is for the emitted particles to have an almost thermal spectrum.[57]

Nonetheless, in an infinite Universe, "everything that can happen will happen an infinite number of times." On this view Luke Skywalker *does* materialise out of the quantum vacuum before us (that is – our astonished doppelgangers) an *infinite number of times*. Some have even speculated, in the spirit of Boltzmann, that the entire universe 'is' a quantum fluctuation that can last indefinitely (so long as its net energy is strictly zero).[58]

This is especially problematic for the 'inflationary Multiverse' according to which our Universe is a small patch of an unimaginably large space-time structure that is, overall, expanding at an enormous rate.

For every universe like ours that the inflationary Multiverse generates, an inconceivably larger amount of vacuum-dominated space is produced. In fact, it is so large that the prospect emerges of macroscopic entities materialising out of the quantum vacuum for brief moments at a non-negligible rate. De Simone et al. (2010) describe the situation in the following way,

> [C]omplex structures will occasionally emerge from the vacuum as quantum fluctuations. . . An intelligent observer, like a human, could be one such structure. Or, short of a complete observer, a disembodied brain may fluctuate into existence, with a pattern of neuron firings creating a perception of being on Earth. . . Of course, the nucleation rate Γ_{BB} of Boltzmann brains is extremely small. . . [However,] if the accelerating expansion of the Universe is truly driven by the energy density of a stable vacuum state, then Boltzmann brains will eventually outnumber normal observers, no matter how small the value of Γ_{BB} might be. . . When extracting the predictions of this theory, such an infinite preponderance of Boltzmann brains cannot be ignored.[59]

---

[57] Hawking & Israel (1979, p. 19).

[58] **?**.

[59] De Simone et al. (2010, p. 1).

Despite insisting BBs are a problem, cosmologists who bring them up are not all agreed on what exactly the problem *is*. Some worry that to believe a theory that entails their existence in greater numbers than ‘normal observers’ would be *epistemically self-defeating*. For if BBs are more common in the Multiverse than observers like us, then the cosmologist ‘would expect’ to be a BB and thus hold non-veridical beliefs regarding the external world.[60]

This is an unusual state of affairs in physics – I know of no other class of theory in physics that is rejected or modified on the grounds of it being ‘epistemically self-defeating.’ For example, no one ever rejected classical mechanics implicating Laplacian determinism even though it seems to leave no room for “rational thinking.”[61]

Other cosmologists don’t think this is a problem since we have *already* concluded that we are not BBs and that we are epistemically justified in believing that our ideas of the external world are veridical – so what does it matter if there are all of these “freak observers” elsewhere in the Multiverse? For some this goes against the spirit of the Copernican Principle as it would make us ‘special observers’ (in the sense that we are not the most populous sort of thing that ‘observes’). For others it is no big deal. James Hartle has suggested that, since insects far outnumber humans, we are obviously *not* especially typical observers, even on earth.

Page thinks consciousness is the key criterion and that humans have, to paraphrase him, “much more of it” than insects.[62] His concern is not that we’ll end up wondering if we are BBs, rather, he thinks that if BBs far outnumber us, then the fact that we (as randomly selected ‘observers’ *qua* the Principle of Mediocrity; see p. 74) turn out *not* to be BBs would count as “very strong observational evidence against any theory predicting such a long-lived universe with a quantum state that can allow localised observations.”[63] His solution is based on reasoning similar to the Doomsday Argument[64] whereby he predicts that our Universe will have to cease expanding (exponentially) in

---

[60] “[T]he next observations that she will make, if she survives to make any at all, will be totally incoherent, with no logical relationship to the world that she thought she knew.” De Simone et al. (2010, p. 1-2).

[61] An expression of this well known problem is attributed to J. B. S. Haldane the quote of which is given on p. 66.

[62] See Page 2008c.

[63] Page (2006, p. 7).

[64] The Doomsday Argument takes the principle of mediocrity seriously enough to predict that, if we are to be typical observers with respect to time we would expect (given the exponential growth rate of the human race) for the last human being to die in about ten thousand years (typically).

about 20 Gyrs.

However, Multiverse-wide decay of the vacuum energy is not an option in the eternal-inflation scenario (to be discussed in §2.5). Its proponents have therefore sought to 'regulate' this problem through some clever choice of 'measure.' Collins has pointed out,[65] that hand-picking a measure that renders us 'typical observers' just seems to create another, rather artificial fine-tuning problem.

In summary, the problem of Boltzmann Brains obviously raises issues regarding consciousness. What is a minimal 'conscious' observer? Is it a human brain, a silicon chip, a file cabinet? Is functionalism (the theory of mind invariably assumed in such discussions) the correct basis for these calculations? The purpose here was simply to direct the reader's attention to the fact that basic epistemological questions – and therefore the nature of consciousness – are issues that physicists can't just ignore in the Multiverse discussions.

2.3.3 The motivations and pragmatics of physical investigation

If you know the wave-function of the Universe, why aren't you rich?
– Murray Gell-Man to James Hartle[66]

Thirdly, and finally, is an often overlooked consideration as to why consciousness is relevant to fundamental physics – the so-called 'pragmatics of explanation.' This concerns the context, philosophical presuppositions and psychological factors that shape one's explanatory framework, i.e. what sort of responses we find "satisfactory" to questions that we are interested in.[67]

Why do we strive to 'explain' anything at all? Unless one rejects folk-psychological explanations right from the outset, the answer seems obvious: we explain things because we *want* to, because there is utility for us in seeking explanations.[68] Firstly, the more we are able to explain the

---

[65] R. Collins at a recent Cambridge conference.

[66] Hartle (2007, p. 275).

[67] See van Fraassen (1980, p. 97-153), Garfinkel (1981, p. 21ff) for accounts. Garfinkel offers this famous example: a priest asked Willie Sutton, when he was in prison, "Why did you rob banks?", to which Sutton replied, "Well, that's where the money is." Clearly the space of relevant alternatives is different for Sutton (grocery stores, petrol stations, etc.) as it is for the priest (not robbing at all).

[68] By 'explanation' here I mean something like a causal account of the associations we observe in various phenomena that we deem parsimonious and thus a promising basis for the employment of 'effective strategies' (see Cartwright 2002, p. 21-43).

workings of nature, the better we are able to proffer through the technological manipulation of our environment. Secondly, even if the prospect of direct technological application seems far-fetched (e.g. parallel-universe theories), there is intrinsic philosophical utility in *feeling* like we understand the world around us, knowledge for the sake of knowledge, so to speak. We *want* to know about its functioning, origins and destiny because this seems utility-relevant. One usually studies physics because it is thought that it might tell us something about who we are, what the nature of things is and thereby indicate where and how to focus our efforts in the pursuit of happiness.

If science were not thought to be a utility-relevant practice, we would abandon science and resume some other practice that we did consider to be utility-relevant. In short, we do science because *and only because* we deem it valuable, in the broadest sense of the word, *to us*. Michael Polanyi illustrates this fact poignantly,

> [I]f we decided to examine the universe objectively in the sense of paying attention to portions of equal mass, this would result in a lifelong preoccupation with interstellar dust, relieved only at brief intervals by a survey of incandescent masses of hydrogen – not in a thousand million lifetimes would the turn come to give man even a second's notice. It goes without saying that no one – scientists included – looks at the universe this way, whatever lip-service is given to 'objectivity.'[69]

The current, highly publicised search for exo-planets is symptomatic of this utility-orientated bias. We are fixated on the search for extra-terrestrial life because *we want* to know what the relationship is between beings like us and the cosmos and we are willing to invest a lot of utility (in the form of dollars) into massively ambitious projects that, in all objective likelihood, will end in null results (in so far as finding life goes). For example, Michael Hart concludes, based upon his analysis of the Drake equation

> Normally, when theoretical conclusions based on existing theories are in complete accord with the observations the conclusions are readily accepted. Why, then, are so many people reluctant to believe that [the expected number of advanced civilisations in a typical galaxy the size of the Milky Way] is a low number? I would suggest that this reluctance is primarily a result of wishful thinking: a galaxy teeming with bizarre life forms sounds a lot more interesting than one in which we are alone.[70]

---

[69] Polanyi (1973, p. 3).

[70] Hart (1999, p. 271). Similarly, planetary scientist Stuart R. Taylor writes, "the evidence that our existence was

Notwithstanding the sobering calculations, discoveries with existential implications have an intoxicating effect on the imagination.[71] To disregard the question of consciousness is to ignore the very thing that motivates us to question anything and the very thing to which we introspectively pay heed in deciding what answers we find "satisfactory" or not. Our motivations in turn influence what we choose to study and how we go about studying it. Although it is common in science to speak of the 'major problems' in a given field, it is not as though nature decides the ordering of our priorities; we do. How else though can one convey the pertinence of a given question than to underscore the way in which it is relevant to some form of human utility? Does the word "pertinence" have any meaning without an underlying notion of utility and thereby conscious experience?

The notion of pertinence becomes highly relevant when we turn to the philosophical questions of physics. For example, it seems to me that the question of fine-tuning (and its interpretation) is an important question because it directly concerns existential questions regarding the origin of life and the Universe, whether there is transcendent purpose, and so forth. But such questions matter because and only because we are conscious beings. How else do you answer the person who says that the fine-tuning of the Universe for intelligent life 'deserves' no more explanation than a Universe sparsely filled with innate hydrogen? There is no 'datum' that one can point to in order to persuade such a person. The only response is to say "because life matters." There is no way to compel someone to *feel* the need to explain something. The oft quoted phrase "it cries out for explanation" has a distinctly non-technical ring to it, as though the exhorter is resorting to psychological tactics rather than 'objective reason.' This is due to the fact that explanation is an endeavour undertaken by *us* and is subservient to our utility-orientated nature.

Yet, some will insist we are being anthropomorphic: so what if there is a coinciding of the laws of physics with the instantiation of stuff mattering in the qualitative sense? Why not just be content to have observed that there is a coinciding pair of events (one pair of many) and leave it at that? We

---

mostly a matter of chance has, in the presence of the Moon, literally been staring us in the face…However, it seems to me better to stand up and face the objective evidence for what it is…The knowledge that we are probably alone in the universe, that conscious intelligence has arisen accidentally, and we are its only keeper," Taylor (1998, p. 203-4).

[71] "The search may prove hopeless – the distances and numbers are certainly daunting – but it is a glorious quest," Davies (2003, p. 153). One never hears a scientist say "so what?" in response to the suggestion that alien life might exist; it is taken as obvious that it is a "worthy" if not "glorious" question that "deserves" an answer. Notice how utility-laden such terms are.

could take such a position to its extreme of course. We could agree that, in some purist sense, the existence of complex life that instantiates pleasure, pain, hopes, fears and all the drama of human history does not "need" to be explained, but the same obtuse stance could also be extended to our first-person phenomena. There is no "need" to believe in an external world.Of course, solipsists will think of their phenomena *as if* the external world exists and behaves according to common sense (in the spirit of Vaihinger), but these acts of compliance can always be construed as heuristic fictions; constructs that aid the intellect in the accommodation of sense-data. The only basis for rejecting solipsism is the fact that it *feels* implausible. But this is a strictly qualitative judgment, a seeming act of voluntarism stemming from the particular constitution of one's mental life.

It is important to stress that what is being claimed here cannot be "proven," it's very much a case of "you see it or you don't." If the reader is waiting for an argument that we *have* to explain certain things and that the things we *have* to explain are x, y, z - it won't happen. We explain what we *want* to explain and we use the framework we *want* to use.

That does not mean that all is relative; often what we want is that which is objective. But when ideology clashes with the positivistic methods of science, one's will usually wins out. As Isham writes,

> [O]ne should not forget that an attachment to a particular philosophical position can have powerful emotional overtones. . . it is not unusual to find a physicist, or philosopher of science, defending a specific position with a fervour and passion that far outreaches the degree of emotion normally associated with scientific beliefs; indeed, sometimes it is as if his or her very existence depended on the outcome of the debate.[72]

By failing to consider the fact that we are first and foremost after utility – a fact intimately entangled with our conscious lives – rather than "pure reason," physicists sometimes fail to see that science has pragmatism built deep into its structure. In turn they often end up confusing metaphysical predilection with empirically-grounded description. In summary, one cannot objectively deliberate on 'truth' *without* considering the subjective factors that affect our choice of ideological commitment and, thereby, the sort of explanations that we (in the first person) find satisfactory.

---

[72] Isham (2008, p. 66).

This is but a short examination of some of the reasons why psychology and philosophy of mind are important considerations to be aware of when doing cosmology; especially in making profound statements about the nature of existence rather than modest attempts to describe that which exists mathematically. It is to these issues we now turn.

2.4 On the Physicalist Identity Thesis

2.4.1 Causation, Explanation and Unification

Superstition is nothing but belief in the causal nexus.[73]
– Ludwig Wittgenstein

Thorough philosophical accounts of ‘explanation’ have shown that there is a close and somewhat circular connection between the concepts denoted by ‘explanation,’ ‘causation,’ ‘understanding’ and ‘evidence.’ To ‘explain’ something scientifically is, more or less, to cite *causal* relations (i.e. laws) between different entities in space or time.[74] The guiding concepts, by which we discover what the “real” (as opposed to the “accidental”)[75] laws of nature are, are *unification* and *universality* (concepts closely associated with ‘algorithmic compressibility’ as discussed below).[76] Once we have figured out some of the general causal relations (e.g. lightning is usually followed by thunder), we can posit specific causes to account for specific effects to help us ‘understand’ or ‘explain’ the world (e.g. the thunder sounded *therefore* there must have been lightning nearby).[77]

While this rough and intuitive description is enough to allow scientists to get on with their research, formulating *exactly* what the principles of explanation are, how we figure them out and

---

[73] Wittgenstein (2009, 5.1361).

[74] These are the well-known deductive-nomological and inductive-statistical models of explanation.

[75] The dictum ‘correlation is not causation’ makes the task of finding the true ‘causes’ (the hurtling rock *caused* the window to beak) as opposed to the mere correlations (night always precedes day) a surprisingly non-trivial task.

[76] As well as, arguably, counter-factual analysis.

[77] To complicate things even further, the term ‘explanation’ sometimes does not seem to concern causation *per se* but mere elucidation – seeing the connections clearly where previously they had been foggy. Giving a solid example of some abstract idea can very often help ‘explain’ to others what they had not previously ‘understood’ even though there is, in a sense, no more conceptual ‘content’ in the solid example than in the abstract notion. Moreover, there is the subtle difference between explanation *qua* causality and explanation *qua* pragmatics concerning what class of explanation one finds relevant to a given ‘why’ question (see §2.3.3).

how one is to get around the obscure counter-examples that philosophers are apt to bring to our attention is all notoriously problematic. As Hume famously pointed out, it is remarkably difficult to say exactly what causes ‘are’ beyond “constant connexion” and this has lead some philosophers to declare their non existence.[78] But if causation is just correlation, doesn’t that reduce explanation to mere description, albeit *efficient* and *useful* description, as Duhem believed? Such debates have been ongoing for millennia and the only thing we can all agree on is that, despite its ubiquitous use in human language as though obvious and unproblematic, ‘explanation’ is an extremely subtle notion. As Stathis Psillos summarises,

> The fact of the matter is that concepts of causation, laws of nature and explanation form quite a tight web. Hardly any progress can be made in the elucidation of any of those without engaging in the elucidation of at least some of the others. All we may then hope for is not strict analysis, but some enlightening account of their interconnections.[79]

If causation is not a stand-alone concept, and if explanation is arguably synonymous with ‘efficient description,’ then one must proceed with extreme caution when addressing the problems of reality and consciousness, which has causation at its very core, if confusion is to be avoided.

2.4.2 The Special Role of Numbers in Physical Explanation

Physics is mathematical, not because we know so much about the physical world, but because we know so little: it is only its mathematical properties that we can discover. For the rest our knowledge is negative.[80] *– Bertrand Russell*

The first identity statement to be defended expresses a form of ‘epistemic structural realism’ that stems from the observation that fundamental physics posits no substances *per se*. When examined closely we find that the *only* things that fundamental physics posits as existing “out there” are (1) numbers (coordinates and fields) and (2) relations between numbers (combinations of arith-

---

[78] Russell’s famous dictum is, “The reason why physics has ceased to look for causes is that, in fact, there are no such things. The law of causality, I believe, like much that passes muster among philosophers, is a relic of a bygone age, surviving, like the monarchy, only because it is erroneously supposed to do no harm,” Russell (1912).

[79] Psillos (2009, p. 12).

[80] Russell (1927, p. 163-4).

metic operations).[81] Hence the first identity,

$\mathbf{I_1}$: all physical states *are* a set of numbers and (combinations of) arithmetic relations between those numbers.[82]

Although the same basic point expressed by $\mathbf{I_1}$ goes back to Locke, Hume and Berkeley,[83] was discussed extensively by Russell[84] and is debated right through to the present day in philosophical circles (under the general heading 'structural realism,' of which there are many nuanced versions),[85,86] it tends to elicit shock or indignation upon first hearing (especially with working scientists) and will therefore require some defence. Surely, one might say, fundamental physics posits the existence of *all sorts* of distinctive substances (matter, energy, photons, charge, electrons, atoms, etc.). The claim of $\mathbf{I_1}$ though is that when each of these terms are analysed, they all turn out to be shorthand labels for collections of numbers that stand in certain mathematical relations to each other. An electron, when treated as a particle just 'is' a set of numbers that we intuitively think of as describing "where it is" (four numbers for its space-time location) and "how much" of it there is (one number for its mass).[87] The coordinates (which are numbers) are distinguished

---

[81] Of course there are many sorts of relations between numbers and sets of numbers in physics, e.g. matrix multiplication, but these can always be reduced to combinations of the four basic arithmetic operations ($+-\times\div$). Even exotic 'numbers' like Grassmann variables can be reduced to isomorphic representations of the basic arithmetic operations via their representation in square matrices (and matrix multiplication is just a long sequence of combinations of arithmetic operators). It is usually the case, especially once groups get very rich and complicated, that the abstract groups are *defined* as isomorphic to the matrix representation. I include calculus operators under the term 'arithmetic' since all the defining concepts involve the usual $+-\times\div$ operators.

[82] A closely related expression of this fact (perhaps a synonymous statement) is the maxim "information is physical," a notion oft attributed to John Wheeler's aphorism "it from bit."

[83] See Locke (*Essay* II viii), Hume (*Treatise*, 1.4.4). See also "Historical Note," Lockwood (1990, p. 169-71).

[84] See Russell's *Analysis of Matter* e.g. "Physics, in itself, is exceedingly abstract, and reveals only certain mathematical characteristics of the material with which it deals. It does not tell us anything as to the intrinsic character of this material." Russell (2007, p. 10).

[85] For example, Simon Blackburn makes the same point, "When we think of categorical grounds, we are apt to think of a spatial configuration of things – hard, massy, shaped things resisting penetration and displacement by others of their kind. But the categorical credentials of any item in this list are poor. Resistance is par excellence dispositional; extension is only of use, as Leibniz insisted, if there is some property whose instancing defines the boundaries; hardness goes with resistance, and mass is knowable only by its dynamical effects," Blackburn (1990, p. 62-3). Chalmers notes how "strangely insubstantial" this view is, Chalmers (1996, p. 153).

[86] This view is also represented in the massive literature of 'structural realism.'

[87] And this number we label "mass" just *is* a quantity relating the rate of change (more numbers) of the coordinates when placed a certain distance (more numbers) from another electron (more numbers), etc.

from the mass (which is also a number) solely by their location in the equation of motion, that is, by their mathematical relation to each other.

Likewise an electron, treated as a quantum-mechanical wave, just *is* two sets of numbers: the coordinate domain $(t, \underline{x}) \in \mathbb{R}^4$ mapped (via mathematical relations) to the field range $\psi(t, \underline{x}) \in \mathbb{C}$ and its mass is again a number that features in the equation of motion (a mathematical relation linking the physical state at one moment to another state at a later time). Thus whether we treat an electron as a particle or a wave, they both have “being numbers” in common. When a Lagrangian description of a physical system is written out, the only thing distinguishing different kinds of particles (for they are all numbers) is their position in the equation. However many extra ‘modes’ one might posit,[88] and however elaborate the (combinations of) arithmetic relations between these modes, it will always remain the case that it is essentially just numbers and relations between numbers that are ‘really out there’ according to fundamental physics.

Likewise an ‘atom’ just *is* a set of particles bound together in a particular configuration and *is* therefore a set of sets of numbers standing in certain mathematical relations to one another. Atoms are said to form structures via their mutual electric fields (which are also just numbers) and all material objects just *are* structures of atoms (sets of sets of sets of numbers and relations between numbers), according to physicists. There are of course philosophically-inclined scientists who take this point seriously (carrying on the tradition of ‘scientific relationalists’ such as Leibniz and Mach). For example, Paul Davies writes,

> [Physicists] invent certain concepts such as ‘energy’ or ‘atom.’ At rock bottom, these concepts are merely code-words that encapsulate in a simplified way certain complicated mathematical properties. However, they become so familiar to us that we tend to treat them ‘out there’, possessing certain objectively real qualities. We then run into trouble that these hypothetical ‘things’ simply cannot be imagined. Whatever mental image you may have of an atom, it is wrong! What, then, is an atom? I would say that it is an abstract concept – a Platonic idea if you like – that helps us relate certain types of observation in a systematic way. ‘Atomic theory’ is actually simply a set of algorithms for effecting these relations.[89]

---

[88] For example, a spinor is an n-tuple of fields that couple with each other in a particular way and are thus not qualitatively different from scalar fields that couple with other scalar fields and modes of spinors, etc.

[89] Davies (1995, p. 264).

Another way to get at this fact (that programmers especially might appreciate) is to consider a computer simulation of a physical system. A galaxy simulation typically has three “substances,” that is, kinds of particle: gas, stars and dark matter. However, to the computer all three kinds of particle are just numbers stored in the RAM and the *only* thing that differentiates them in the simulation is the way in which these numbers ‘couple’ with all the other numbers, that is, the mathematical relations that determine how these numbers get updated in the computer’s memory. It is only when these numbers are mapped to an ‘observable’ output, such as a screen that is configured so that the pixels emit different wavelengths of light (400 nm for a gas particle, 700 nm for a star, etc.), or some other pictorial mapping, and thus end up putting our brains into specific physical states that *we* visually recover a sense of their ‘substantive’ distinctness. Up until that moment everything - the computer RAM, the screen, the brain, are all just numbers standing in specific mathematical relations to each other (from the particle-physics perspective). Thus, numbers are the only thing that the physicist ever really posits as “out there.” Descriptions of ‘substance,’ e.g. ‘water,’ ‘gold,’ etc. are higher-level labels that ‘soft sciences’ use as a shorthand for the underlying physics,[90] but real physics deals exclusively with numbers and relations between numbers. Notice moreover that all of this is based on analysis before we’ve mentioned anything about the weirdness of quantum mechanics.

Perhaps the reader will insist that these numbers, that are truly “out there,” merely *describe* the “stuff” that the real world is made of. We can grant that for the sake of argument; but the important point is that this is the *only* thing we can say about the “stuff.” Whenever we might ask the skeptic of $\mathbf{I}_1$ to tell us something about what this stuff *is* other than it is such as can be described by numbers (or things that are composites of things that are numbers, etc.), the only thing that is left to say (other than to exchange synonyms like “the stuff is matter,” etc.) is “the potentiality to be measured” or “the potentiality to couple with numbers that couple with numbers, etc. that can be measured.” But the measuring device again just *is* numbers and relations between numbers,

---

[90] As Poincaré describes, “these are merely names of the images we substituted for the real objects which Nature will hide for ever from our eyes. The true relations between these real objects are the only reality we can attain, and the sole condition is that the same relations shall exist between these objects as between the images we are forced to put in their place. If the relations are known to us, what does it matter if we think it convenient to replace one image by another?” Poincaré (1905, p. 161).

according to reductionistic physics.

This view leads to deep perplexity when we try and reconcile the fact that the world *feels* so very non-abstract and tangible. The equations describing the evolution of these numbers "out there" have no apparent need or capacity in and of themselves to be draped over with "substance." That this is the case is suggested by the following materialist "solution" offered by J. J. C. Smart,

> There seems, however, to be no reason why we should not say that if an electron has to have non-relational properties, then these properties are properties of which we know nothing. ('Properties we know not what', to parody Locke.) In this way our metaphysical principle could be satisfied and no harm done.[91]

The fact is, physicists only ever assign numbers and relations between numbers to the category of "existence" because only these are *useful* to science (see §2.3.3). It is *only* when these numbers corresponding to "particles" come together into the configuration we call the "brain" that something substantive suddenly seems relevant to the description of the world, that is, when *we* make mental contact with the world.[92] But apart from those working on the mind-body problem, other scientists only ever posit numbers as being "out there." Many great minds have puzzled over the startling meagreness of this apparent mathematical ontology. Penrose remarks,

> The more we understand about the physical world, and the deeper we probe into the laws of nature, the more it seems as though the physical world almost evaporates and we are left only with mathematics.[93]

Similarly Erwin Schrödinger commented,

> I am very astonished that the scientific picture of the real world around me is very deficient. It gives a lot of factual information, puts all our experience in a magnificently consistent order, but it is ghastly silent about all and sundry that is really near

---

[91] Smart (1963, p74-5). Note: even if there really are ontologically irreducible relata, "of which we know nothing," they are superfluous to science and so, given the pragmatic structure of science, will be treated as such. These "unknown properties" certainly won't help the physicalist in their attempt to identify the mental with the physical. If the "unknown properties" just *are* the qualia, then we have panpsychism. Worse, we would *still* need psychophysical laws determining/describing why these 'latent qualia,' which on this scheme just *are* the properties of which we know nothing, give rise to the *particular* qualia they do in the given arrangements of the brain. But the only information we have regarding their arrangement are the numbers associated with the relata.

[92] That is at least according to the view that pan-psychism (consciousness is 'everywhere') is false and that qualitative experience only takes place "in" biological nervous systems.

[93] "... The deeper we understand the laws of physics, the more we are driven into this world of mathematics." Penrose (2000, p. 3).

> to our heart, that really matters to us. It cannot tell us a word about red and blue, bitter and sweet, physical pain and physical delight. . . Science sometimes pretends to answer questions in these domains, but the answers are very often so silly that we are not inclined to take them seriously.[94]

How does one end up going from this rich world of appearances – colours, sounds, solidity, etc. – to this mathematical "evaporation of the physical world"? To see how this originates a brief review shall be given for the original motivation for science to focus on numbers rather than substance. This will require appreciation of two concepts that are essential to science and hence to our discussion: (i) measurability and (ii) algorithmic compressibility.

2.4.3 Measurability and Algorithmic Compressibility

If we take in our hand any volume; of divinity or school metaphysics, for instance, let us ask, Does it contain any abstract reasoning concerning quantity or number? No. . . Commit it then to the flames: for it can contain nothing but sophistry and illusion.[95]
– David Hume.

Measurability is a key concept in the process of 'objectifying inquiry.'[96] The ancient approach to natural philosophy was, for the most part, to intuit on what basis the physical world operates and then argue through sophistry and rhetoric who had the 'superior' account. This resulted in what, retrospectively, seem like strangely anthropomorphic projections onto nature. For example, Aristotle 'explained' the motion of different substances (rocks falling, fire rising, etc.) in terms of 'final causes.' The rock fell to the ground 'because' that is its natural state, nature tends towards the 'good' (its τελος) and therefore the rock fell because it is 'good' that it do so.

Although it might seem utterly arbitrary to us to that it is 'good' that rocks make their way downwards, it is difficult to express why this view is wrong beyond appeals on strictly pragmatic grounds. What is behind the thought that our modern account of nature is "better" than Aristotle's?

One can quickly see that, if we try and defeat Aristotle on his own terms, we'll end up in frustration. For if he *defines* the future state of the system to be such that it is closer to 'the good' then

---

[94] Schrodinger (1996, p. 95).

[95] Hume (1962, p. 163)

[96] I take the phrase from van Fraassen (2002, Lecture 5). The term refers to the methodological directives of (an ideal) science enabling us to bypass 'intuition bickering' (see §2.3.3).

no matter what the future state is, his hypothesis will remain in tact because, by definition, whatever happens will be closer to 'the good.' If we bicker over intuitions, asserting that the modern view of science just *feels* more 'natural,' then Aristotle can always reply in like manner, leaving us all in a stalemate. Besides, if the modern scientific approach is so 'natural' and 'intuitive,' why did it take millennia to figure this out? What about the many perplexing conclusions resulting from the scientific approach, such as those of quantum mechanics, that seem far from being 'natural.' Clearly our assertion that the modern approach is the 'natural' approach is retrospective in character – how would we have convinced Aristotle to adopt our strategy *in his day*?

It turns out that there is not much more to say to Aristotle other than that his approach is not very *useful*. It gives us no predicative power and it is helpful to know what the future state of physical affairs will be.[97] In short, the *only thing* we can all agree on is that our modern account is better, i.e. *more good* in the literal sense that it is more utility-yielding in its practical applications.[98]

Once one appreciates that *usefulness* is the key notion that gives content to our belief that our modern approach to science is 'better' than Aristotle's, one will quickly see why it is that numbers are key to science. After centuries of bickering about metaphysical intuitions, natural philosophers eventually decided to simply let nature *describe* to us what it does, rather than telling nature how we expect it to behave.

To describe nature we could, in principle, observe the evolution of the world and write down long lists of apparatus in before- and after-states using words. But if this were all there were to science then it would be a *very* inefficient way to go about things and hence would not be very useful. The special thing about numbers is that they allow lists to be compressed via mathematical

---

[97] Interestingly, on the one occasion when Aristotle did advocate a mathematical relation, it turned out to be wrong and thus falsifiable: "A given weight moves a given distance in a given time; a weight which is as great and more moves the same distance in a less time, the times being in inverse proportion to the weights," *On the Heavens* i.6 (translated by J. L. Stocks). Such is the power of experimentation: until people started seeking experimental *measurements*, our knowledge was stuck in the false minimum of intuition-based speculation.

[98] The deeply pragmatic structure of science is evidenced by the significance scientists attach to its 'usefulness.' This is implied by Feynman's famous quip, "Philosophy of science is about as useful to scientists as ornithology is to birds." Ironically, if he takes this to be significant or 'true,' then it says something profoundly philosophical, that what goes into science *needs* to be useful. What would Feynman have said to the philosopher who replied, "science might be *useful*, but does it tell us what's *true*?" I suspect Feynman would not have entered into further dialogue and voluntaristically acted *as if* 'to be useful' is 'to be true.'

relations. No other type of entry into a list makes such “information compression” possible. We are therefore constrained to extract numbers out of nature – i.e. to focus our efforts on *measuring* things – if we are to encapsulate in the most efficient manner possible the many patterns that it clearly exhibits.

These mathematical relations between various instrumental readings then allow extrapolation and prediction which is crucial in deliberating between competing hypotheses, especially when our primal intuitions, feelings and ideologies tend to get in the way. For example, despite it’s anti-intuitive ‘shortcomings,’ quantum theory predicts measurable quantities that have been verified to ten significant figures (the anomalous magnetic moment). If quantum theory did *not* correctly describe what is going on “out there” in the world, then the probability that these numbers coincide to ten significant figures would be $(1/10)^{10}$ (the probability of ‘guessing’ a given decimal-digit to the power of, in this case, ten).[99] This ‘prediction’ of the theory would have been a tremendous fluke therefore unless the algorithms that constitute the quantum formalism really did describe the evolution of numbers that are “out there” and so whether we find quantum theory ‘intuitive’ or not is – in some significant sense – completely immaterial. Whether we like it or not, find it intuitive or not, this must be *how* the world really is (though it tells nothing about *what* it is, besides such as can be described by numbers). The key point then is that it is only by obtaining numbers via measurements that we can ‘objectively’ assess the accuracy of a given theory (by comparing its predictions with measurements) with a highly perspicuous and clear sense in which a model is ‘close’ to a reality that virtually all of us can agree upon (as opposed to the murky, vague and disagreeable realm of ‘feeling’). For numbers offer us the clearest sense of *comparison* that there can be since the operators “greater than,” “less than” and “equal to” bear an unrivalled sense of Cartesian clarity about them.[100]

---

[99] I am making a crucial albeit extremely ‘natural feeling’ assumption here that if quantum theory did not correctly (or very approximately) describe something going on in nature then the probability of it getting any particular digit right is 1/n where n is the total number of possible digits in our counting system. Of course, our convention of counting to the base 10 doesn’t affect this probability. If the counting system had been binary the measured quantity would have agreed with prediction to $10/\log 2 \sim 32$ significant figures.

[100] There is a subtle and important rejoinder worth mentioning. Although it may sound as if I am portraying measurement and mathematics as the antidote to “intuition bickering,” it remains the case that *some* intuition is completely unavoidable in doing science and making sense of the world. For it is purely in virtue of a *qualitative judgment* that any equation written down is deemed to be ‘sensible.’ For example, one could, if they so desired, challenge the equation

This example of quantum theory's prediction of a measurable quantity is illustrative of an important connection between coincidence and causation. We reject the hypothesis that the prediction of a measurement to ten significant figures was a fluke and thereby conclude that quantum theory really does describe what is going on in the world. Why? – because this prediction is an indication that quantum theory correctly captures the intricate patterns that we find in nature and so, by adopting it, we are able to describe the patterns of nature more efficiently than just accepting many different measurements as brute facts to be compiled in long lists. Without quantum theory, the digits 1001159652188 obtained by experimental measurement constitute a list of numbers bearing no relationship to each other and so their information content cannot be reduced. But the algorithms given by the mathematics of the quantum formalism generate this list of numbers precisely (and beyond) and thereby allow this list, that is infinitely long (assuming the world agrees with quantum mechanics "all the way down"), to be compressed into a relatively simple algorithm. There is thus a close connection between the rejection of brute-fact coincidences (in favour of a causal account between observed correlations) and algorithmic compressibility – the shortening of lists to statements of pattern. Our acquisition of knowledge of the world depends crucially upon spotting such (what would otherwise be) coincidences and correlations.[101]

Consider a heuristic illustration of this claim. Suppose we go out and measure the heights of all the mountains in the world. Although any given combination of heights is extremely unlikely, these mountains have to have *some* combination of heights and so we do not find it surprising that the mountains of the world have the particular heights they do (given our current background knowledge).

---

written above: $p(Q|E) = 1 - p(-Q|E) \sim (1/10)^{10}$ where Q is the hypothesis that the quantum formalism describes reality (i.e. the physical world 'is' quantum mechanical) and E is the measurement of the anomalous magnetic moment found to agree with the prediction of the quantum formalism to ten significant figures. In writing this down it was assumed that if quantum mechanics had nothing to do with reality then the probability of 'predicting' any single digit correctly is 1/10. This cannot be "proven" of course. A skeptic might challenge this assumption and suggest that the probability of the relevant apparatus producing any particular digit correctly was, in fact, more like 0.9999999999 *even though* quantum mechanics has nothing to do with reality. When we ask the skeptic why *this* would be the probability, the person could reply "this is a brute fact about the world" or that "my choice of prior probability is no less arbitrary than yours." Clearly, there is no way to falsify such a position other than to report our intuition that "that seems completely absurd." Likewise, there isn't anything more to the claim that the *a priori* probability of guessing each digit right is $\sim 1/10$ other than that it "seems utterly plausible."

[101] As Davies notes, "the question "Why is the universe knowable?" reduces to "Why is the universe algorithmically compressible?" and "Why are human beings so adept at discovering the compressions?" Davies (1991, p. 63).

Now suppose we had in fact found that the highest mountain in any range never rose above some maximum height x above sea level, and that this height was instantiated dozens of times around the world. In such a case we would encounter a deeply engrained psychological desire to seek a causal account of this phenomenon. For example, we might posit some powerful atmospheric effect that erodes mountains at a rate proportional to the exponent of its altitude above some critical height near to x, or we might attribute it to the calling card of an alien visitation. But why would we be loathe to attribute it to chance? The answer is connected to the fact that there is algorithmic compressibility exhibited in the description "highest possible mountain = constant," allowing the list of mountain heights to be *shortened*. Instead of having to give a number for a certain set of mountain tops, one can give a single number for all of this set and it is this shortening of demands on our memory that impels us to seek an underlying connection.

This in turn is connected with the role of simplicity in theory-choice. 'Simple' graphs of the form $y=constant$ need only one free parameter to be specified. Straight-line graphs need only two free parameters and so are also rather simple. But as the polynomial order increases, so the lines become less 'simple' as you need to specify more and more free parameters. Our preference for the 'smoothest' curve through all the points (in the classic underdetermination problem) is closely connected with this fact. One could always, of course, fit a function between the actual heights of mountain tops in the world (and any other measurement). For example, one could in principle fit a relation between mountain heights and their distance from the equator. But this relation would require a monstrous high-order polynomial involving so many free parameters that need to be empirically determined that one would not end up shortening the list of required measurements but increasing it. It is this lack of free-parameter reduction that makes us think that there is no causal connection between mountain height and, say, distance from the equator.

To generalise, the *compressibility* of the patterns of nature is closely associated with its causal structure and this is closely associated with its underlying capacity to undergo unification. This is why science, at its most fundamental (i.e. physics), only posits numbers and relationships between numbers – because this is the only way one can encapsulate the patterns of observable phenomena *efficiently*. Once one has extracted these patterns, physics has done its job and there is no role whatsoever for descriptions of “substance” at the most fundamental level.

Defining Physical Explanation

Furthermore, we can take the centrality of algorithmic compressibility one step further and *define* ‘physical explanation’ in terms of a theory’s capacity to algorithmically compress the measured phenomena of nature. According to this criterion, if a new physical theory is proposed that does *not* bring about an increased amount of mathematical conciseness, reduction of free parameters, etc. in comparison with pre-established theories then it is not an improvement over them. In other words, we can say that of two physical theories A and B, A is a ‘better physical explanation’ if it more efficiently encapsulates the relevant patterns exhibited by the phenomena in question, i.e. if it exhibits more algorithmic compressibility than B.[102] One needs to distinguish ‘physical explanation’ here from the more general concept of ‘scientific explanation’ since the former is *essentially* characterised by mathematics and the latter need not be (at least, not to the same degree).[103]

2.4.4 The Irreducibility of Consciousness

It is well recognised that the success of modern science came about via the methodological edict to focus on measurements and that the role of theory was to best account for why it is that *those* numbers, on any particular occasion, were measured in terms of equations that relate those numbers to ‘universal’ numbers embedded, so to speak, in the environment.[104]

---

[102] Take as an example Newton’s phenomenological theory of gravity and Descartes’ vortex-theory of gravity. Although Newton’s involved ‘spooky’ action at a distance, it mathematically ‘saved the phenomena’ to great accuracy (hence his famous dictum,“hypotheses non fingo”). Descartes’ theory, by contrast, gave no predictive power at all. By the proposed criterion for the goodness of a ‘physical explanation,’ Newton’s is the better one since it compresses lists of measurements algorithmically; Descartes’ does not.

[103] So, for example, the hypothesis of common-descent of animal species might be a good ‘scientific explanation’ akin to a good historical hypothesis that unites otherwise disparate phenomena under a single coherent scheme (and is in an obvious sense rather parsimonious therefore), but it does not involve ‘free-parameter’ reduction *per se*, which is central to a (fundamental) ‘physical explanation’ being a ‘good’ one. Similarly, a ‘good historical hypothesis’ rarely involves mathematics, but trades on common-sense notions of human psychology and basic physical knowledge of how the world works.

[104] Over what exact period this transition occurred is debated. Jaki (2008) credits the rise of modern quantitative science to Galileo, d’Espagnat (2006, p. 249) picks out Fourier’s phenomenological treatment of heat (amidst the great caloric-phlogiston debates) as suggestive that, by the 19th century, the transition from ‘natural philosophy’ to ‘quantitative science’ was more or less complete.

Since the hard sciences only posit numbers and relationships between numbers, they are faced with difficult options regarding consciousness, namely, eliminativism, physicalism or property-dualism.[105] Eliminitavism states that there just isn't any such thing as consciousness and we are bracketing this option for the time being.[106]

The second view, physicalism, is also called the 'identity theory' of the mind as it aims to *identify* consciousness *as being the same thing* as the physical brain or subsystems of the physical brain. (Functionalism, the broad idea that consciousness is to be identified with something like a computer program, is usually considered to be a particular version of physicalism. It is, as far as I can tell, the most commonly presupposed philosophy of mind amongst cosmologists; see p. 17 for an example statement). My own construal of the identity thesis aims to establish that physicalism is false. Firstly, it is well acknowledged that physicalism is *a priori* implausible. However hard its proponents try to make this position work, it remains the case that to say one's "feeling of pain 'is' C-fibres"[107] (or any other combination of electrons, protons and neutrons in motion), just seems clearly wrong or, worse, plainly unintelligible. This is the informal case against physicalism, that if one could be wrong about this, then one cannot really be sure of anything. Roderick Chisholm makes a similar comment,

> To the extent that we *can* understand the statement in question, we can *see* that the two properties referred to are not the same property. . . It has been held, not implausibly, that to deny the validity of such rational insights is to undermine the possibility of every type of reasoning.[108]

A slightly more formal basis for the rejection of physicalism derives from the previous assertion (**I_1**) that the only thing we can say about physical states is that they just *are* sets of numbers and arithmetic relations between numbers and that qualitative experiences – "being appeared to redly," "the taste an orange," etc. – *are not* numbers or relations between numbers. We now have

---

[105] There are of course many variant takes on the mind-body problem, but these are the major ones to consider. See Searle (2004a, p. 29-58); Chalmers (2010, p. 111-39), for an overview of the various positions in more detail.

[106] The following comment by Searle might be helpful to the reader, "Dennett [who is an eliminitavist] denies the existence of consciousness... I think most readers, when first told this, would assume I must be misunderstanding him. Surely no sane person could deny the existence of feelings... I have understood him exactly." Searle (1998, p. 120-1).

[107] C-fibres are peripheral nerves in the central nervous system. Saul Kripke famously used them in his analysis of the physicalist identity theory (see Kripke 2001).

[108] Chisholm (1991, p. 556).

two identity statements:

$\mathbf{I_1}$: all physical states *are* a set of numbers or (combinations of) arithmetic relations between numbers.

$\mathbf{I_2}$: qualia *are not* a set of numbers or (combinations of) arithmetic relations between numbers.[109]

From $\mathbf{I_1}$ and $\mathbf{I_2}$ it follows that:

$\mathbf{I_3}$: physical states *are not* qualia.

Let it be clear from the outset that there obviously are *relations* between physical states and mental states generally, but the qualitative experience is not *itself* a physical state, i.e. the qualitative experience *is not* a number, a set of numbers or (combinations of) arithmetic relations between numbers. This seems exceptionally clear. Conversely, it seems unintelligible to say that "qualia *are* numbers or relations between numbers."

As obvious as it might seem that numbers are not the same thing as "pain," "the smell of primrose," "back ache," etc., to say that this is the case is liable to be met with stiff resistance as it automatically entails that there are things in the world that are *not* the same things as what physicists deal with (i.e. there is more to the world than mathematics). The main objection that always comes up is to claim that the anti-physicalist argument (in this case steps $\mathbf{I_{1-3}}$) is an argument from ignorance: we don't *presently* see that physical states are in fact mental states, but that is because our knowledge is incomplete – future insight and clever experiments (that we cannot even imagine!) will unveil the fact that qualia really are physical states. (Notice that this response is similar in form to the claim – discussed in §2.2 – that we are ignorant of what future physics will reveal and that it will in fact dissolve the problem of fine-tuning.)

---

[109] I focus on qualia because I find these to be the clearest instances of consciousness that serve to illustrate the point. I could replace the word qualia here with 'conscious states,' 'mental states,' 'qualitative experiences,' 'beliefs,' etc. but shall stick to qualia for clarity sake.

Probably the most extreme version of the 'future-discovery-will-reveal-all' stance belongs to McGinn. He thinks that the human race might evolve or undergo genetic-engineering, thereby increase its capacity to do philosophy and then will be able to see what we are not presently able to grasp (because, allegedly, evolution has not granted us the proper noetic equipment to do philosophy very well), namely, that mental states are in fact physical states (or 'emerge' from physical states).[110]

To avoid $\mathbf{I_3}$ McGinn would have to back these imaginary *Überphilosophen* to see (by inspection?) that numbers *are* qualia (denying $\mathbf{I_2}$) or perhaps that they will dispense with numbers and/or mathematics in defining physical states (denying $\mathbf{I_1}$). Neither of these options seem plausible and so this theory, like all empty speculation of future unknowns masquerading as a 'solution,' is bound for the horns of Hempel's dilemma.[111]

If the steps leading to $\mathbf{I_3}$ are an 'argument based on ignorance,' (as Patricia Churchland would claim; see Churchland (1998)) then what is the reductionist's stance based upon? Speculations of future unknowns? The "properties of which we know nothing" proposed by Smart? Nagel tries to ward off the *prima facie* absurdity of the physical-mental identity by trying to pack all the alleged ignorance into the verb 'to be' (the linch-pin in any identity statement), using an analogy from mass-energy equivalence.

> I believe it is precisely this apparent clarity of the word "is" that is deceptive .[112] Usually, when we are told that X is Y we know how it is supposed to be true, but that depends on a conceptual or theoretical background and is not conveyed by the "is" alone. We know how both "X" and "Y" refer, and the kinds of things to which they refer, and we have a rough idea how the two referential paths might converge on a single thing, be it an object, a person, a process, an event, or whatever. But when the two terms of the identification are very disparate it may not be so clear how it could be true. . . . For example, people are now told at an early age that all matter is really energy. But despite the fact that they know what "is" means, most of them never form a conception of what makes this claim true, because they lack the theoretical background. At the present time the status of physicalism is similar to that which the hypothesis that matter is energy would have had if uttered by a pre-Socratic philosopher. We do not have the beginnings of a conception of how it might be true. In

---

[110] See, for example, McGinn (1999, 218-28).

[111] See p. 30 for brief description of Hempel's dilemma.

[112] As in my use of the words "is" and "are" in identities $\mathbf{I_{1-3}}$.

> order to understand the hypothesis that a mental event is a physical event, we require more than an understanding of the word "is."[113]

Nagel could not have picked a worse example – it actually helps illustrate the very point set forth. It is *precisely because* 'energy' and 'mass' are both *numbers* given by, in this case, the well-known relation $E=mc^2$ that we can make sense, indeed *the only way* we can make sense, of their being equivalent. Nagel seems to think that, because physicists have a "theoretical framework," this enables them to "form a conception" of how matter *is* energy, as though physicists have a mental image in their mind of some sort of 'matter-energy gooiness' that the pre-Socratics wouldn't have been able to envisage. *On the contrary*, physicists are often quite forth-right in admitting their complete incapacity to "form a conception" of what their equations describe.[114] It is for this very reason that mathematics allows us to push far beyond the limits of our conceptual intuitions (see §2.4.3) – it's just immaterial whether or not we can "form a conception" so long as we can relate the numbers embedded in nature to observable outcomes (e.g. atomic bombs as a manifestation of mass-energy equivalence). [115]

In summary, the identity of the mental with the physical amounts to the extraordinarily implausible claim that mental states "are" numbers (and, more specifically, those numbers that go into describing a brain, unless one embraces panpsychism). The unintelligibility of this identity accounts in large part for why the mind-body problem is yet to be solved (and, according to many, will never be solved) and why cosmologists who subscribe to functionalism end up making confusing claims on ontological matters (see §2.5).

---

[113] Nagel (1974, p. 447).

[114] For example, "[W]ords can only describe things of which we can form mental pictures... Fortunately, mathematics is not subject to this limitation, and it has been possible to invent a mathematical scheme - the quantum theory - which seems entirely adequate for the treatment of atomic processes; for visualization, however, we must content ourselves with two incomplete analogies - the wave picture and the corpuscular picture." Heisenberg (1949, p. 10). See also quote by Davies given above p. 43.

[115] Interestingly, Nagel's example was pre-empted by Poincaré who was himself a pioneer of the formula $E=mc^2$ a few years before Einstein's 1905 paper. Poincaré wrote, "the principle of the conservation of energy simply signifies that there is *something* which remains constant. Whatever fresh notions of the world may be given us by future experiments, we are certain beforehand that there is something which remains constant, and which may be called *energy*. Does this mean that the principle [of energy conservation] has no meaning and vanishes into a tautology? Not at all. It means that different things to which we give the name of *energy* are connected by a true relation... How, then, shall we know when [this principle] has been extended as far as legitimate? Simply when it ceases to be useful to us - i.e., when we can no longer use it to predict correctly new phenomena." Poincaré (1905, p. 166-7).

If one does not find the route from $\mathbf{I_1}$ and $\mathbf{I_2}$ to $\mathbf{I_3}$ convincing, one may prefer to get to the same conclusion through other means: maybe the reader does find type/token identity theory enlightening (in which case they might be persuaded by Kripke's analysis and critique), some might prefer to focus on supervenience as Chalmers does. However one might get there, if one does reject physicalism then, since we are leaving aside eliminitavism as an option till the end, one is committed to there being *relations* between the physical and mental – so called "psychophysical" relations. This is known as 'property-dualism' and is easy to understand: when physical state Y obtains, there co-occurs some mental state X. And, as Chalmers claims, it is compatible with naturalism,

> There is no *a priori* principle that says that all natural laws will be physical laws; to deny materialism [i.e. physicalism] is not to deny naturalism. A naturalistic dualism expands our view of the world, but it does not invoke the forces of darkness." Chalmers (1996, p. 170).

On this view then, there are two sorts of things in the world, and it is the goal of Chalmers and his ilk to discover the relations between the physical and the mental. In the full essay from which this work is largely an extract (see p. xiii), this project of Chalmers is critiqued since, on $\mathbf{I}_{1-3}$, mental states are not numbers and so cannot undergo algorithmic compression which, we postulated, is the essential basis of a 'physical explanation' (see p. 51). However, the infinite Multiverse plus mind-selection effect approach *can* solve this problem and I show this as demonstration of its metaphysical extravagance.

2.5 The Multiverse 'Explanation' of Consciousness

2.5.1 Multiverse Overview

In this section I shall examine the Multiverse hypothesis and its relation to the anthropic. A fairly systematic presentation of the Multiverse is given by Tegmark's "four levels,"[116] which are (roughly in order corresponding to their degree of controversy or speculation):

---

[116] See Tegmark (2008, p. 122-3).

Level 1: Regions beyond our cosmic horizon
Level 2: Other post-inflation bubbles
Level 3: The Many-Worlds Interpretation of Quantum Physics
Level 4: Other mathematical structures (*viz.* Tegmark’s ‘Mathematical Multiverse’).

Each of these Multiverse scenarios, according to Tegmark, naturally entails an infinity of universe-domains that are just as ‘real’ as our Universe is. This is usually taken to imply the truth of the dictum often stated in this subject area “everything that can happen, will happen an infinite number of times.” For example, taking the Level 1 scenario of our Universe extending out to spatial infinity, Tegmark calculates that a physical copy of us exists $10^{10^{29}}$ metres away and concludes that “we will just have to live with it, since the simplest and most popular cosmological model today predicts that this person actually exists” Tegmark (2004, p. 459).

Few cosmologists are satisfied with the Level 1 Multiverse since it does not thoroughly resolve the fine-tuning problem. Even if spatially infinite, there is still significant surprise associated with the proposition that *this* Universe is the only one to exist with *just these* incredibly precise laws and parameters suitable for life. Clearly, for the strategy to work, a sufficient degree of variegation is required between different universe-domains.[117] The most interesting proposal to bring this about is the ‘String Theory Landscape’ based on M-theory that, if correct, would naturally entail the Level 2 ‘eternal-inflation’ scenario where the different ‘post-inflation’ bubbles can acquire radically different (effective) laws and ‘constants.’ The main appeal of the String Landscape is that it is links independently developed ideas in particle physics and relativity (String Theory and inflationary cosmology) in a rather natural way. It thereby gives a theoretical framework for what would otherwise be a somewhat gratuitous postulation of myriads of parallel universes with just enough physical variation between them to ‘explain away’ the FTL. It is worth underscoring the ‘eternal’ in eternal-inflation: once it gets going it would self-propagate and never end thus providing the Multiverse-proponent with an actual infinity of ‘explanatory resources.’ As Vilenkin

---

[117] Note, one can of course allow the laws and constants of physics to vary between different Hubble volumes, only there is not a ‘natural’ way to do this that will not at the same time generate something like a Level 2 scenario. (If, say, you allow the parameters to vary in particle physics you will tend to alter the vacuum energy and induce eternal inflation). Cosmologists therefore tend to prefer Level 2 and the question then becomes what sort of underlying meta-laws will govern the way laws and parameters vary between domains.

explains,

> [I]t is conceivable that inflation is not eternal. This outcome, however, can be achieved only at the cost of making the theory rather contrived. In order to avoid eternal inflation, the energy landscape of the scalar field needs to be custom-tailored specifically for that purpose.[118]

In other words, trying to make the number of universe-domains finite would undermine the original motivation for the scenario (the fact that the theory is not *ad hoc* but emerges rather elegantly from ideas pertaining to 'known' physics). This is quite generic: actual infinities are a natural concomitant of Multiverse theories as one typically requires fine-tuning to make these theories only bring about the existence of a large but finite number of universes.[119] It is in the context of such 'actualized infinities' that Boltzmann Brains (and the measure problem) become an especially relevant issue as already discussed.

The Many-Worlds interpretation of quantum mechanics (Level 3) is relatively popular amongst cosmologists due to its apparent observer independence (thus allowing one to speak about 'the Universe' without reference to 'measurement,' 'observer,' 'instrument' etc. as these don't seem to be applicable concepts in the early Universe when no one was around). According to this view, each quantum possibility represented by individual terms in the wave-function of the Universe (which is the product of all the wave-functions of all the particles therein) is realized, and every combination of realizations constitutes a unique 'branch' that, once formed, has (for all intents and purposes) no further causal contact with the others.[120] 'Our branch' would therefore be just one within an infinity of other branches, each one realising a different history of the world. When conjoined with the eternal-inflation scenario (as several cosmologists propose we do), the mere

---

[118] Vilenkin (2006, p. 117). He adds, "The theory of inflation is by far the best explanation we have for the big bang. If we accept this theory, and refuse to mutilate it by adding any ad hoc, unnecessary features, then we have no choice but to accept eternal inflation – with all its consequences, whether we like it or not" (Vilenkin 2006, p. 117).

[119] It is commonly reported that the String Landscape 'has' or 'predicts' the existence of 10^{500} universes, thus giving the impression that only a finite number of universes are entailed by the theory. But this is misleading. Firstly, as has been mentioned, the String Landscape entails eternal inflation and thus an infinity of universes each of which is *characterized* by one of 10^{500} types. Secondly, it is not clear that there is an upper-limit to the exponent (500). So it is more appropriate to say that the calculation, if veridical, shows there to be *at least* 10^{500} different *types* of universe, according to this scenario.

[120] Technically, according to the proposal, there is always some non-zero (albeit minuscule) interference between all the different branches but it is so negligible that the branches can really be regarded as non-interacting (*viz.* decoherence).

cardinality of this ‘actual infinite’ becomes unfathomably large.

Finally, Tegmark’s Level 4 is what we might call a form of ‘reified Platonism’ where all ‘Mathematical structures’ exist in the same way that our Universe exists. This position is comparable to David Lewis’ modal realism where ‘all possible worlds’ exist. Tegmark identifies his position as a form of ‘ontic structural realism.’ This is to be distinguished from ‘epistemic structural realism,’ which says that we are simply ignorant of any properties of the objectively existing relata that constitute the world external to the mind *other than* the fact that they stand in certain mathematical relations to each other (see Smart’s quotation p. 45). Ontic structural realism goes one step further and denies that there are any relata, it’s only the relations themselves that ‘exist.’ At first glance then, Tegmark’s Multiverse seems to stand at the extreme end of a substance-less ontology. All there is, is mathematics.

How then does Tegmark reconcile the fact that the world *feels* so very tangible? What does it mean to say all mathematical structures (e.g. the mathematical structure isomorphic to the set of imaginary numbers) ‘exist’ in the same way our world does? He writes,

> Given a mathematical structure, we will say that it has *physical existence* if any self-aware substructure (SAS) within it subjectively. . . perceives itself as living in a physically real world.[121] [Emphasis original]

It can hardly be denied that Tegmark’s position is rather confusing. He first stated (see §2.3.1) that understanding consciousness is not necessary for “a fundamental theory of physics,” but he then seems to define ‘physical existence’ as that which is perceived subjectively (which sounds ironically close to Berkeley’s *esse est percipi*).[122] Now, for the philosopher of mind, this choice of words just begs the question. The problem of consciousness *just is* to do with how physical states can give rise to *subjective* perceptions.[123] So for Tegmark to equate physical existence with “that which is perceived subjectively” just is (contrary to his stated position on p. 30) to effectively treat consciousness as the essential ingredient of a fundamental theory being *physical*.

---

[121] Tegmark (2004, p. 473).

[122] “To be is to be perceived” Berkeley 1710.

[123] As Chalmers puts it, “The hard problem [of consciousness]. . . is the question of how physical processes in the brain give rise to subjective experience.” Chalmers (1995).

> [T]he answer to the question ‘what breathes fire into the equations and makes a universe for them to describe?’ would then be ‘you, the SAS.’[124]

At other times though Tegmark seems to go back on this notion of something “existing physically” when he claims that other mathematical structures devoid of SASs exist in the same sense as our Universe. (For example, he writes that “all mathematical structures exist “out there” in the same sense [as the physical world].”[125] Tegmark’s use of terms is, at best, idiosyncratic and, at worst, incoherent. Such confusions are an inevitable consequence of denying $\mathbf{I_2}$, that is, equating mental states with physical states. Those physicists who equate that which gives the appearance of the world being substantiated (i.e. consciousness) with numbers and mathematical relations invariably end up drawing unintelligible conclusions such as the generation of the world from ‘nothing,’ which we shall briefly survey.

2.5.2 Tunneling from Nothing

Today’s scientists have substituted mathematics for experiments, and they wander off through equation after equation, and eventually build a structure which has no relation to reality. – Nikola Tesla[126]

High-profile cosmologists gather much attention when they speculate about the Universe’s coming into being ‘out of nothing.’ How can *non-being* generate anything? The physicist sometimes tries to get around what appears to be a plainly incoherent, non-sensical statement by simply reifying mathematics. It comes at little cost to the physicist to write down an equation which, they then claim, is representative of this *ex-nihilo-ad-rem* process. This amounts to saying that ‘nothingness’ is in fact something,[127] namely an eternal (perhaps timelessly-eternal?) random number generator (“quantum fluctuations”) whose outputs are funnelled by (combinations of) arithmetic

---

[124] Tegmark (2007, p. 120).

[125] Tegmark (2004, p. 473).

[126] Tesla (1934, p. 42).

[127] One might complain that if nothingness is in fact something then the term nothingness is a misleading choice of term. The speculative physicist could invent a new word which denotes the collection of properties that they are referring to but, presumably for socio-economic reasons (i.e. selling popular books), they choose not to, although sometimes they put quotation marks around the word “nothingness” in acknowledgment of its questionable appropriateness.

relations (i.e. laws that exist in addition to the ‘nothingness’) into an enormous variety of space-times. After all, space-time coordinates and their contents are essentially numbers; and where else do these numbers come from except some other numerical domain? One might assume therefore that since ‘nothingness’ apparently has the capacity to generate numbers, numbers will eternally be generated and instantiate an infinite number of space-times.

But why call those original numbers ‘nothing’ and the ones to which they are mapped ‘something’? An example of such a claim is given by Vilenkin, who writes

> The entire eternally inflating spacetime originated as a minuscule closed universe. It tunnelled, quantum-mechanically, out of nothing and immediately plunged into the never-ending fury of inflation... The tunnelling process is governed by the same fundamental laws that describe the subsequent evolution of the universe.[128]

It seems unavoidable to me that this extra ‘something’ needs to be the presence or absence of psychophysical relations (as suggested by Tegmark’s definition that physical existence is that which is perceived by SASs). The numbers describing the physical state of one’s brain might have a corresponding form in the Platonic realm – but why would just *this* set of numbers and relations (or the mathematical structure isomorphic to it) enjoy the particular qualitative experience that it does (say the ‘what it’s like to taste an orange’) and not some other (say the ‘what it is like to be imagining eternal-inflation’)? Some extra, very specific set of relations is needed to supervene over the infinite set of Platonic forms, specifying what qualitative experiences, if any, are to obtain.

2.5.3 Multiverse or Mindscape?

What then sets the precise psychophysical relations that obtain in our Universe? If one simply posits that the precise psychophysical relations that obtain here and now are the only ones that exist in *any* possible universe, then this creates a serious fine-tuning problem. For if the psychophysical relations that seem to obtain in our Universe are the *only* ones that can obtain in any universe, then it becomes extraordinary that they be so appropriate in having us make coherent sense of the world. Likewise, to say that such a precise set of relations was ‘necessary’ is to suppose that some

---

[128] Vilenkin (2006, p. 204-5).

sort of ‘rationality principle’ is embedded into the nature of existence (similar to what what Keith Ward calls the ‘Supreme Informational Principle’ Ward 2010, p. 291).

The Multiverse could give the answer though and it resembles the ‘quantum suicide experiment.’ Just as the laws of physics and associated free parameters are allowed to vary across universe-domains, so the set of psychophysical relations could be allowed to vary between universe-domains. Suppose, as Tegmark does, that there is a physically identical person to the reader $10^{10^{29}}$ meters away and that the psychophysical relations are allowed to vary. In this case, the reader’s physical replica will experience (epiphenomenally)[129] distinct mental states (or perhaps none at all) and, in general, the replica’s mental states will not constitute coherent thoughts. Of course, for all those universes where the physical replicas do not happen to have structurally-coherent psychophysical relations (as we do in this Universe at this very moment), they will not be able to ‘mentally register’ the fact that they are in such a world. (I take the phrase ‘structurally-coherent thoughts’ from Chalmers 1996; see Darg 2012b for expansion.) We can therefore use something like the weak anthropic principle - but applied to mental states - as a selection effect to remove the surprise as to why we find our mental lives structurally coherent (if they were not structurally coherent at this moment, we would not appreciate this fact mentally). After all, we have an infinity of such worlds to play with on the Multiverse scenario so every combination of mental states, including those very occasional ones that are structurally coherent, will obtain. Only where they do will the individual coherently understand this fact.

This ‘solution’ allows the would-be materialist to embrace the intuitively-compelling, qualitative distinction between mental states and physical states (expressed by $\mathbf{I_2}$) while accounting for their structural coherence within a naturalistic framework.

Several objections will no doubt have arisen by now in the reader’s mind. The first one is that, if the psychophysical relations that characterise this Universe are generated entirely at random, then at any point in the future a new physical state could obtain in one’s brain such that they cease to be accompanied by structurally coherent thoughts. Although this might disconcert the reader in

---

[129] Epiphenomenalism is the view that physical states give rise to or are accompanied by mental states but that these mental states do not in turn affect the course of the physical system’s evolution. See Darg 2012b for argument as to why causal closure requires epiphenomenalism.

so far as we all desire to have control over our (mental) lives, it is not a *technical* problem for the position. When one falls into a dreamless sleep, one's brain enters a set of physical states that are not accompanied by structurally coherent thoughts (for one is having no thoughts at all). The only times when we are able to worry about our thoughts being structurally incoherent are those times when our minds enter back into a structurally coherent phase. Being epiphenomenal in nature, any structurally incoherent thoughts we may have had in our lives will have left no mark on our memories (as is the case for the vast majority of dreams we have had in our lives). Thus, when we *do* find ourselves having thoughts that we take to be structurally coherent (and correspond faithfully to the external world), we will not have been aware of previous times when our mental lives fell out of structural coherence. For all the reader knows, their thoughts may have re-entered structural coherence a few moments ago and any memory they may have of being structurally coherent a few moments ago is simply because the psychophysical relations that obtain for them *now* are such as to supervene in a structurally coherent manner over the physical memory states recently recorded in the brain.

The second objection is that this is not a very 'simple' or 'parsimonious' theory. One response to this is to call the principle of parsimony ("Ockham's Razor") into question on the grounds that it is vague and suspiciously pragmatic. Another response is that it *can* be construed as parsimonious in a similar way to how the physical Multiverse is purported to be 'simple.' As Tegmark argues,

> The first [objection] is that multiverse theories are vulnerable to Ockham's razor, since they postulate the existence of other worlds that we can never observe. Why should nature be so ontologically wasteful and indulge in such opulence as to contain an infinity of different worlds? Intriguingly, this argument can be turned around to argue *for* a multiverse. When we feel that nature is wasteful, what precisely are we disturbed about her wasting? Certainly not "space", since the standard flat universe model with its infinite volume draws no such objections. Certainly not "mass" or "atoms" either, for the same reason — once you have wasted an infinite amount of something, who cares if you waste some more? Rather, it is probably the apparent reduction in simplicity that appears disturbing, the quantity of information necessary to specify all these unseen worlds. However... an entire ensemble is often much simpler than one of its members. For instance, the algorithmic information content of a generic integer n is of order $\log_2(n)$..., the number of bits required to write it out in binary. Nonetheless, the set of all integers 1, 2, 3,... can be generated by quite a trivial computer program, so the algorithmic complexity of the whole set is smaller than that of a generic member... Loosely speaking, the apparent information content rises when we restrict our

> attention to one particular element in an ensemble, thus losing the symmetry and simplicity that was inherent in the totality of all elements taken together. In this sense, the higher level multiverses have less algorithmic complexity. Going from our universe to the Level I multiverse eliminates the need to specify initial conditions, upgrading to Level II eliminates the need to specify physical constants and the Level IV multiverse of all mathematical structures has essentially no algorithmic complexity at all.[130]

The same could be said of the position represented here - that *all* possible psychophysical correlates that supervene over the existing mathematical structures obtain. (This view resembles the 'mindscape' proposed by Rucker 1997.) In other words, saying that

$\mathbf{P_{mm}}$: "every possible combination of mental state exists"

is, in one sense, simpler than specifying the particular correlations that happen to obtain in *this* Universe.[131] Notice that *even on the physicalist construal* of the mind-body problem (the position that denies $\mathbf{I_2}$), one is committed to $\mathbf{P_{mm}}$ since every possible combination of physical brain states obtains (an infinite number of times) and, since on physicalism the physical state is identical to the mental state, $\mathbf{P_{mm}}$ follows.

Thirdly, one might object that this 'solution' to the mind-body problem is just to give up on trying to find a more-satisfactory solution. But again, this is a highly pragmatic complaint. If the scenario described just *is* the case, then yes, we *would* be wasting our time. One can only object to this position if one already knows *in advance* that we are *not* wasting our time. But until one finds an alternative solution, one obviously does not know that we are not wasting our time. If, to the best of our ability, we conclude that a problem is insoluble, why on earth would one carry on trying to solve the insoluble just because they don't like that conclusion? There surely comes a point when we can understand a problem well enough to see why it is that it is intractable, otherwise why not invest money in the Feynman ratchet? As McGinn writes,

> We have been trying for a long time to solve the mind-body problem. It has stubbornly

---

[130] Tegmark (2008, p. 121).

[131] To write down a description of all the mental states that have taken place in one's life time would require much more information content than just saying "every possible combination exists." In this sense, $\mathbf{P_{mm}}$ is 'simple.'

> resisted our best efforts. The mystery persists. I think the time has come to admit candidly that we cannot resolve the mystery.[132]

The same criticism can equally apply to the physical Multiverse theory. Given an infinite number of worlds just like ours, *any* highly improbable state of affairs will eventually happen. Carter & McCrea (1983), Barrow & Tipler (1996, p. 556-70) and Hart (1999) have all argued that certain hurdles for the evolution of life (e.g. the genesis of the first self-replicating cell) that seem, on the face of it, to be highly improbable were in fact overcome by the brute-force capacities of the infinite-universe hypothesis (whose metaphorical horde of monkeys has eternity to play at the typewriter). If this is the case then biologists would indeed be wasting their time searching for chemical-evolutionary precursors for life since there aren’t any – we happen to be in the universe where the tornado fortuitously encountered the junkyard, else we wouldn’t be here to make that observation (and we are likely alone within our Hubble volume).

Fourthly, one might object that this ‘solution’ would imply that it is highly unlikely that other people we interact with, at any given time, are experiencing structurally coherent thoughts (even though they give every physical appearance of doing so). Again, although this is not a *desirable* outcome, it is not a *technical* problem (since when does reality conform to what we *want* to be the case? See Tegmark’s quote below on emotivism, p. 67). The Multiverse ‘solution’ would just imply a concrete position with respect to the philosophical problem of other minds. (We can never be sure what sort of mental life (if any) other people experience.)

Fifthly, and most importantly, the reader might object that this proposal undermines its own epistemic justification. If “we” have no control over our thoughts (since they are random and entirely epiphenomenal) then we have no reason to believe the scenario. This is of course a worry but is nothing new and is not particular to this proposal – this is just the classic problem of induction and epistemology: how can we have any confidence in our intuitions when we don’t know the underlying reality that generates our intuitions? To say that “we *do* know the underlying reality that generates our intuitions, it’s the brain,” is to miss the problem altogether and argue in a circle.

---

[132] McGinn (1989, p. 1). He goes on to argue that our brains suffer from ‘cognitive closure’ such that evolution has not granted us the fortune to be able to make the physicalist identity in a manner that makes sense to our minds. (See §2.4.4).

One had to trust their intuitions *in the first place* to reach the conclusion that the brain exists and that the brain generates the right sort of mental states to allow the individual to introspectively conclude that one's intuitions are reliable. (In fact we know from dreams that we *often* make non-veridical inferences from our mental states about the nature of the external world.) In other words, one has already chosen to disregard the possibility that our beliefs are non-veridical as soon as one posits the existence of the external world based purely upon a purported sense of 'intuitiveness' characterising those very mental states.

The same basic problem of 'us not being in control' of our mental lives or having free will is not particular to this proposal either, but to a depiction of the mind supervening on strictly deterministic physics in general, as Haldane famously expressed,

> It seems immensely unlikely that mind is a mere by-product of matter. For if my mental processes are determined wholly by the motions of atoms in my brain I have no reason to suppose that my beliefs are true. They may be sound chemically, but that does not make them sound logically. And hence I have no reason for supposing my brain to be composed of atoms.[133]

So while it must be granted that this proposal is problematic in this regard, it does not create *new* epistemological problems. The realist has already concluded that the external world exists because, it is claimed, the whole external-world hypothesis entertained within one's phenomenal introspection is deemed to be logically consistent and to have an associated intuitiveness, that is, a "properly basic *feel*" about it when contemplated. If a 'properly basic feel' is all that is required then this is no problem for the proposal since an infinite Multiverse will generate an infinite number of sequences of 'properly-basic feelings.' In other words, the Multiverse would have its own capacity not only to 'understand itself' (as many authors have marvelled) but to also 'epistemically justify itself,' so to speak. To the complaint 'this scenario is counter-intuitive,' the reader is referred to the standard apologetic of Multiverse proponents that encourages us to disregard our intuitions when they militate against infinite-reality scenarios,

> The perceived weirdness is hardly surprising, since evolution provided us with intu-

---

[133] Haldane (1927, p. 209).

> ition only for the everyday physics that had survival value for our distant ancestors.[134]

In other words, the propsal might be counter-intuitive, but hardly more than the Multiverse itself which entails that *everything that is possible happens an infinite number of times*, even the Star Wars universe (see quote by Hawking & Israel, p. 34). As anti-intuitive as this is, it seems that this is part and parcel of the infinite-Multiverse scenario.

Finally, let me remind the reader that any attempted solution of the mind-body problem will *either* create new mysteries *or* involve highly anti-intuitive conclusions (for example, the claim of material eliminitavists that consciousness is illusory – the only thing that, by its nature, it seems it cannot be). Once one has posited every combination of matter as 'actually existing,' why not every combination of mind? It also complies with Copernican ideology by ensuring that one's mental states are not 'special,' as Tegmark remarks,

> [The Mathematical Universe Hypothesis] is arguably extreme in the sense of being maximally offensive to human vanity. . . The most compelling argument *against* the MUH hinges on such emotional issues: it arguably feels counterintuitive and disturbing. On the other hand, placing humility over vanity has proven a more fruitful approach to physics, as emphasized by Copernicus, Galileo and Darwin.[135]

Thus we see that the MUH has an answer to every objection except for the one that the reader alone can judge for its intrinsic worth: it just seems absurd. It is the result of equating abstract mathematics - of which there are countless forms - with that which we know to exist, our finite, tangible world. Ellis strongly urges, we "need to realise explicitly that the models and theories on which we base our understandings are partial representations of reality, not to be confused with reality itself." Ellis 1999, p. 286.

2.6 Summary

The reader will be relieved to know that I do not endorse the Multiverse "solution," rather, it just goes to show what sort of metaphysical baggage infinite-Multiverse scenarios can lead to. It is not

---

[134] Tegmark (2004, p. 17).

[135] Tegmark (2008, p. 142).

extra-universe theories *per se* that are the problem; indeed, it would be extraordinary if *this* were the only reality. We concur with Davies who argued that allowing the infinite into nature is to give a “catch-all, blunderbuss” solution to the puzzles of reality, and is no more of an ‘explanation’ than naive deism (Davies 2007). On the other hand, we have no alternative suggestions for the demarcation between reality and possibility. We suspect that this will forever remain a mystery.

The proposed ‘Multiverse solution’ to consciousness also highlights the appeals of eliminitavism; the world appears *much* simpler if we can take consciousness - with all its mysteries - out of the world as and when we do science. But this requires science to focus on measurements and descriptions, that is, to take a rather positivist stance. In this case science would not rule on the existence of an infinite universe until or unless such a construction proved empirically useful. We conclude then with where we started: ‘existence’ is full of mystery; but simply saying ‘everything exists’ leads to absurd conceptual and epistemological problems, well outside the practical domain of science whose power consists in description of phenomena.

Part II

Astrophysical Investigations

Chapter 3

Is Lambda Optimal for Life?

God was infallibly led by His wisdom and goodness to give the world the best form possible; but He was not led to it necessarily. – Leibniz[1]

3.1 Introduction

In this chapter we transition from philosophical investigations to more mainstream astrophysical ones. We describe a new research program relevant to the study of the AP and discuss preliminary findings and its future potential.

For the first few decades since it was proposed by Brandon Carter in 1974 (Carter 1974), the Anthropic Principle (AP) was deemed highly unsatisfactory by most cosmologists and particle physicists, no doubt in part due to the metaphysical overtones of the proposal.[2] There was something of a revolution however in the early 2000s chiefly spawned by theoretical developments in String Theory and empirical consolidation of the ΛCDM cosmological model (see e.g. Komatsu et al. 2009 for analysis).

Two empirical finds gave particular backing to anthropic considerations within the cosmological community. Firstly, the WMAP data (Spergel et al. 2003) and distant supernovae (Riess et al.

---

[1] Taken from the interpretation of the French translation as found in (Adams, 1982, p.266).

[2] As Schellekens described, “the number of string papers before 2000 containing the “A-word” can be counted on the fingers of one hand” (Schellekens 2008, p.8). Even getting anthropic calculations published in major journals proved difficult in some cases (Weinberg 2007).

1998; Perlmutter et al. 1999; see Perlmutter 2005 for review) point strongly to a non-zero value of the cosmological constant an order of magnitude or two below the anthropically-allowed upper limit calculated by Weinberg (1987a) (a limit some $\sim 60-120$ orders of magnitude below the expected value, see Carroll et al. 1992; Rugh & Zinkernagel 2001; Bousso 2008) that allows for the gravitational formation of stars and galaxies. We shall call this the 'Weinberg Window' (WW) following Bousso & Polchinski (2000) where $-10^{-120}\mathrm{M}_{Pl}^4 < \Lambda < 10^{-118}\mathrm{M}_{Pl}^4$.[3]

Secondly, the data are (strongly) consistent with some of the predictions of the simplest models of inflation: a flat, homogenous, isotropic Universe with near-scale-invariant Gaussian inhomogeneities giving rise to structure formation (see e.g. Boyle et al. 2006). If correct, then the Multiverse scenario seems to follow quite naturally. The hypothetical inflaton, permeating all space-time, would take on a range of different values that drive the exponential expansion of space for the most part. So long as the volume of exponentially expanding space out-proportions the volume where the inflaton has been driven to the minimum of the inflationary potential (corresponding to the observed vacuum energy), run-away inflation will self-propagate and generate 'bubble universes' *ad infinitum*. It has been argued that this condition is readily entailed by the theory (Vilenkin 1983; Linde 1986).[4]

Inflation thus seemed to solve several fine-tuning problems, account for the initial expansion of the Universe,[5] and furnish a mechanism for generating the sort of large-ensemble scenario in which anthropic selection effects could play a role akin to Darwinian natural selection. Just as biological organisms might appear 'pre-ordained' for their environments due to selection effects

---

[3] The lower bound for negative Λ corresponds to a short-lived universe ending in a Big Crunch.

[4] There are two ways in which this is possible: 'eternal' and 'chaotic' inflation. Chaotic inflation is based on the idea that *only* the patch of inflating space that directly gave rise to our Universe would be sufficient to generate bubble universes in virtue of the fact that, above a threshold energy, the amplitude of quantum fluctuations of the inflaton, ϕ, are great enough to match the characteristic fall in the potential as the inflaton rolls down the hill; this creates positive feedback and generates exponential growth of bubble nucleation (see e.g. Linde 2007). A more generic 'eternal' inflation simply supposes that other regions of space-time naturally possess differing values of ϕ such that all regions with significant vacuum energy will rapidly expand, and those with zero or negative energy will contract away.

[5] In the context of eternal inflation the initial expansion of our Universe - what used to just get taken as rather curious initial condition - is understood simply to be the inherited value of $\dot{a}(t)$ come the end of inflation. As Blau & Guth 1987, p.543-4 explain, "While the inflationary model does not attempt to explain the formation of the initially hot expanding regions which subsequently supercool into the false vacuum state, it does explain the origin of most of the momentum of the cosmic expansion: the big bang gets its big push from the false vacuum." The question of the 'beginning' can thus be pushed arbitrarily far-back in time if eternal inflation is in fact past eternal (though see Borde et al. (2003) for an argument against this being possible).

operating on many life forms and many environments, so in an inflationary Multiverse only in the very small life-permitting subvolumes would one be able to find life as we know it. As Wilczek notes

> It is simply a fact that intelligent observers are located in a minuscule fraction of space, and in places with special properties. As a trivial consequence, probabilities conditioned on the presence of observers will differ grossly from probabilities per unit volume (Wilczek 2007a).

Around the same time the astrophysical data was coming in, fresh developments in String Theory, starting with Bousso & Polchinski (2000), were establishing the consistency of a large number of compactification schemes in 11D supergravity. Each topological fixture (characterised by moduli) can be populated by a set of fluxes and brane parameters that, through combinatorics, all give rise to a vast number of effective field-theories. Since the potential energy at any given point in space-time would depend on the local values of these string parameters (that play the role of the inflaton), each world-line observer would find their vacuum energy driven to a local-minimum in the potential (and eventually to the true vacuum state $\Lambda = 0$; Suskind 2007). If the altitude and slope of the potential are just right then this gives rise to slow-roll inflation with the lost potential energy fuelling the 'reheating' process and giving rise to what would look like a hot Big Bang. Given the large number of possible vacua (estimates have suggested *at least* $10^{100} - 10^{500}$ and possibly an infinity of such; Ashok & Douglas 2004), the theory entails the existence of a (potential)[6] infinity of space-time patches with widely varying physical 'constants.' Susskind termed this the String Landscape (Susskind 2003).

While some remain resistant to this new paradigm (see Starkman & Trotta 2006; Maor et al. 2008 and references in Kragh 2011, p.241-6), for an increasing number within the particle and cosmological communities the salient question is not *whether* we live in a Multiverse but, rather, what becomes of their disciplines in view of this development. In particular, how does the essential

---

[6] Whether global space-time constitutes an 'actual' versus 'potential' infinity depends on the one's philosophical stance within the philosophy of time. B-theory or 'Block Universe' proponents of time see it as ontologically similar to space, existing always or "timelessly." Conversely, those who militate against the existence of 'actual infinities' tend to embrace the everyday notion of temporal becoming: only the present 'exists' and events can only ever accumulate in number towards a 'potential' infinity, without ever 'traversing' it; see Ellis et al. 2004; Ellis & Stoeger 2009.

scientific notion of testability feature into the paradigm, if indeed it does, when we have the single statistic of our Universe from which to infer its generating mechanism? Two chief proposals have been offered to this problem. These are based upon (i) the prediction of observable effects *within* our Universe owing to universe-generating mechanisms and (ii) the Principle of Mediocrity.

The first proposal is the less philosophically contentious of the two as it need not, in principle, make special reference to the notion of an ‘observer’ (at least, no more so than any standard scientific observation). However, it faces several practical problems. A key prediction of eternal inflation arising from, say, the String Landscape is the nucleation of an infinite number of bubble universes. The density and parameterisation of such events (expansion speeds, etc.) in a volume of space-time will therefore depend on the local terrain within the landscape. This means that, although one might derive *relations* for the probability of a bubble-related observable, it is difficult to see how any sound numbers could be inserted unless we know where we are in the Landscape (and thus how steep the potential is around us, whether there is a false minimum nearby, etc.). If an anomaly were to ever show up in the sky, doubtless a bubble-cascade configuration could be chosen that would ostensibly give rise to such an observation and so exactly how *ad hoc* such an “explanation” would be, whether it is similar to the fitting of planetary orbits by spheres and epicycles, is difficult to gauge.[7] Often these sorts of arguments make implicit use of the principle of mediocrity as when, for example, Aguirre et al. 2007 write “assume ourselves to be in a typical surviving region” (p.13). (See Aguirre 2007 for discussion of Multiverse predictions.)

This, the Principle of Mediocrity (PoM), is the second broad proposal which “suggests that we think of ourselves as a civilization randomly picked in the metauniverse” (Vilenkin 1995). As already discussed, it leads to profound philosophical questions such as the measure problem (see e.g. Linde & Noorbala 2010) and the choice of reference class for observer (Bostrom 2003a). Notwithstanding these concerns, the principle trades on the common sense notion that to assume

---

[7] For example, it has been claimed that Holman et al. (2008) ‘predicted’ the discovery of a void in the CMB based upon their calculations of “entaglement and backreaction contributions” to the wave function of the Universe as it propagates through the String Landscape and was reported in New Scientist as “the unmistakable imprint of another universe beyond the edge of our own” Mersini-Houghton (2007). Of course, had the number that appeared from their calculation ($\sim 5 \times 10^8$ light years) been much less (and thus indistinguishable from normal Gaussian inhomogeneities) or much more (obviously ruled out), one wonders if such a “prediction” would have been published.

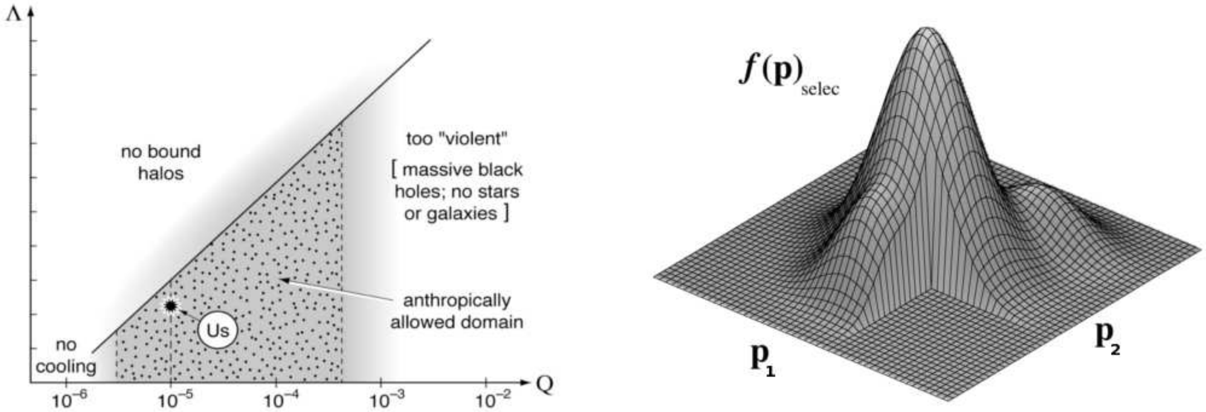


Figure 3.1: *Left:* An example of a standard anthropic-limits diagram marking the boundary where life is possible but says nothing about its probability.[8] *Right:* Illustration of the dependency of $f(p)_{selec}$ on p_i where critical transitions are depicted by sudden 'cliffs' on the life-permitting islands (as in the 'diproton disaster' with changing strong-force; see Appendix A.1). PoM-reasoning places us at or near the peak.

typicality for any given situation is more likely to prove correct than to assume the extraordinary and leads us to examine the intrinsically interesting question as to whether or not this Universe is optimal for life (or 'observers') as we know it. For the remainder of this study, we shall place the first proposal to one side regarding potential observables like bubble-nucleations and focus on this question related to the PoM.

3.2 The Research Program

In this section we shall explore some of the *principles* of PoM-reasoning. The classic fine-tuning arguments, as set out by Barrow & Tipler (1988) and others, focussed on anthropic *boundaries* of the fundamental constants and initial conditions that characterise our Universe. The PoM goes one step further and states that all the parameters upon which life depends are expected to be such that life per volume in this parameter space *peaks* near to our observed values. This has resulted in an increased effort to work out the functional dependency of 'life' on changes to these parameters (Martel et al. 1998; Tegmark & Rees 1998; Weinberg 2000; Graesser et al. 2004; Tegmark et al. 2006; Garriga & Vilenkin 2006). Following Tegmark et al. (2006), we can treat the list of 31 free parameters in the standard models that they compiled as components of a 31 dimensional vector $p_i = \{\Lambda, Q, ..., p_{31}\}$ and let $p_1 = \Lambda$ for convenience. Again, following their notation, we can represent the probability of observing p_i as

$$f(p_i) \propto f_{prior}(p_i) f_{selec}(p_i) \tag{3.1}$$

where $f_{prior}(p_i)$ is some observer-independent, theoretical prior probability as would arise from a Multiverse scenario and $f_{selec}(p)$ is the relative probability that, given a universe with p_i, it gets 'observed' therein. A philosophical question worth raising is what exactly is getting 'observed' in the universe with p_i; is it the values of p_i themselves (i.e. is our reference class one of scientists?) or an observation of *anything*? After all, we are clearly not *just* in any ordinary reference class of observers, but we are also in the very special class of *cosmologists* - capable of working out the values of p_i due to our (apparently fortunate) position in cosmic history where $\Omega_\Lambda \sim \Omega_m$ enables us to detect dark energy and perform extra-galactic astronomy.[9] By contrast, it could be that 'observers' more generically populate high Λ universes (near the upper bound of WW) where galaxies have become eternally isolated by the time advanced life manages to evolve.

Doubtless, cosmologists will generally, on methodological grounds, prefer *not* to insinuate that we are 'special' just because we can do cosmology (though it's worth noting that Weinberg 2000 describes the reference class as that of a "scientific society"). But this presupposes unwarranted bias towards 'mere life' as opposed to 'life like us.' After all, it is *a posteriori* obvious that of the vast number of animal species on the planet, we are the only ones that do cosmology.[10] Perhaps in other much more frequently recurring universes there will be very simple life - the most common in the Multiverse - but no one in a position to do cosmology therein. This highlights once again the ambiguity of 'observer' and choice of reference class in such discussions.[11]

---

[9] It is worth noting that several arguments have been made as to why life likely coincides with $\Omega_\Lambda \sim \Omega_m$ (e.g. Garriga & Vilenkin 2006, §II), but this misses a subtle point in so far as it *still* seems fortunate that a common origin give rise (deterministically) to life and something to which *we* attach value (scientific discovery). This mimics the FTL discussion as found on p.16.

[10] Similarly, George Efstathiou once commented that he doesn't puzzle over the fact that he is not Chinese; even though that might be *a priori* the most likely outcome for a randomly chosen human being, once the datum is established we need to adjust our expectations to accommodate what we have learnt to be the case.

[11] This is a point taken seriously by Starkman & Trotta (2006), who write that choices for f_{selec} suffer "from an acute dependence on poorly understood microphysical processes involved in the evolution of life, especially of conscious beings interested in making observations of the fundamental constants" (p.2).

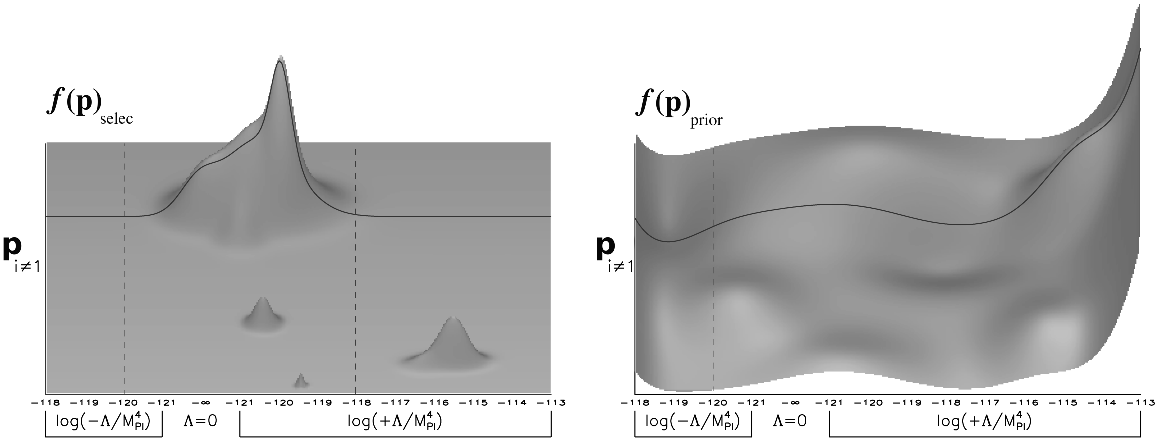


Figure 3.2: *Left:* Illustration of the possible distribution of $f(p_i)_{selec}$ with $p_1 = \Lambda$ on the x-axis and the remaining components of $p_{i\neq 1}$ on the y-axis (a 30-dimensional space). The claim of FTL is that the majority of this plane (i.e. volume in the 31-dimensional space) hosts no life, and so these 'biofriendly islands' are relatively rare. Standard FTL diagrams, as in Figure 3.1 (*left panel*), focussed on the perimeter of the bases of these islands, whereas in this study we enquire about the overall dependency of f_{selec} on p_i. *Right:* Illustration of possible distribution of $f(p_i)_{prior}$; it is typically assumed that in the region of interest (the WW inside the dashed-lines), $f(p_i)_{prior}$ is fairly flat. The shape of $f(p_i)$ would be obtained by convolving these two distributions together. The solid-black line represents universes like ours except for variations in Λ (and assumes that our p_i is optimal for life). Note: there is an implied break in the x-axis at $\Lambda = 0$ because it is logarithmic.

Placing this issue to one side, if we are to follow the advice of the PoM, then we would expect the value of $f(p_i)$ to peak at p_i' which we use to denote the values of our Universe. In other words, any change in any component of p_i would most likely reduce $f(p_i)$,[12]

$$\forall i \, \frac{\partial f}{\partial p_i} \approx 0. \tag{3.2}$$

The shape of $f(p_i)$ can be illustrated graphically as shown in Figure 3.1. Whereas early studies on anthropic bounds could be plotted on a 2D plane (*left panel*), for our purposes we must illustrate the principles of (3.2) on 3D graphs to show variations in $f(p_i)$. We can distinguish

---

[12] Of course, this could be compensated by changes to other parameters as discussed below between Λ and Q; but if $f(\Lambda, Q)$ (all else constant) *both* give $\partial f(\Lambda,Q)/\partial\Lambda|_Q \approx 0$ and $\partial f(\Lambda,Q)/\partial\Lambda|_Q \approx 0$, then we are likely near the peak of $f(\Lambda, Q)$.

between smooth, continuous paths in p_i-space and paths that subject $f(p_i)$ to sharp or discontinuous changes. Gradual changes in Λ about p'_i (while keeping $p'_{i\neq 1}$ constant) are likely to be of the former kind, since the anthropic dependency arises from DM-halo formation which will vary continuously with Λ over the range of the WW before fading to $f = 0$ (although, as we shall see, changes to the DM-mass function produce non-negligible feedback effects on galaxy formation, so the dependency of $f(p_i)$ on Λ is not as smooth as one would expect just in terms of DM growth). The diproton disaster, by contrast, is an example of the latter kind, arising due to the fact that two protons fail to bind by a marginal ~ 92 keV and would bind if α_s were $\sim 13\%$ larger (Barrow & Tipler 1996, p.322). Thus variations in the strong force (keeping all else constant) would result in a sharp drop off at $\sim 1.13\alpha_s$ due to this transition (as most of the hydrogen would have burnt up in the early universe leaving no resources for long-lived stars).

The presence of such sharp transitions resulting from the complex shapes of nuclear potentials and chemical shells means that it is extremely unlikely that we shall be able to wander far or (any distance) from p'_i for particular directions whilst being able to ascertain quantitative changes to f_{selec} with any confidence.[13] However, if we are *only* aiming to answer whether or not *our* Universe is optimal for life, small changes to each of p_i is all that we need to see if we are at or near the peak. This seems like an intrinsically interesting project. If it turned out that

$$\forall i \; \frac{\partial f_{selec}}{\partial p_i} \approx 0 \tag{3.3}$$

then it would imply that our Universe is near-perfect for members of our reference class and we would not want there to be strong dependence on f_{prior} near p'_i; on the other hand, if we could see that it were plausible that the frequency of members of our reference class would be increased by variation in *any* single component of p_i (keeping the rest constant) then we could conclude that our reference class is not maximised at p'_i and we would be able to tell roughly what direction f_{prior} would need to go in order to satisfy (3.2). This could prove important since different a priori

---

[13] The anthropic bounds, such as those of the diproton disaster, are *known* bounds, but given the complexity of biochemistry and critical resonances in stellar nuclear synthesis, it could be that sharp ‘crevasses’ exist within the ‘island’ depicted in Figure 3.1.

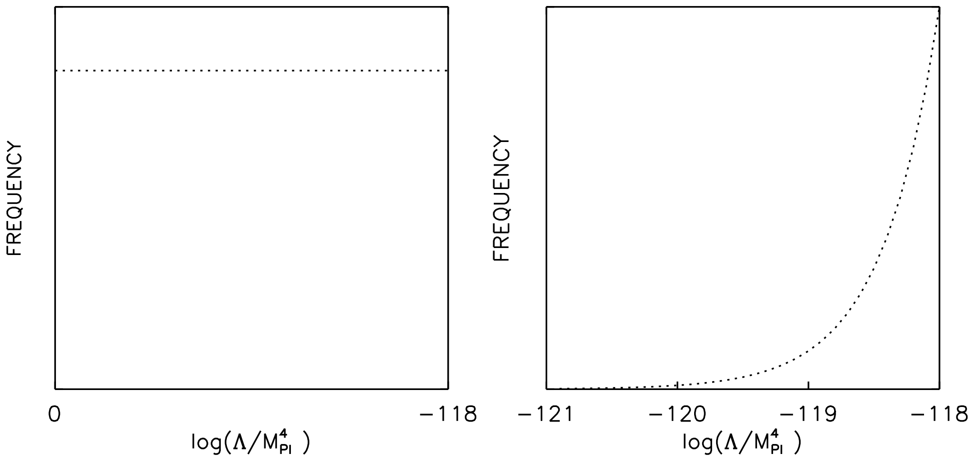


Figure 3.3: Figures showing the relative scalings of a uniformly distributed random variable (*left panel*), as Λ is assumed to be in the range $\Lambda/\mathrm{M}_{Pl}^4 \ll 1$, and when considered in the same interval but in log space (*right panel*). It is because the density of points exponentiates in log space that the anthropic *limit* is taken to imply an anthropic *prediction* (within an order of magnitude) given a flat prior.

models could thereby be ruled out on PoM grounds. The different contributions from f_{selec} and f_{prior} as functions of p_i are illustrated in Figure 3.2.

The advantage to this approach is that one need not worry about 'far distant' islands. One of the key criticisms of the claim of FTL is that, for all we know, radically different forms of 'life' might arise in universes with physics markedly different from our own. The claim of FTL however is that, plausibly, even if distant regions of p_i-space do permit 'life,' the majority of the volume of p_i-space is such that $f(p_i) = 0$. [14]

Although, as we have acknowledged, we can only plausibly explore the parameter space very close to p_i' for certain parameters, this is enough to test the overall principle. The cosmological constant is the obvious parameter of interest to begin with. Its small observed value of $\Lambda \sim 10^{-120}\mathrm{M}_{Pl}^4$ has been described as "the worst fine-tuning problem in physics" (Krauss 2004) and, owing to its relatively simple physical effects, we can allow it to vary over the WW and remain reasonably

---

[14] This would mean that habitable 'islands' appear widely separated mimicking the Pacific Ocean as depicted in Figure 3.2 (*left panel*). See (Leslie, 1996, p.17-8) for discussion.

confident that no ‘cliffs’ will be encountered unexpectedly. This is the basis of the study by Martel et al. (1998) who evaluated the probability $f(p_i)$ of observing our value of Λ by assuming a flat prior $f_{prior} \sim constant$ and estimating the fraction of baryons that would collapse into DM halos (using the Press-Schechter formalism) as a proxy for life. The assumption that $f_{prior}(\Lambda) \sim constant$ is a general result if we assume that the distribution is peaked at the expected value of $\Lambda \sim \mathrm{M}_{Pl}^4$ and we live in the far end tail (Weinberg 2000). The key consequence of this assumption is that the expected value of Λ will be biased towards the upper bound of the WW on a logarithmic scale as shown in Figure 3.3. They concluded that the probability that we measure our value of Λ appears to be low compared to the median value of $f(p_i)$ - somewhere in the $5\% - 12\%$ range. Loeb (2006) suggested that if Λ were 3 orders of magnitude larger then halos corresponding to present day dwarf galaxies might form up to $z \sim 10$ making them rather abundant in a Multiverse with flat prior on Λ, though he acknowledged that, plausibly, such systems are much less efficient at retaining and converting baryons to ‘observers.’[15]

Variations in Λ are anthropically tied to variations in the Q parameter - the standard deviation of the amplitude of primordial density perturbations. Its value would arise from the detailed shape of the inflationary potential and so its prior, like Λ, could be predicted statistically in principle from some eternal-inflation theory (see e.g. Vilenkin 1995). Tegmark & Rees (1998) studied variations in Q and found that $f(p_i)$ appears to be peaked near to its observed value of $\sim 10^{-5}$ (an order of magnitude smaller and the baryon density in halos falls by factor $\sim 10^3$ making cooling inefficient, higher and the increased stellar densities in galaxies becomes hazardous).[16]

Changes in Q can be compensated by changes in Λ by the approximate relationship $life \propto \Lambda/Q^3$ (Tegmark & Rees 1998). On this basis Graesser et al. (2004) argue that if both Λ and Q are allowed to vary then it is far more likely that they both be larger than their observed values by at least an order of magnitude since this takes up much more volume in the p_i-phase space to which f_{prior} is proportional. Garriga & Vilenkin (2006) attempt to mitigate this outcome by treating

---

[15] For example, the gas in the shallow potential wells of small halos is not tightly bound and once vacuum domination sets in and the galaxy becomes isolated there will no longer be any gas in the IGM for further accretion.

[16] It is worth reiterating that we are not saying that observers *can’t* come about under such circumstances, only they are less likely, and this is the concern of the PoM.

$y \propto \Lambda/Q^3$ as the independent parameter and considering inflationary models that distribute Q with low dependence on Q itself. There is much room to manoeuvre with regards to $f(p_i)_{prior}$ and even staunch Multiverse proponents question the predictive power of anthropic-PoM reasoning (see for example Mersini-Houghton & Adams 2008) and this further motivates us to concentrate on $f(p_i)_{selec}$.

The use of the number of baryons that collapse into DM halos as a proxy for life, used in all the aforementioned studies, is what we might term a ‘first-order’ proxy. In an ideal analysis, one would wish to consider the many finer processes that go into the production of ‘conscious observers,’ but we are limited by the capacity of analytic representations to capture such complicated processes. The aforementioned studies have done remarkably well in evaluating the functional dependencies of the baryon mass in DM halos but this is probably as far as they will ever go - numerical methods are needed to move beyond.

3.3 The Semi-Analytic Approach

The inspiration for the semi-analytic approach goes back to the proposal of Rees & White (1978) that galaxy formation takes place in two chief stages. Firstly, DM halos collapse and merge as described by the Press-Schechter formalism (Press & Schechter 1974) and then baryons collect in their potential wells, radiatively cool and form stellar populations. They also were alert to the need for feedback to suppress the abundance of smaller galaxies.

It was not until the 1990s however that semi-analytic models (SAMs) first began to appear (White & Frenk 1991; Cole 1991; Lacey & Silk 1991). One of the key motivations for their development was to test different cosmologies against observables such as the present day galaxy luminosity function (GLF) which meant that they suffered from significant degeneracies stemming from a combination of poorly constrained baryonic processes and cosmic parameters (see e.g. Kang et al. 1994 and references therein). For this reason, they were considered suspect by certain parts of the astrophysical community for most of the decade.[17]

---

[17] Carlton Baugh is reported to have said the following, “Another problem with the perception of semi-analytical

Things began to change with the narrowing down of cosmic parameters and, by the time the ‘standard’ or ‘concordance’ model (ΛCDM) based upon the discoveries noted earlier (§3.1) was established, they came to be recognised as an important astrophysical tool. Over the past decade, several major ‘families’ have arisen, each building on the previous generation and, unsurprisingly, have managed to reproduce synthetic galaxy catalogues that match observations to impressive precision. We shall describe some of the details of the Millennium ‘families’ in Chapter 6.

Now that the role of SAMs in helping to pin down cosmic parameters has been made more or less obsolete, it may seem like there is little left for them to do except undergo endless refinement in the bid to emulate the details of the GLF and so forth to arbitrarily great detail. This is a worthy goal, no doubt, as we wish to understand the processes of our cosmos, but this role will likely get taken over by cosmic-scale hydrodynamic simulations in time as computing power increases.

However, there is a new and interesting motivation to the refinement of SAMs in order to help explore the anthropic landscape. As discussed, the cosmological parameters that feature in SAMs can now be fixed to good accuracy in most cases leaving the galactic parameters to be tuned to reproduce observables within our Universe. Although these still exhibit degeneracies to date (see Neistein & Weinmann 2010 and references therein), over time more and more have become broken by the development of increasingly sophisticated prescriptions and, no doubt, future developments will improve the situation.

If we could have confidence that such prescriptions faithfully capture the ‘real’ physics of galaxy formation and evolution then the situation could then be reversed: now we hold the galactic parameters constant and vary the cosmological parameters to explore what would happen in other universes, namely, those in which gravitational physics is allowed to vary and generate different DM mass functions. This would allow us to go beyond the ‘first-order’ proxies for life discussed in the previous section to which analytic studies are constrained to more sophisticated proxies based upon studies of galactic habitability, such as stellar mass in thin metal-rich *disks*. We shall give this topic a brief overview before describing our preliminary explorations with the SAM of Khochfar

---

models probably lies with the name ‘semi-analytical’, which some in the community have clearly taken to imply some half-baked witches’ brew of ingredients, from which any result can be coaxed with a suitable incantation, as and when required to fit new observational data” (Baugh 2006, p. 3109).

et al. 2011.

3.4 The Model

3.4.1 Galactic Habitability

The SAM approach we are exploring offers a variety of potential ways with which to model ‘life.’ Sensible choices require an appreciation of the finer details that go into the production of ‘life as we know it’ (or just ‘life’ from hereon). Unfortunately, the origin of life remains an unsolved mystery. Anthropic considerations provide several necessary conditions ranging all the way from the cosmological constant to the molecular bonding-angle of water (Barrow & Tipler 1996, §8.3), but it is not known what the sufficient conditions are. As a result, opinions vary widely as to whether or not life is common in the Universe (e.g. Forgan & Rice 2010) or exceptionally rare, unlikely to be repeated in our Hubble volume (e.g. Taylor 1998; Hart 1999).

It is worth mentioning in regard to the AP that the same ‘large-ensemble plus selection-effect’ reasoning that has been applied to account for the necessary conditions of life (namely, that the constants of nature lie within specific ranges) could be applied equally to the *sufficient* conditions for life. So even if life came about due to a series of remarkable flukes, in an infinite ensemble, to quote Guth “anything that can happen will happen; in fact, it will happen an infinite number of times” (Steinhardt 2011, p.42). This was pointed out by the proponents of the AP from early on (Carter & McCrea 1983; Barrow & Tipler 1996, §8.7).

All the same, we are only able to proceed by considering the necessary provisions for life which takes us to galactic habitable zones - locations within galaxies that are sufficiently metal rich and hazard-free to allow the formation of stable planets around long-lived stars and the evolution of life over Gyr scales (Gonzalez et al. 2001; Lineweaver et al. 2004).

The first advance that the SAM approach offers over the analytic approach of the previous studies is to distinguish between ‘bulge’ and ‘disc.’ The present day global galaxy population is bimodal with a stellar transition mass at $\sim 3 \times 10^{10}$ above which galaxies tend to be ‘bulge’ dominated and below which they are ‘disc’ dominated (Kauffmann et al. 2003a). Understanding the origin of this bimodality is an important ongoing area of research that will be discussed in the following chapters. It is therefore standard for SAMs to model properties for both disk and bulge components of a galaxy for a variety of different properties with the aim to reproduce the observed bimodality (e.g. Cattaneo et al. 2006b).

Conveniently, several studies of galactic habitability have argued that life is unlikely to last long enough in bulges to make it into the reference class of ‘advanced civilisations’ we are most interested in. Bulges likely host planets (Gonzalez et al. 2001), but the hazards are considerable. Firstly, bulges are crowded with others stars and black holes increasing the likelihood of orbital perturbations (the central super-massive black hole present in most bulges is likely to be particularly hazardous) and since the orbits of stars are pressure supported they will pass close-to the center periodically (see Tegmark et al. 2006, §III.D for descriptions of ensuing hazards). Secondly, the high density of stars results in a pervasive, intense radiation field and frequent gamma-ray bursts which inhibit long lived civilisations (Lineweaver et al. 2004; Scalo & Wheeler 2002). Remember, on the PoM we are not so interested in strict possibility but rather probability; it seems much more likely that a long-lived habitable planet will come about in circular orbits within the disk - as we have - rather than in the bulge.

This fact would naturally encourage us to examine the properties of the Milky Way (MW) in some detail to see how, if at all, it differs from other disk galaxies. In a recent study by Mutch et al. (2011), MW and M31 were matched to a large sample of similar-size disk galaxies visually identified by the Galaxy Zoo project and both were found to lie in the ‘green’ valley between the global galaxy bimodal populations. They conclude that both galaxies are on their way to reddening via in-situ gas depletion (since they have had quiet merger histories) at which point they are liable to transform into ellipticals in the event of a major merger (which they will in a few Gyrs; see Cox & Loeb 2008). See also Masters et al. 2010 for a detailed study of Galaxy Zoo ‘red spirals.’

Probably the most note-worthy feature of the MW is its thin disk suggestive of an unusually quiet merger history. Stewart et al. (2008) calculate from their N-Body ΛCDM simulations that 95% of MW-like galaxies have undergone a major merger in the last ~ 10 Gyrs, whereas Mutch et al. (2011) suggest it is unlikely that the MW has had a merger with an object more massive than $\sim 10^9 \mathrm{M}_\odot$ in that same period. This is suggestive that mergers are significant for galactic habitability, which seems intrinsically plausible for two reasons.

Firstly, in the hierarchical scheme of galaxy formation, which the ΛCDM unavoidably is to a large degree, mergers are responsible for the growth of bulges in the Universe (see e.g. Hopkins et al. 2010a and references therein) thus depleting habitable zones for otherwise potential future civilisations. Secondly, the merger process itself cannot be good for life. Cox & Loeb 2008 simulate the merger between the MW and M31 and show that, with large probability, the sun will be pulled close to the galactic center at some point on its chaotic journey, with star-bursts and perturbations to the Oort cloud triggering lethal comet impacts constituting added dangers (c.f. Tegmark et al. 2006, p.17).

Some mergers are needed of course to build up MW-like galaxies in the first place, but too many will rapidly result in a universe filled with bulge-dominated galaxies. Since mergers are controlled primarily by the DM-mass function, and since that mass-function is closely controlled by the cosmic parameters Λ and Q, the study of mergers proves important with regards to PoM-related questions of observer-sensitivity to cosmic parameters.

SAMs typically keep track of galaxy metallicity (which scales with luminosity), star-formation rates (SFRs) and gas content - all of which could be used to create ‘third’ or ‘fourth’ order proxies for life or to be used as inputs into specialised models of galactic habitability (e.g. Forgan & Rice 2010; Gowanlock et al. 2011). However, since our work is still preliminary we shall simply stick to ‘disk-mass in stars’ as a second-order proxy for life.

3.4.2 The Semi-Analytic Model

The SAM used is described in detail in Khochfar et al. 2011. It generates DM-merger trees using a Monte Carlo routine based on the extended Press-Schechter formalism (e.g. Lacey & Cole 1993) as presented by Somerville & Kolatt (1999). We use a comoving volume of side 100 Mpc and start tracking halos at a redshift where they exceed a minimal resolution mass of $10^{10}\mathrm{M}_{\odot}$. This is the natural choice for generating merger trees for this sort of study since it is fast and we wish to explore a range of values of Λ. The baryonic physics uses standard prescriptions for gas cooling, cooling shut off at critical DM halo mass of $\sim 10^{12}$ (which is likely related to the Kauffmann transition mass at $\sim 3 \times 10^{10} \mathrm{M}_{\odot}$ - see Kauffmann et al. 2003a; Dekel & Birnboim 2008), star-formation, supernovae feedback, mergers and bulge formation. Such complicated feedback mechanisms are obviously far beyond encapsulation by analytic formulae.

It has been ‘tuned’ to our Universe by comparisons to the galaxy mass function, bulge-to-total mass ratios and gas fractions (see paper for details). With those parameters fixed, we can now vary the cosmological constant while keeping the initial DM mass function from our Universe established at $z = 20$ and evolve it forward to $z = 0$. One draw-back, as we shall see, is that we are not able at present to evolve past $z = 0$ due to the way the merger trees are constructed which means that for high Λ universes we can only track their evolution for a relatively short time. In future implementations we hope to overcome this, but for now we can get a basic overview of the effectiveness and difficulties of this approach.

3.4.3 The Cosmological Transformations

We assume slow-roll inflation arising from, say, the String Landscape scenario and eternal inflation. All of our universes are therefore spatially-flat, homogenous and isotropic. The only parameter to be varied is the absolute value of the false vacuum corresponding to changes in the cosmological constant. We further assume that these variations to the potential either do not affect the characteristic amplitude of density perturbations Q or are compensated by adjustments to the shape of the potential (in other words, we are only varying Λ). We relate these varying values of Λ to that of our own Universe by a simple factor such that $\Lambda \to \Lambda' = f\Lambda$ and f labels each universe uniquely. Note that this f has no connection to that of the previous sections, as in equation (3.2), etc.

We assume that the *shape* of the inflationary potential is such as to give rise to the same matter content (via reheating) per comoving volume come the end of inflation, i.e. $\rho_m = \rho'_m$. To see how these transformations affect each universe’s expansion we apply them to the usual Friedmann equation for a flat universe ($\Omega_k = 0$)

$$1 = \Omega_m + \Omega_\Lambda = \Omega'_m + \Omega'_\Lambda. \tag{3.4}$$

Since $\rho_m = \rho_m'$ is true for all redshifts we can evaluate all the remaining transformations at the expansion factor of our present day where H_0, Ω_m and Ω_Λ are all known. The Hubble constant, H_0, governing the expansion rate at $z = 0$, must be allowed to vary to compensate for varying Λ (and fixed $\rho_m(z = 0) = \rho_0$) in (3.4) leading to the constraint

$$\begin{aligned}
1 = \frac{8\pi G\rho_0}{3H_0^2} + \frac{\Lambda}{3H_0^2} &= \frac{8\pi G\rho_0'}{3H_0'^2} + \frac{\Lambda'}{3H_0'^2} && (3.5)\\
1 &= \frac{8\pi G\rho_0}{3H_0^2}\left(\frac{H_0^2}{H_0'^2}\right) + \frac{f\Lambda}{3H_0^2}\left(\frac{H_0^2}{H_0'^2}\right). && (3.6)\\
\therefore\ \alpha^2 &= \Omega_{m_0} + f\Omega_\Lambda && (3.7)
\end{aligned}$$

where $\alpha^2 = H_0'^2/H_0^2$. We thus obtain the following transformations from our Universe ($\Omega_{m_0} = 0.27$, $\Omega_\Lambda = 0.73$, $H_0 = 71$ kms^{-1}Mpc^{-1}) to one with arbitrary f

$$\begin{aligned}
H_0 \rightarrow H_0' &= \alpha H_0\\
\Omega_{m_0} \rightarrow \Omega_{m_0}' &= \Omega_{m_0}/\alpha^2\\
\Omega_\Lambda \rightarrow \Omega_\Lambda' &= f\Omega_\Lambda/\alpha^2.
\end{aligned}$$

The values of Ω_Λ, Ω_m and H_0 are used as inputs into the SAM which then outputs galaxy catalogues at chosen redshifts between $z = 20$ and $z = 0$.

3.5 Results and Discussion

As shown in Figure 3.4, the larger Λ is made, the faster the scale factor of a given universe reaches that of our present day. The arrows on the x-axis show the time at which $\Omega_\Lambda = \Omega_m$ for each universe where it is noted that we live in the special circumstance of being able to register Λ observationally before it takes over. When f takes Λ down two orders of magnitude it is so close to zero that subsequent reductions make little difference.

These trends are reflected in the DM mass function at $z = 0$ shown in Figure 3.5. An order of magnitude higher and halos have not formed by $z = 0$ above $10^{13}\mathrm{M}_\odot$ and reductions in f lead to a shifting of the mass function towards more massive halos. Clearly, the merger rate has responded

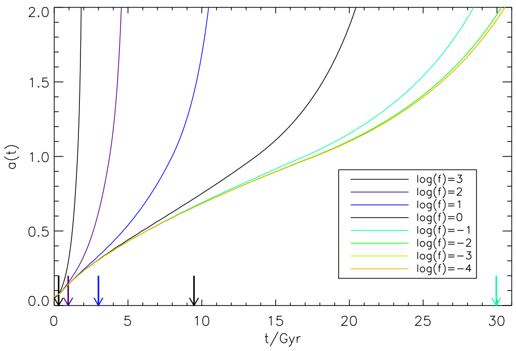


Figure 3.4: The evolution of the expansion factor with age for different universes.

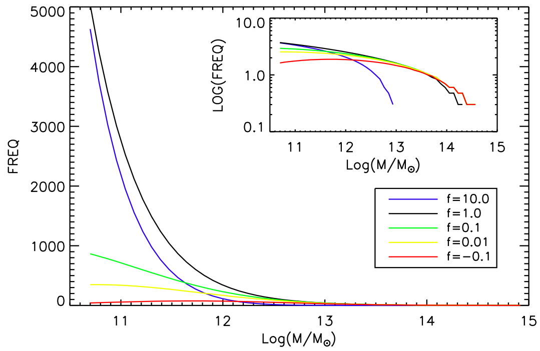


Figure 3.5: The DM mass functions at $z = 0$ for different universes (inset uses log scale).

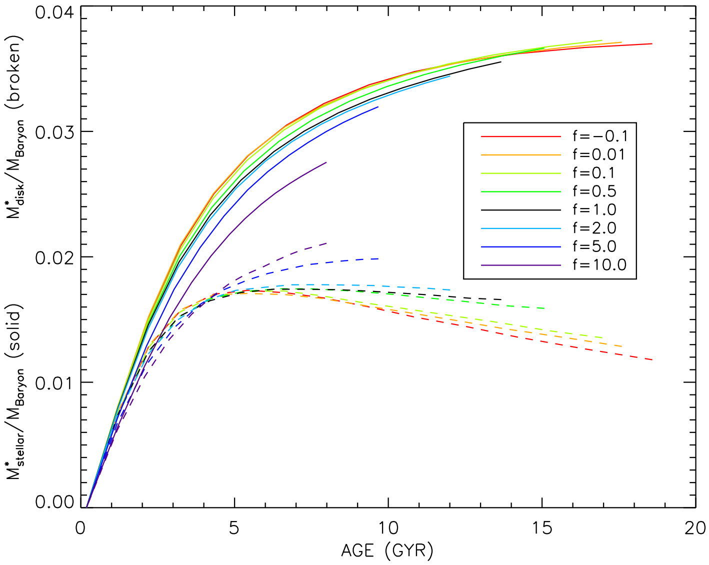


Figure 3.6: Distribution of the total stellar mass per baryon (solid line) and total-disk mass per baryon (broken line) in the DM haloes in each universe. The universes with higher merger rates convert more gas into stars but most of this ends up as bulge by $z = 0$ whereas the universes with the highest disk mass at $z = 0$ have Λ an order of magnitude higher ($f = 10$) than our Universe.

significantly to changes in Λ over the WW, as is expected.

To determine the effect these altered merger-histories have on the total disk mass in each galaxy, we need to consider two contributions - the total number of baryons that end up in halos (which should favour low Λ) and the disk-mass per baryon ratio for each universe (which should favour higher Λ). The latter is easy to extract for each universe and we plot them in Figure 3.6.

We find that the total-stellar mass per baryon increases with higher merger rate (due to lower values of f) but, as expected, the *disk* mass per baryon favours the lower merger rate (higher f) peaking at $f = 10$ with $\sim 15\%$ more disk-mass per baryon than our Universe. So although universes with the higher merger rate convert more gas to stars, they increasingly end up in bulges with lower f at $z = 0$.

Since we only track the halos to $z = 0$ we cannot be certain, of course, that by the time the $f = 10$ universe reaches the same age as ours, the disk-to-baryon ratio has not dropped, but this does not look likely upon examining the trends. Λ has already begun to dominate and so merging has effectively ceased leaving the galaxies to undergo passive evolution. If the merger process is the primary one by which disk mass is converted to bulge mass, then the galaxies will be frozen into the morphologies they possess at the time when vacuum domination sets in.

Thus far we have considered the *relative* disk-mass per baryon. The *absolute* disk mass, however, is more difficult to gauge. The growth of the halos that are tracked and updated in the DM merger tree must absorb DM from the background in addition to merging with other halos. This is calculated using standard growth factors (Hamilton 2001) and results in a greater average mass in the halos that we are tracking (above the minimal halo mass which is $\sim 5 \times 10^{10} \mathrm{M}_{\odot}$ at $z = 0$) and should be quite accurate.

However, the halo-occupation distribution (the average amount of baryonic mass in a DM halo of a given mass) is not a simple relation but peaks at L^{*} (Hopkins et al. 2010a) and it would not be surprising if this were different in other universes. The model is presently set up so that the fraction of mass in baryons in each universe is exactly 0.17 that of the mass in the DM haloes that are tracked, which is simplistic considering the feedback mechanisms at play. Nonetheless, the halo occupation distribution is a monotonic function and so, assuming baryon mass is proportional to DM mass in these halos, we can get a first order approximation that gives rise to the distributions shown in Figure 3.7.

At first glance, Figure 3.7 looks highly suggestive with the absolute disk mass *and* absolute stellar mass peaking at $f = 0.5$. Such a result could come about because the universes with lower Λ build up their merger trees rapidly and the increased virial temperature that is communicated to

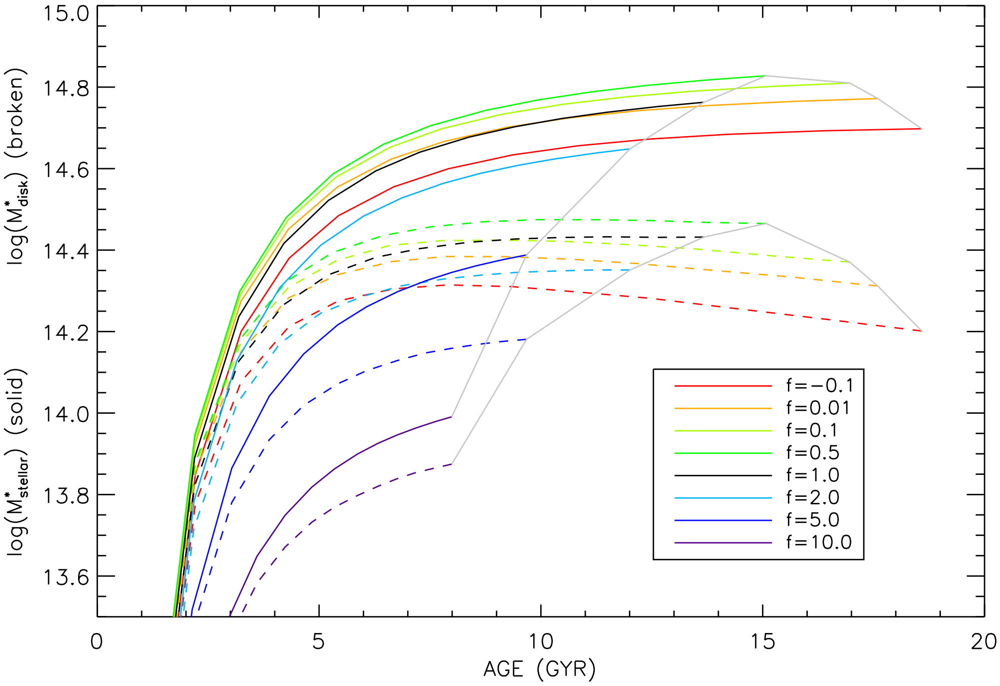


Figure 3.7: Distribution of the total-stellar mass (solid line) and total-disk mass (broken line) in the DM haloes in each universe. The universes with the most stars - both bulge and disk - appear to be peaked at $f \sim 1$, though the distribution is very broad. The grey lines are added to guide the eye with varying f.

the cold gas causes it to heat and shut down star formation. Similarly, the increased merger rate, as we have seen, results in a relative increase in bulge mass such that, as Λ decreases to $f = -0.1$, the total disk mass actually begins to *decrease* in the universe.

Superficially then, it looks as though $f \sim 1$ optimises the conditions for life but we urge extreme caution here. The differences are very small at around a few dex between the plotted values of f at most. This means we are talking about differences in factors $\sim 2-5$ and not orders of magnitude difference. If a more sophisticated proxy for life were used then maybe the differences could be accentuated,[18] but then this increasingly leads to the same, uncontrolled territory that analyses of f_{prior} suffer from.

---

[18] For example, extrasolar planets show a strong correlation between the presence of large close-orbiting massive planets and the metallicity of the host star (Santos et al. 2003; Laws et al. 2003) and, since metallically scales with galaxy luminosity, so perhaps one could choose the proxy $life \propto \mathrm{M}_{disc} \times \mathrm{M}^{n}_{stellar}$ where n reflects the scaling relation.

Nevertheless, we are confident of the result for the relative disk-baryon ratio shown in Figure 3.6 and it highlights the fact that too many mergers inhibit the preconditions for life. Exactly how peaked the dependency of life on Λ will eventually turn out to be will thus depend crucially on the efficiency of the process by which mergers convert disk into bulge, promote new star formation and trigger feedback. For this we need to study mergers in depth and, as was noted in the preface, this brings us full-circle: if our reference class is that of a "scientific society" then we need to be highly adept at pattern recognition in order to identify mergers to start with. As shall be discussed in the chapters to follow, *all* pattern recognition techniques in astrophysics trace back to (and try to replicate) human, visual classifications and this is the main motivation for the Galaxy Zoo project.

Chapter 4

The Morphologies and Fraction of SDSS Major Mergers for $z < 0.1$

Men trust their ears less than their eyes. – Herodutus[1]

4.1 Introduction

As we have discussed thus far, mergers and interactions are connected to many pressing questions concerning the origin, evolution and properties of galaxies. We are especially interested in their role in converting disks to bulges as this pertains to how bio-friendly the Universe will turn out to be. The complexities of the merger process are numerous though, requiring detailed study and, as we shall see, the varied structures of merging galaxies make locating and separating their photometry a difficult pattern-recognition problem.

Ongoing, merger-related research programs include the formation of galaxies (Rees & White 1978; Lacey & Cole 1993; Conselice 2006; De Lucia et al. 2006b), environmental effects on morphology (Capak et al. 2007; Park et al. 2007; Ball et al. 2008; van der Wel 2008) and our understanding of the dark matter scaffolding that drives the merger process (Bond et al. 1991; Cole et al. 2000; Fakhouri et al. 2010). On a slightly smaller scale mergers have been invoked

---

[1] *The Histories*, 1.8.

to explain a variety of observations, notably localised bursts of star formation (Kennicutt et al. 1987; Schweizer 2005; Di Matteo et al. 2005; Geller & Woods 2007; Barton et al. 2007; Li et al. 2008; Cox et al. 2008) and induced nuclear activity (Keel et al. 1985; Schawinski et al. 2007a; Jogee 2006). The far-reaching effects that mergers are thought to produce makes their empirical examination an important task.

To date though, such studies have concentrated mostly on merger *rates* (Carlberg et al. 2000; Le Fevre et al. 2000; Patton et al. 2002; Conselice et al. 2003; Bundy et al. 2005; Bell et al. 2006; Conselice et al. 2008; Lin et al. 2008; Lotz et al. 2008a; Hsieh et al. 2008, Patton & Atfield 2008), with comparatively little carried out to examine their morphologies and internal properties (though see Li et al. 2008; Ellison et al. 2008) for reasons to be discussed (§4.1.1). This is unfortunate - to understand the exact role played by mergers in galaxy evolution, it is inadequate to measure their rates alone since the processes that determine the morphological outcomes of mergers are still not fully understood.

It has been widely believed since the simulations of Toomre & Toomre (1972) that two spirals *can* merge to form an elliptical but this does not mean that they *must*. On the contrary, recent studies have argued convincingly that, in some cases at least, disc galaxies are able to survive (multiple) major mergers (Hopkins et al., 2009). Where this does happen, the probability of disc survival must be assumed *a priori* to depend on the properties of its progenitors such as environment, gas content and feedback mechanisms. These in turn correlate with galactic morphology. It has also been shown in the detailed studies of Lotz et al., 2008b, Lotz et al., 2010a and Lotz et al., 2010b using simulations of merger-detection techniques that the time interval over which a merger is detectable as such depends on the detection-technique and properties of the galaxies. Ideally then, calculations that convert merger fractions into merger rates as part of some hierarchical-structure scheme (such as modeled by Burkert & Khochfar, 2003) should take the properties and morphologies of their sample into account. Only then can models of hierarchical galaxy formation be properly tested.

The Galaxy Zoo project contributes to this important task by providing a snapshot of mergers as they appear in the local universe (in this study we focus on the range $0.005 < z < 0.1$) and the

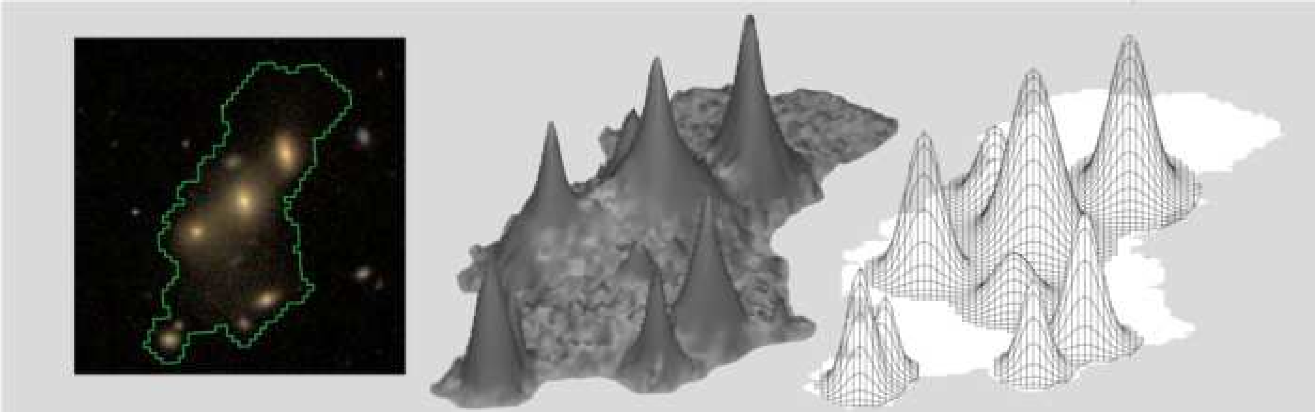


Figure 4.1: Schematic of the SDSS deblending routine. *Left:* Example image of a cluster within the isophote defining the SDSS parent image. *Middle:* a 3D representation of the pixel-array within the isophote to which photometric objects are constructed by the 2D fitting of the SDSS pipeline. *Right:* a schematic of gaussian fits to the individual peaks that should sum to reproduce the parent flux. Each fit determines the position about which model and Petrosian magnitudes for each photometric object are calculated and their PSF shapes are used to separate galaxies from stars (Strauss et al. 2002).

follow up project 'Hubble Zoo' will allow us to study mergers for $z \leq 2$. Here we present the simple but powerful method for identifying mergers using the world-wide web and the robust sample of 3003 merging systems that was derived from it (§4.2.1). We use this catalogue - the largest of its time - to discuss three important ratios: the merger fraction of the local universe (§4.3.1 and 4.3.3), the fraction of spectral pairs in merging systems in SDSS (relevant to discussions for the close-pairs technique; §4.3.4) and the spiral-to-elliptical ratio of galaxies that are in merging systems (§4.3.5). In the following chapter we present the environment and internal properties of these merging galaxies.

First though it will be useful to review the background of merger-location techniques and what the Galaxy Zoo project does differently.

4.1.1 Locating Mergers: Past Methods

Humans are the final epistemic authority when it comes to deciding morphologies (who else is there?). We only trust short-cut methods if we understand how they were designed in the first place, and we can only design them based upon what we take to be sensible morphology-related decisions. For this reason visual inspection is and always will be the most trustworthy way of determining whether or not a galaxy is merging.[2] However, the advent of large galaxy surveys such as SDSS (York et al. 2000) involving $\sim 10^6$ objects has rendered classification by individual researchers impractical. Automated methods have therefore been developed to approximate the human decision making process but, being only approximations, encounter certain difficulties that the Galaxy Zoo project can potentially overcome.

Close-Pair Statistics

Accurate measures of position and redshift in large scale surveys have made straightforward the task of finding close pairs in the (local) universe. However, the peculiar velocities of the individual galaxies can significantly offset their redshift-inferred line-of-sight separation producing spectral pairs of non-interacting systems which may or may not merge. One can apply statistical arguments as to what fraction of close-pairs within some ensemble will soon merge, but no single system can be safely assumed to be merging without cross-examination. The method is best used, therefore, to estimate merger *rates* parametrised by the convention: *merger rate* $\sim (1+z)^m$.

Another limitation of close-pairs methods in surveys such as SDSS is the requirement that *both* galaxies have spectra. This requires a delicate act of deblending by the data-reduction pipeline. SDSS will convert the photometry of an extended body like a galaxy in the following way. It will first fit isophotes around a body of light to distinguish it as a source (and not background). The array of pixels inside this isophote is referred to as the the 'parent' image. The routine will then attempt to fit 2D profiles to this body of light and these peaks (one can think of them as guassians) are referred to as 'children objects.' This process is known as 'deblending' and the original parent image is sometimes called the 'blended' image (Stoughton et al. 2002). This is illustrated in Figure 4.1. Iterations are performed allotting different magnitudes to the child-objects until an optimal distribution is attained so that all children sum to give the total flux of the parent. The goal of this

---

[2] Of course, this does not apply to less-directly observable processes such as inferring the distribution of DM in the Universe; but the claim is that all posited astrophysical entities must make eventual recourse to rather basic visual assertions such as 'this is a spiral galaxy.'

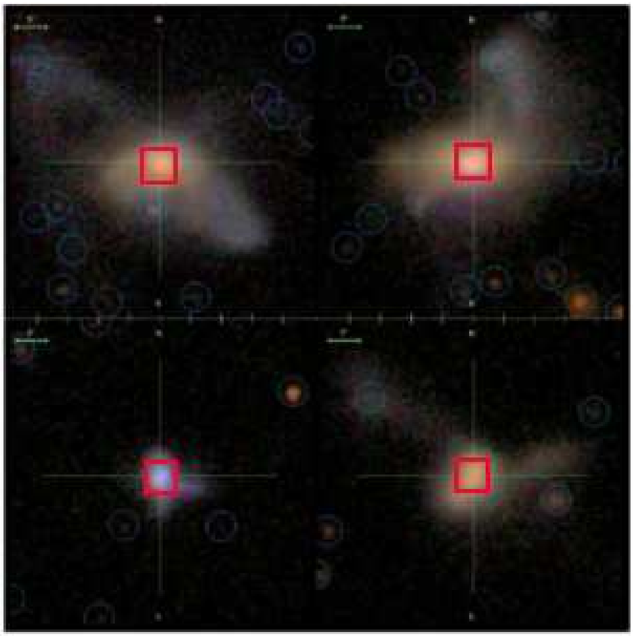


Figure 4.2: Example images of ‘strongly-perturbed’ systems which are not deblended into two photometric objects that plausibly represent the photometry of the progenitors. These are usually late-stage mergers and cannot be detected by the close-pairs technique. Blue circles mark the centre of SDSS photometric objects. Red squares mark the centre of SDSS spectral objects. The scale bar is $5''$ for each example image.

is to separate out peaks corresponding to stars from those corresponding to galaxies. This can be achieved since the profile of light - the points spread function (PSF) - is considerably sharper for stars. Deblending also converts a long list of numbers for each pixel in an image to a manageable few with which we can do science.

Any photometric-child object with apparent Petrosian magnitude $r < 17.77$ is designated as a spectral target by the SDSS pipeline. It follows that only when a contiguous body, such as two interacting galaxies, is deblended into (at least) two photometric objects both having $r < 17.77$ can it contain two spectral targets. Therefore mergers with only one deblended object of $r < 17.77$ cannot be identified by the close-pairs technique (Strauss et al. 2002; Patton & Atfield 2008). This will occur for many minor mergers or for late stage mergers where the cores have drawn close to each other and the pipeline reads them as a single peak. Figure 4.2 shows examples of strongly-perturbed systems with only one spectral target.

Even when two objects are deblended in a contiguous image and registered as spectral targets

- relatively few systems will obtain spectra on *both* objects due to fiber collisions within the spectrometer. Two SDSS spectroscopic targets cannot acquire spectra simultaneously if they are within $55''$ of each other and so only systems contained within 'tile overlap regions' can have spectral objects with an angular separation less than this (Strauss et al. 2002, Blanton et al. 2003). Only about $\sim 30\%$ of the SDSS sky rests within overlap regions thus limiting the sample size of such systems.

Conversely, a system where the image has been deblended into multiple targets, as in Figure 4.3, can acquire too many spectral objects so that a single galaxy might appear as a close-pair or a binary merger might appear as a multi-merger. Close-pairs studies typically limit the redshift and magnitude ranges in order to avoid this effect. Geller & Woods (2007), for example, limit their close-pairs sample to $\sim 0.027 < z < 0.17$ and require $> 20\%$ of the galaxy's total flux land within the fiber aperture in order to exclude very extended nearby galaxies. They still find though that $\sim 15\%$ of their minor-pairs catalogue are false pairs after visual inspection.

To summarise, without visual cross-examination, close-pairs methods are prone to include false pairs and non-gravitationally bound systems and are best used, therefore, to estimate merger *rates* via application to large ensembles after estimations for contamination and incompleteness are taken into account. To examine the *properties* of merger systems, one should robustly identify *actual* mergers as opposed to claims that some fraction of an ensemble is 'likely' to be merging.

Automated Quantification of Morphological Disturbance

Pattern recognition techniques applied to galaxy images pose a formidable programming challenge. Background noise and contaminants first need to be removed, then an automated technique needs to quantify how 'disturbed' a morphology is independent of viewing angle. This might not be so difficult if it were not the case that unperturbed galaxies themselves vary so much from the structurally simple (ellipticals) to the complex (spirals). In particular, filtering asymmetric systems like mergers from spirals with extended star-formation requires great finesse.

Nonetheless, promising automated techniques have been developed that generate parameters related to morphology. A common technique has been to convert an image array into the single numbers concentration (C), asymmetry (A) and, in some cases, clumpiness/smoothness (S). For

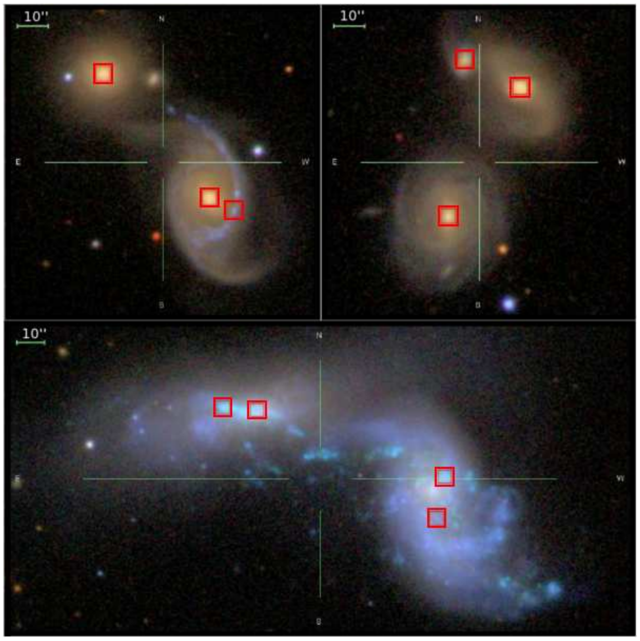


Figure 4.3: Examples of possible distributions of SDSS objects with spectra (red squares) in merging systems. The close-pairs technique in particular would be unable to distinguish which of these systems is a ‘multi-merger’ (for example, the top two panels have three spectral objects each but the the left-hand system is a binary-merger while the right-hand system is a triple-merger; the system on the lower panel is a binary-merger but has *four* spectral objects).

example, a rough description of the asymmetry parameter is that it is calculated by cleaning an image (removing foreground stars, etc.) - which has to be done in an automated fashion or it defeats the whole purpose of side-stepping direct human labour - then iteratively slicing the image in half and rotating one half 180 degrees to overlie the other, subtract the differences (for they are just numbers to the computer) and add them all up (and keep doing this about different points in the image until the resulting asymmetry parameter is minimised). One then partitions CA(S) space into morphological categories and identifies an object as a merger if it lies within the designated sub-volume (see Conselice 2003a and Conselice et al. 2003 on the use of the ‘CAS’ system to locate mergers).

Another pair of parameters used in this fashion are the Gini-coefficient (G) (Abraham et al. 2003) and second-order moment of the brightest 20% of the galaxy’s light (M_{20}), most notably by Lotz et al. (2008a). (For a concise description of how to calculate C, A, S, G and M_{20} see Conselice et al. 2008.) It is argued in Lotz et al. (2004) that this technique operates better at low signal-to-noise ratios and is more sensitive to late-stage morphologies than the CAS system (though see Lisker 2008 for a critique of its effectiveness). More recent studies have combined and compared the two techniques (e.g. Scarlata et al. 2007; Conselice et al. 2008; Lotz et al. 2008b). Artifical Neural Nets are another promising technique for identifying morphologies (Lahav et al. 1996, Ball et al. 2004) though they have not yet been applied to merger studies specifically. This is likely a long way off; the neural nets thus far have only been used with *structural* inputs derived from the deblending outputs of the SDSS pipeline - not on the original images themselves. Mergers are far too complex and variegated for to be identified in this way at present.[3]

CAS and GM_{20} remain effective at high redshifts so long as the image quality remains high and, since they are automated, can process images quickly once the pipeline has been established. However, these techniques also require visual examination to cross-check results and to fine-tune the partition boundaries that define a merger.

Systematic uncertainties usually remain. Jogee et al. (2008) recently report that the CAS criterion failed to pick up $37-58\%$ of their visually classified “strongly disturbed” morphologies while including a “significant number of relatively normal galaxies” - an effect that was predicted by simulations in Conselice (2006b). Conselice et al. (2008) recently classified 993 images from the Hubble-Ultra-Deep Field by visual inspection, the CAS volume and the GM_{20} area. They found some notable disagreements, in particular, some systems identified as mergers by their location in GM_{20} space are not identified as mergers using the CAS system and vice-versa (see for example Figures 8 and 9 plus captions). Within the $0.4 < z < 0.8$ range only $44 \pm 6\%$ of the galaxies mapped into the GM_{20} merger region were visually classified as ‘peculiar.’

Recently Lotz et al. (2008b) performed an extensive study on the merger-detection sensitivity of the CA, GM_{20} and close-pairs techniques using simulations. They find that C, A, G and M_{20} methods are only sensitive to mergers at specific stages of the process, particularly the first pass and final coalescence of the galaxies. The study also confirms that the merger time-scales and parameters (such as gas-fractions, pericentric distance and relative orientation), for which these

---

[3] We’ve tried and the results are totally unbelievable when we visually compare the supervised outputs to the images themselves; again, humans are the final authority.

three techniques remain sensitive, differ significantly.

Visual Inspection by Research Groups

In the pre-digital age, surveys of morphological classification by visual inspection were mostly limited to studies based on cluster images (Oemler 1974, Dressler 1980). With the modern development of large surveys and high resolution imaging, the potential to extract large samples of morphologically classified galaxies in differing environments has vastly improved. The largest visual classification project by a research group is Schawinski et al. (2007a) who visually examined 48,023 SDSS galaxies in compiling the MOSES catalogue (MOrphologically Selected Ellipticals in SDSS). (In close second is the study we performed (presented in Chapter §7) of $47,475$ SDSS images.) They found a significant blue-population that had been excluded by studies such as Bernardi & al. et (2003) which identified ellipticals by their presumed properties. Selecting morphologies by *a priori* assumptions is often pragmatic and necessary but ultimately begs the question as to what the properties of a given morphology actually are. Unless we can be certain that a set of properties maps one-to-one with morphology we must continue with visual examination.

Studies to select *mergers* by visual-selection did not reach such scales as MOSES until the Galaxy Project (if one can call it a 'research group'). Le Fevre et al. (2000) visually examined 285 Hubble images and found a merger fraction of $10 \pm 2\%$ over $0 < z < 1.2$. Nakamura et al. (2003) visually classified 2418 images of SDSS galaxy objects with Petrosian $r < 16.0$ (i.e. low redshift) finding that 35/1875 of their morphological classifications were Im ('highly irregular' following Hubble's notation). A similar study by the same group, Fukugita et al. (2007), visually classified 2658 images from SDSS with Petrosian $r < 15.9$ and found that $1.5\% - 1.7\%$ of these nearby magnitude limited galaxies were 'interacting.'

Thus, until now, merger studies have been limited to catalogues of $\sim 10^3$ galaxies due to the time-consuming and monotonous nature of the task. By contrast Galaxy Zoo allows us to acquire effective visual classification for morphologies and mergers for samples of $\sim 10^5$ galaxies with relative ease.

4.1.2 Locating Mergers with Galaxy Zoo

Galaxy Zoo (GZ) is a user interface on the world-wide web[4] drawing upon images from SDSS. Volunteers from the public are instructed and commisioned with the collective task of visual classification of $\sim 900,000$ galaxies from SDSS DR6. A complete description of the project including design details and initial data reduction is given by Lintott et al. (2008). It is also shown that public users are, in large numbers, about as good as 'experts' at identifying morphologies.

The project has proved to be a tremendous success. To date, over 140,000 volunteers have participated and collectively offered classifications for all $\sim 900,000$ images, on average, fifty times over. Data from the project have already been employed to find the statistical properties of spiral-galaxy-spin orientation (Land et al. 2008; Slosar et al. 2009), the relationships between environment, morphology and colour (Bamford et al. 2009; Skibba et al. 2009), to study optically blue early-type galaxies at very low redshift (Schawinski et al. 2009) and has also led to some serendipitous discoveries (Lintott et al. 2009; Cardamone et al. 2009). This work concentrates on the results of the merger-location functionality of Galaxy Zoo whose details we now describe.

4.2 The Galaxy Zoo Data

4.2.1 Constructing a Merging-Pairs Catalogue

Galaxy-Zoo users are asked to classify an SDSS target as

1. elliptical (e)
2. spiral (s)[5]
3. star/bad image (b), or
4. merger (m).

---

[4] http://www.galaxyzoo.org/

[5] More specifically, users are asked to specify whether a spiral galaxy is rotating clockwise, anti-clockwise or is edge-on/unclear.

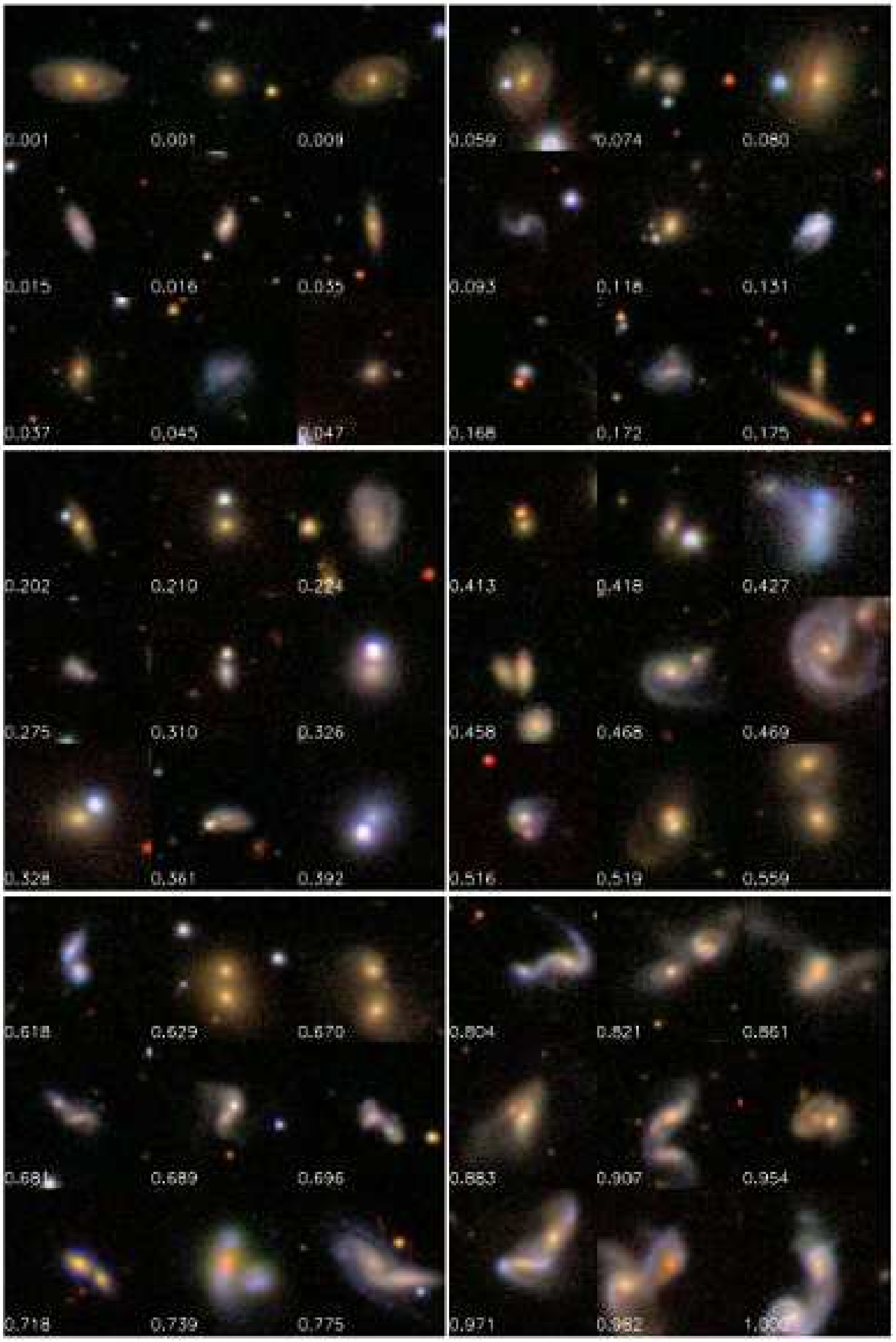


Figure 4.4: Example images of prospective merger systems. The number given for each image is its weighted-merger-vote fraction, f_m. The panels of nine images are grouped into the following bins: top-left: $0 < f_m \leq 0.05$, top-right: $0.05 < f_m \leq 0.2$; middle-left: $0.2 < f_m \leq 0.4$, middle-right: $0.4 < f_m \leq 0.6$; bottom-left: $0.6 < f_m \leq 0.8$, bottom-right: $0.8 < f_m \leq 1.0$. Our catalogue is made up of mergers with $f_m > 0.4$. Each image tile is $40'' \times 40''$.

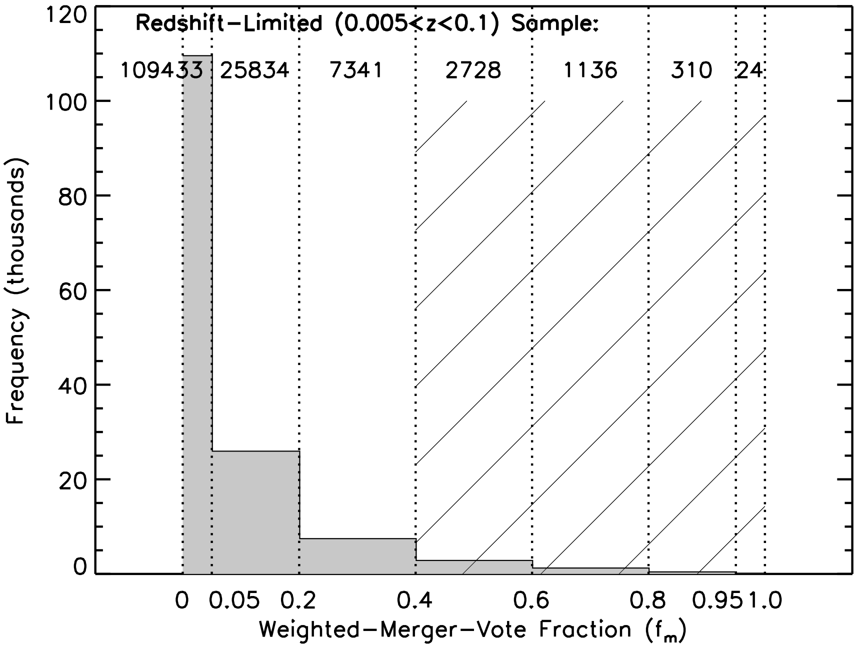


Figure 4.5: The distribution of weighted-merger-vote fractions in the Galaxy Zoo database for objects with spectra for $0.005 < z < 0.1$. From these we use objects with $0.4 < f_m \leq 1.0$ to construct our merging-pairs catalogue (cross-hatched). There are $157,376$ objects with $f_m = 0$ exactly. The numbers on the graph show the occupancy of each bin (e.g. there are $109,433$ with $0 < f_m \leq 0.05$). In total, 304,182 Galaxy Zoo spectral objects lie between $0.005 < z < 0.1$.

The Galaxy Zoo project is the first of its kind and so, not knowing how well it would be taken up by the public, the design of the interface prioritised simplicity over detail. A single button labeled ‘merger’ is all that was offered.

The raw data we use to build our catalogue is what we call the *weighted-merger-vote fraction* (f_m).[6] GZ has obtained a value for this parameter for $893,292$ SDSS galaxies from DR6.[7] The f_m values are calculated by taking the number of *merger* classifications (n_m) for a given GZ object and dividing it by the *total* number of classifications ($n_{e,s,b,m}$) for that object multiplied by a weighting factor W that measures the quality of the particular users that have assessed the object. The quality of an individual user is determined by measuring to what extent that person agrees with the majority

---

[6] Similar parameters are calculated for the other categories such that $f_e + f_s + f_b + f_m = 1$.

[7] This is the same parent population obtained after six-months of running Galaxy Zoo that is used in Lintott et al. (2008), Land et al. (2008), Bamford et al. (2009) and Schawinski et al. (2009).

opinion for all objects the individual has viewed. The weighting factor, W, thereby represents all the iterations carried out by equations (1) & (2) of Lintott et al. 2008).[8]

$$f_m = \frac{W n_m}{n_{e,s,b,m}}. \tag{4.1}$$

The parameter f_m ranges from 0 to 1 so that an object with $f_m = 0$ should look nothing like a merger and $f_m = 1$ should look unmistakably so. Figure 4.4 shows some example images taken from GZ labeled by their f_m values. It is interesting to see how low f_m is when these images start to look, at least superficially, like mergers ($f_m \sim 0.2 - 0.4$). Evidently, users were rather conservative in calling something a merger.

Figure 4.5 shows the distribution of f_m for the entire GZ catalogue. In building our first merger catalogue we determined a cut-off point for f_m above which most systems will be proper galactic mergers and involve a sample size manageable by a research team. By comparing the merger-vote fraction with images like those in Figure 4.4, we decided to build our first catalogue using only systems with $f_m > 0.4$ and only using GZ objects with spectra whose spectroscopic redshift lies in the range $0.005 < z < 0.1$. SDSS spectroscopic targets are selected for galaxies with apparent magnitude $r < 17.77$ which corresponds to $M_r < -20.55$ at $z = 0.1$. This absolute magnitude corresponds to a minimum stellar mass of $\sim 10^{10}\mathrm{M}_{\odot}$ (see Figure 4.9) so that our upper limit ($z = 0.1$) of our volume-limited sample will be inclusive of intermediate size galaxies.[9] The resolution of images beyond $z > 0.1$ is rapidly diminishing which would lead to unreliable visual classifications of morphology.

---

[8] W here is *not* the w_k of Lintott et al. 2008. w_k is the weighting of each individual user whereas W represents their combined weighting for each individual GZ object.

[9] For clarity, the merger catalogue that we construct is *not* volume-limited, i.e. the systems are red-shift limited ($0.005 < z < 0.1$) but the absolute magnitude (M_r) is subject to no formal constraint in order for that object to belong to the catalogue, although its apparent magnitude must have been such that the SDSS pipeline deblended the system into a spectral target (with $r < 17.77$). For certain investigations, however, it is important to impose an absolute-magnitude cut of $M_r < -20.55$ on the catalogue in order to ensure completeness across the redshift range we are using. We state when we do this and refer to such a subset as a 'volume-limited' sample.

The lower limit $z = 0.005$ is to minimise the number of mergers that go undetected due to an incomplete field of view.[10] These cases are rare since the number of SDSS objects peaks near $z = 0.08$ and only a few percent have $z < 0.02$.

After applying the cut to only those objects with spectral redshifts between $0.005 < z < 0.1$, we have $304,182$ objects (see Figure 4.5). To find mergers within this set, we apply the cut $0.4 < f_m \leq 1.0$ leaving 4198 GZ objects with spectra. We exclude those SDSS targets which are yet to acquire spectra as we desire accurately measured redshifts.[11]

Although the purpose of the Galaxy Zoo project is to significantly reduce the need for research teams to visually inspect large catalogues, it is still necessary at this stage to double check the results. Visual re-examination of the sample by our group allowed us to

1. remove any non-merging systems,
2. visually select an appropriate SDSS object to represent the merging partner, and
3. assign morphologies to the galaxies in each merging system.

We briefly describe our methods for each of these tasks.

4.2.2 Removing Non-Merging Systems

The examples of Figure 4.4 demonstrate that the weighted-merger-vote fraction is strongly correlated with how ‘merger-like’ an image appears to be. The outcomes of GZ are therefore similar in effect to automated methods like CAS and GM_{20} which also map images to parameter spaces. In our case though f_m is a single parameter (making it easier to divide up ‘merger’ and ‘non-merger’ zones) and, by utilising the pattern-recognition capacity of many human minds, overcomes the

---

[10] This arises because GZ images are scaled for viewing according to the Petrosian radius of the object’s model magnitude. The photometry of very large and close-by galaxies is often deblended into multiple SDSS objects. The more deblended objects there are, the less the Petrosian radius of any single deblended object represents the galaxy as a whole and this brings about an inappropriately small image-scale for viewing some close-by galaxies. Such systems would be viewed by users as nothing but a galaxy core and not, consequently, voted as a merger.

[11] Mergers are inherently ‘messy’ systems and so photometric redshifts calculated by comparison to standard templates are prone to error. In fact we found the *mean* absolute difference between all the photometric and spectroscopic redshifts in our merger sample to be ~ 0.051 - more than half of our redshift range!

need to remove background noise, recognise anomalies, etc. We find that for $f_m \gtrsim 0.6$, all systems are robust mergers. However, three causes for mis-classification begin to emerge as f_m decreases and become common for $f_m \lesssim 0.4$:

1. projection of **galaxies** along the line of sight,
2. projection of nearby **stars** onto distant galaxies and
3. cases which are 'border-line' mergers.

Galactic projections occur when two galaxies have similar celestial coordinates but are separated by a significant radial distance. We can easily spot projections when *both* galaxies have spectral redshifts. However, many of our candidate systems have only one redshift. Spotting a projection in such cases can only be done through visual examination of the image for signs of interaction. Our choice to use only systems with $f_m > 0.4$ meant, however, that the need for such difficult decisions was rare.

Stellar projections were the more common problem. We were able to eliminate stars easily from our sample though by their characteristic point spread function (PSF) using the associated parameter 'type' from the SDSS PhotoTag table. This is a discrete label given to every photometric object in the SDSS database that indicates whether an object is 'point-like' or 'extended' and can, on this basis, reliably determine ($>$ 98%) whether a luminous object is a star or not (Strauss et al., 2002).

'Border-line' cases involve galaxies that *are* morphologically disturbed but do not necessarily merit the term 'merger.' All galaxies are merging with *something* which can range from molecules (accretion) to a small galaxy (minor merger) to a galaxy roughly its own size (major merger). Deciding where in this spectrum of possibilities the term 'merger' becomes appropriate is rather subjective. At this stage, therefore, our strategy was simply to decide by visual inspection whether a given GZ galaxy had a 'strongly-perturbed' morphology. By 'strongly-perturbed' here we mean that a galaxy was in a morphological state that was unlikely to have occurred without some external interaction. Starting with this inclusive criterion allows us obtain completeness for anything deserving the term 'merger.' We found in fact that borderline cases were again rare for systems with

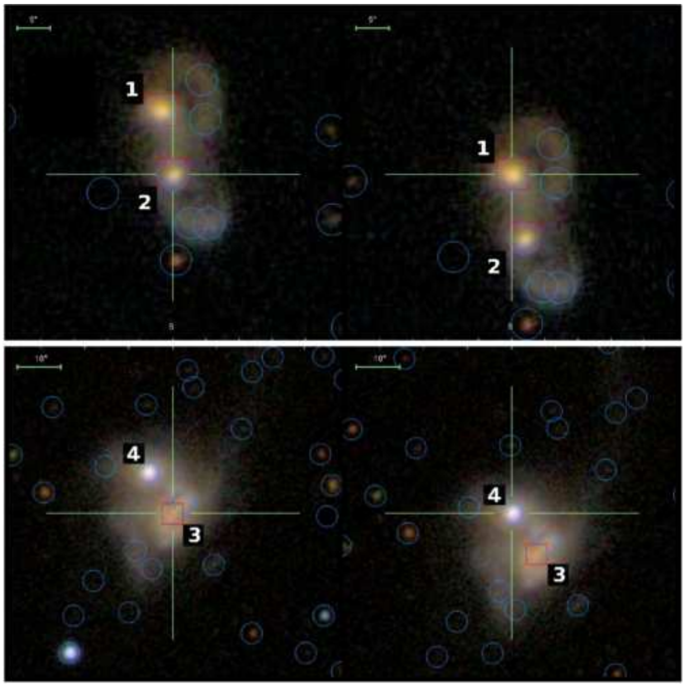


Figure 4.6: Images exemplifying the construction of the merging-pairs catalogue. All spectral targets (red boxes) are Galaxy Zoo objects. In the upper panel, we select the two spectral objects (1 and 2) from Galaxy Zoo to represent the merging pair. The merging system in the lower panel only has one spectral target (3) which was found by Galaxy Zoo. We therefore examine all neighbouring SDSS objects in order to select one (in this case 4) to represent the merging partner galaxy. Our final catalogue has 3003 such pairs.

$f_m > 0.4$. However, difficult decisions regarding projections and border-line cases are abundant for systems where $0.05 < f_m \lesssim 0.4$ (for example the image of Figure 4.4 with $f_m = 0.175$) and it will therefore require a great deal of care if we wish to expand our catalogue into the $f_m < 0.4$ range in the future.

We then examine each 'strongly-perturbed' system with the aim of selecting an SDSS object to represent the body responsible for the disruption caused to the galaxy labeled with $f_m > 0.4$ (if any is identifiable). The details of this procedure are discussed below. With photometric objects representing the 'perturber' we can distinguish major mergers more objectively and their completeness can be assumed since they are a subset of 'strongly-perturbed' systems.

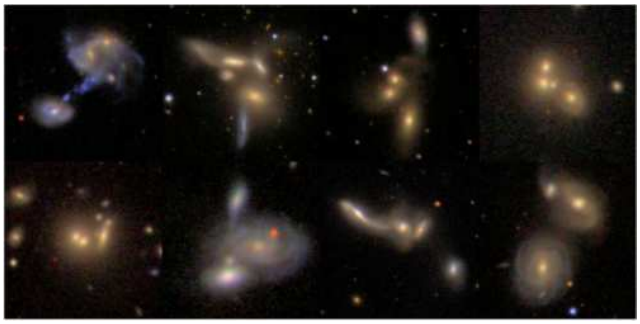


Figure 4.7: Example images of multi-merging systems. We generally included these in the binary merger catalogue by selecting the closest and brightest galaxy to accompany the Galaxy-Zoo object. We found 39 systems that could confidently be described as multi-mergers.

4.2.3 Visual Selection of Merging Partner

As mentioned, in order to create a catalogue of merging pairs, we needed to manually select an appropriate SDSS object as a partner for the object supplied by GZ with $f_m > 0.4$. We did this using an IDL routine that allows for the rapid examination of the image and photometry of all objects within $30''$ of the GZ object given by the `Neighbors` table in the SDSS database. We choose whichever object appears to be the most ‘plausible’ representation of the body responsible for the morphological disruption to the galaxy represented by the GZ object. Plausibility was judged on the basis of object brightness (with brighter objects in the r-band being preferable) and visual ‘common-sense.’ See Figure 4.6 for examples of this procedure. For most systems, which are binary mergers, this choice was straightforward as they usually have either

(a) spectra centred on both galaxies or

(b) a spectral object centred on one galaxy and only photometry on the other.

However, not all ‘strongly-perturbed’ systems appear as simple binary mergers. Additionally, there are cases where

(c) galaxies are in the final stages of a merger and its progenitors are no longer distinguished by the SDSS pipeline (‘post-mergers’),

(d) a galaxy has been perturbed by a close encounter with a neighbour no longer in view ('fly-by') and, occasionally,

(e) a merging system involves three or more galaxies.

The wide range of possibilities makes merger taxonomy a difficult task. In constructing a merging-pairs catalogue we therefore proceed as follows for these various cases.

For case (a) we usually choose these two spectral objects to represent our merging pair (see figure 4.6). If the merger companion does not have spectra then we visually select the best photometric object available to represent the merging partner (case b).

Cases (c) and (d) are sometimes difficult to distinguish and usually occur when only one galaxy core is apparent with the peripheries undergoing extensive tidal disruption. This usually means that no photometric object is available to plausibly represent the perturbing body and so, in such cases, we simply decline to select a merging partner. They remain in the category of 'strongly-perturbed' systems (and are included in our calculation of the merger fraction; see §4.3.1 and §4.3.3) but are not included in the merging-pairs catalogue. Figure 4.2 shows examples of these two categories.

In the case of (e), where several galaxies are merging at once, we decided to first note them and then include them in the merging-pairs catalogue by selecting the closest and brightest object to the GZ-supplied galaxy. The catalogue is technically a mix between 'binary-mergers' and 'multi-mergers' and so we call it the 'merging-pairs' catalogue since it contains 3003 pairs of galaxy objects which are all in merging systems. In Chapter 6 we study these multi-mergers and compare them to the SAMs of the Millennium Simulation.

To summarise, through this refining and pairing process we converted 4198 objects to 681 pairs where *both* objects have spectra (case a) and 2322 pairs where only one object has spectra (case b). These make the 3003 pairs of the catalogue. 370 of the 4198 systems were considered strongly-perturbed but unsuitable to be put into a pair (cases c and d). Only 39 of the 3003 pairs are confirmed to be multi-mergers (case e). The remaining 144 objects[12] were discarded because they were deemed to be in non-strongly-perturbed systems (mainly stellar overlaps).

---

[12] $4198 - 3003 - 681 - 370 = 144$.

4.2.4 Assigning Morphologies

Morphologies were assigned to each SDSS object in our merging-pairs catalogue by a single classifier (DWD) working with consultation. We use four classifications for the merging galaxies: E, S, EU and SU. The E and S classifications respectively label those galaxies which are clearly elliptical and spiral by morphology. No appeal to colour should be necessary. The EU and SU are those ellipticals and spirals about which we are 'unsure,' in other words, this is our best guess.[13] The 'unsure' morphologies are usually more distant objects whose image resolution is too poor to distinguish features like spiral arms. Choosing between EU and SU can be very difficult and is based mostly on apparent surface-brightness profile and, in very difficult cases, on colour. (See Figure 4.8 for examples and further details of our decision-making criteria.)

A simple means to select morphology in SDSS is via the SDSS `fracdev` parameter measured in the r-band that ranges from 0 to 1. This is a measure of the goodness-of-fit of a galaxy's surface-brightness to a de Vaucouleur profile. Ellipticals tend to have a `fracdev` ~ 1 whereas spirals have a wide distribution. We find that our morphological categories S, SU, EU and E have mean `fracdev` values of 0.48, 0.85, 0.93 and 0.94 respectively fitting qualitatively with expectation. The high value of 0.85 for the SU category suggests there is contamination by bulge dominated discs or ellipticals as discussed in §4.3.5. This is expected since distant, poorly-resolved spirals can look like ellipticals (Bamford et al., 2009). To avoid such contamination we can restrict ourselves at anytime to using only the 'sure' morphologies.

4.3 The Merger Fraction of the Local Universe

Our large merging-pairs catalogue and f_m values given by GZ for $893,292$ spectral objects enables us to address two distinct and important questions which are highly relevant to the field of galaxy evolution:

1. what is the **fraction** of merging galaxies in the local universe? and

---

[13] We refer to the set of merging galaxies with elliptical classifications as 'E+EU' galaxies, etc.

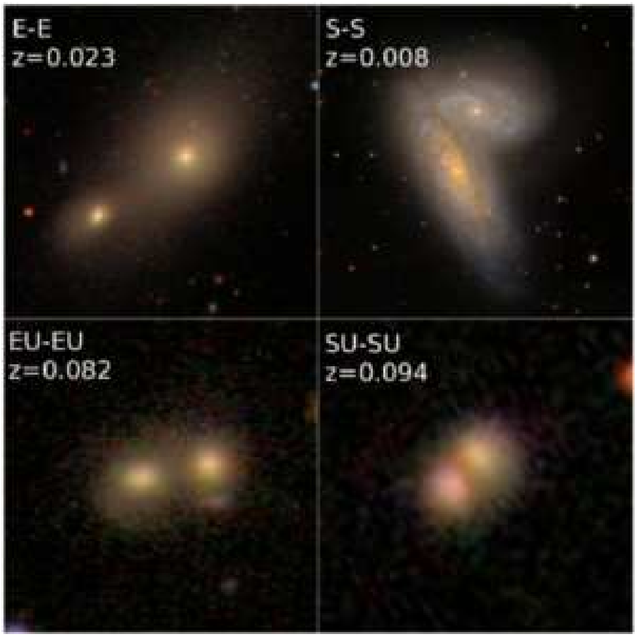


Figure 4.8: Example images of galaxies for morphological categories E, S, EU and SU. Any combination of these is possible. Poorer image resolution as $z \to 0.1$ affects certitude of morphological components. The bottom panels show examples of 'unsure' morpholgies. If a morphologly is unclear, it will normally be assigned EU type by surface brightness profile if there is a drop off in brightness from the centre. SU types generally have a more uniform surface brightness profile in our approach. The colour of the RBG images was also used as a visual guide in very difficult cases under the assumption that EU types should be more red. Image widths: E-E $\sim 120''$, S-S $\sim 240''$, EU-EU $\sim 40''$ & SU-SU $\sim 30''$.

2. what is the **ratio** of spirals to ellipticals (N_s/N_e) in mergers in the local universe?

4.3.1 Estimating the Merger Fraction (I)

Our merger location technique is different to those before it and is suited therefore to a different procedure for finding a meaningful 'merger fraction' which we make explicit here. First, we must find the fraction of volume-limited galaxies in the local universe currently in a 'strongly-perturbed' state. To accomplish this we use the subset of our 893,292 GZ spectral objects that are members of the Main-Galaxy-Spectral sample (MGS; Strauss et al. 2002) in SDSS and estimate what fraction of them are 'strongly-perturbed.' By using only objects with spectra we are able to volume-limit the sample (by the usual $M_r < -20.55$ constraint) which is necessary for a meaningful merger fraction.

$$f_{mgs} = \frac{\sum \left[\begin{array}{c} \text{`Strongly-perturbed' volume-limited} \\ \text{MGS spectral objects in SDSS} \end{array} \right]}{\sum \left[\begin{array}{c} \text{All volume-limited} \\ \text{MGS spectral objects in SDSS} \end{array} \right]}. \tag{4.2}$$

The use of only those spectral objects which are in the MGS leads to a good approximation for the *real* merger fraction, f_{real}, so long as an appropriate factor C is applied to correct for spectroscopic incompleteness, i.e. $f_{real} = C f_{mgs}$ where we estimate $C \sim 1.5$. Justification for this claim with a brief discussion of the MGS and spectroscopic targeting in SDSS is given in Appendix A.

The merging-pairs catalogue produced in §4.2 is large but incomplete since it is constructed only from systems with $f_m > 0.4$. Finding f_{mgs} therefore requires extrapolation into the $0 < f_m < 0.4$ region. To find the numerator of (4.2), we therefore took volume-limited samples of 100 GZ-spectral objects from the bins $0 < f_m \leq 0.05$, $0.05 < f_m \leq 0.20$ and $0.20 < f_m \leq 0.40$ which are also in the MGS. By visually inspecting each set of 100 galaxies *twice* (the first time round we made our decisions very conservatively, the second time round very liberally) we obtained estimates for the percentages of 'strongly-perturbed' galaxies within these bins. These were: $0-2\%$, $18-34\%$ and $50-59\%$ for the $0.0 < f_m \leq 0.05$, $0.05 < f_m \leq 0.20$ and $0.20 < f_m \leq 0.40$ bins respectively.[14] There are, of course, many more objects in these bins than in those with $f_m > 0.4$ (see Figure 4.5) and so end up contributing to at least two thirds of all 'strongly-perturbed' systems. We assumed that no GZ object with $f_m = 0$ would be 'strongly-perturbed.'

---

[14] We also double checked our results with an additional interface on the world-wide web designed to re-examine all objects within the range $0.2 < f_m < 0.4$. After a few months, enough users had re-classified these images of interest in order that a new-weighted-merger-vote fraction, f'_m, could be calculated for each image based upon clicks of the 'merger,' 'not-merger' and 'don't know' buttons. By then volume-limiting all spectral objects from this sample as before with $0.005 < z < 0.1$ and $M_r < -20.55$ we are able to filter out more actual 'strongly-perturbed' systems. However, we again needed to decide a cutoff for the vote fraction, f'_m. We examined twenty sets of ten images across the entire f'_m range and estimated how many of these were genuine 'strongly-perturbed' systems. We found that $\gtrsim 80\%$ of images were actual 'strongly-perturbed' systems for $f'_m > 0.6$ and, following Lintott et al. (2008), made this number the cut off. The fraction of objects with $f'_m > 0.6$ is $\sim 53\%$ which is in good agreement with our estimate that $50-59\%$ of objects in this range are 'strongly perturbed.'

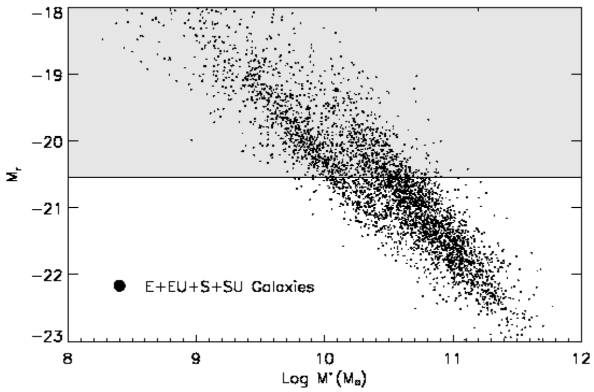


Figure 4.9: Relation between stellar mass and absolute magnitude in the r-band. The solid horizontal line at $M_r = -20.55$ corresponds to the cut used to obtain our volume-limited samples. This cut removes virtually all galaxies with mass $M < 10^{10} M_\odot$ as well as galaxies up to a mass of $M \sim 7 \times 10^{10} M_\odot$.

Applying these estimated fractions to the total number of MGS objects in each bin and adding the ‘strongly-perturbed’ and volume-limited MGS objects from the 4198 GZ objects with $f_m > 0.4$ gives us the numerator for equation (4.2). The denominator of equation (4.2) is found to be 157,801. Dividing these gives the fraction $f_{mgs} = 4 - 6\%$. We sum up our result for f_{real} in the following way:

> **The Merger Fraction (Weak Statement)**
>
> $\sim 4 - 6 \times C\%$ of all galaxies in a volume-limited sample ($M_r < -20.55$) in the local universe ($0.005 < z < 0.1$) are ‘strongly-perturbed.’

We call this the weak statement because of the subjective nature of deciding whether or not a system is ‘strongly-perturbed’ or not. The error in this percentage arises from the upper and lower bounds estimated for the three samples of 100 images (before the correction factor $C \sim 1.5$ is applied). In §4.3.3 we use the 3003 systems from the merging-pairs catalogue (plus a few more plausible assumptions) to offer a stronger statement giving the fraction of *major* mergers in the local universe.

4.3.2 The Stellar Masses of Merging Galaxies

Of the ‘strongly-perturbed’ systems, we need to find what subset comprise major mergers. For this study, we define a major merger to be two merging galaxies of stellar masses M_1^* and M_2^* where $1/3 < \mathrm{M}_1^*/\mathrm{M}_2^* < 3$ and so, to estimate the subset of major mergers, we need to calculate stellar masses for the galaxies in the merging-pairs catalogue.

We do this by fitting the SDSS photometry for each object in our catalogue to a library of photometries produced by a variety of two-component star formation histories. The approach is similar to that of Schawinski et al. (2007a) except that we do not use the information contained in the stellar absorption indices. The library SEDs are generated using the Maraston (1998, 2005) stellar models. Both components have stellar populations with variable age with fixed solar metallicity and Salpeter IMF (Salpeter, 1955). The first (older) burst is a simple stellar population (SSP), the second (more recent) burst is modeled by an exponential with variable e-folding time. The purpose of the varying e-folding times is to account for galaxies with extended star formation histories. This is especially important for mergers which are likely to have undergone recent star-formation episodes. Dust is implemented using a Calzetti et al. law (Calzetti et al., 2000) that is free to vary for E(B-V) over 0 to 0.6. It should be noted that mergers, by their very nature, are prone to mix and overlap and this could lead to additional reddening.

It is important that our cut for the merger fraction be based upon magnitude and not mass since it is the photometric brightness of the object that determines whether or not it will end up in the MGS (which is integral to our defintion of the merger fraction). In Figure 4.9 we examine the effect of imposing our volume-limiting cut on the mass distributions. Mass scales with brightness, though the scatter is substantial, such that the magnitude limit $M_r < -20.55$ removes all galaxies with $< 10^{10}\mathrm{M}_\odot$ and some as massive as $\sim 7 \times 10^{10}\mathrm{M}_\odot$. It is therefore undesirable to estimate the merger fraction using a mass cut (instead of a magnitude cut) for this redshift range since one would need to cut at no less than $\sim 7 \times 10^{10}\mathrm{M}_\odot$ to ensure completeness and this would greatly reduce the sample size. It would also make a calculation of the merger fraction impractical since we would then need masses calculated for the entire MGS sample to get the denominator of equation (4.2) and this would be an enormous computational task. In the next chapter we examine the

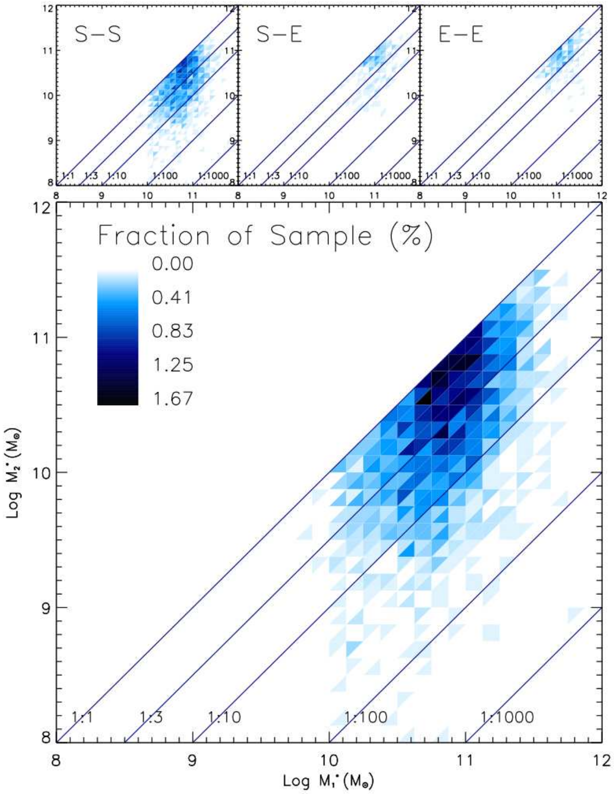


Figure 4.10: This figure illustrates the occupancy of regions in mass-mass space for all the merging-pairs where the *more massive* galaxy has $M_r < -20.55$. Points between the $1:1$ and $1:3$ lines are major mergers. We only assume completeness within this strip in this study. The boxes in the upper panel divide the sample by morphology.

distributions of these stellar masses in more detail and in comparison to a control sample.

4.3.3 Estimating the Merger Fraction (II)

We now apply the information obtained in §4.3.1 (the fraction of 'strongly-perturbed' galaxies) with that obtained in §4.3.2 (stellar-mass estimates for objects in the merging-pairs catalogue) in order to estimate the fraction of major mergers in a volume-limited sample ($M_r < -20.55$) in the local universe ($0.005 < z < 0.1$).

Figure 4.10 illustrates the occupation of the mass space of the merging pairs in our catalogue with the magnitude limit imposed on the *more massive* galaxy in the pair.[15] This criterion allows

---

[15] As a reminder, the catalogue of 3003 merging pairs is *not* volume-limited, i.e. there is no formal constraint for either

us to view both major and minor mergers. We find that $\sim 50\%$ of these points lie within the major-merger strip. Estimation of the number of minor mergers within our volume-limited ranges is difficult since their completeness rapidly diminishes as $\mathrm{M}_1^*/\mathrm{M}_2^*$ increases.[16]

However, we can plausibly assume completeness for major mergers since, by the nature of the images they produce, they are easy to spot. Knowledge of the stellar-masses thus allows us to estimate what subset of the 'strongly-perturbed' MGS spectral objects in the local universe which we found in §4.3.1 are major mergers by the technical definition of $1/3 < \mathrm{M}_1^*/\mathrm{M}_2^* < 3$.[17]

To get a merger fraction, we again need to apply our analysis solely to volume-limited objects within the MGS.[18] Of the 3864 spectral objects in our 3003 binary-merger pairs, 2306 have $M_r < -20.55$. Of these, 1243 are in major mergers, leaving 1063 in minor mergers. We therefore find that $1243/2306 \sim 54\%$ of the volume-limited objects with spectra taken from our catalogue (which all have $f_m > 0.4$ according to how they were selected) are in major mergers.

We can now estimate an upper-limit for the fraction of major mergers in the local universe by supposing that this fraction of major mergers ($\sim 54\%$) from what was originally classified as a set of 'strongly-perturbed' systems will be the same for *all* strongly-perturbed systems in the range $f_m < 0.4$.[19] This is certain to be an *overestimate* since there are bound to be a higher proportion of major mergers in systems with high f_m. The reason for this is that most 'strongly-perturbed' systems obtain a low $f_m \sim 0.2$ precisely because they are mostly 'border-line' cases (i.e. perturbations caused by interactions or very minor mergers). Figure 4.11 confirms this expected relationship over the range of f_m for our catalogue, that is, the ratio of major-to-minor mergers in

---

object in the pair to have a minimum absolute brightness. This means that in order to get a sample that is complete over the redshift range in use, we need to impose an absolute magnitude cut to all systems therein ($M_r < -20.55$ since, at $z = 0.1$, this will select all galaxies with $r < 17.77$, the minimum brightness needed to be designated as a spectral target). However, for mergers where we have two objects, one can choose to impose this absolute-magnitude constraint *either* on both objects in the pair *or* only on the largest/brightest object. We choose the latter option for this particular graph since it is more inclusive of minor-mergers.

[16] Mergers between systems with $\mathrm{M}_1^*/\mathrm{M}_2^* > 1000$ are of course abundant in the universe (every galaxy is merging with *something* small) but will not, by their very nature, get spotted in a merger study. We would therefore not be able to derive the abundance of minor-mergers in the local universe here with much confidence.

[17] As opposed to a purely subjective decision based upon visual inspection of the image.

[18] Since we use the MGS to establish the denominator of equation (4.2).

[19] Recall that, when we estimated the fraction of 'strongly-perturbed' systems as expressed in the Weak Statement, we needed to estimate how many MGS objects with $f_m < 0.4$ would be classified as 'strongly-perturbed.' Some of these will be major mergers, the rest minor. By assuming that the fraction of major mergers in our catalogue (with $f_m > 0.4$) is the *same* for all the rest ($f_m < 0.4$), we obtain an upper limit for how many major mergers are in the local universe.)

our sample is seen to increase with f_m. In other words, users tended to more readily spot mergers involving galaxies of roughly equal mass. Applying this fraction of 54% to the upper limit of our f_{mgs} gives $0.54 \times 6\% = 3.24\%$ which, being an overestimate, we can plausibly round down to $\sim 3\%$.

We can also obtain a lower-limit to the major-merger fraction by supposing that the major mergers in our catalogue comprise *all* of the major mergers in the local universe. That is, we can suppose that there are *no* major mergers at all in the range $f_m < 0.4$ for our volume-limited sample. This is of course an *underestimate* since there are bound to be at least some major mergers in, for example, the range $0.2 < f_m < 0.4$. Applying this assumption gives the lower limit of $1243/157{,}801 \sim 0.8\%$.[20] Again, since this is undoubtedly an underestimate, we can plausibly round this limit up to $\sim 1\%$. We summarise this working in the following way.

> **The Merger Fraction (Strong Statement)**
>
> $\sim 1 - 3 \times C\%$ of all galaxies in a volume-limited sample ($M_r < -20.55$) in the local universe ($0.005 < z < 0.1$) are observed in a major merger.[21]

The large error obtained here arises due to the simplicity of the Galaxy Zoo interface. The recently released Galaxy Zoo Two project, which focuses on more specific questions (e.g. is the system ‘merging’ or ‘interacting’) and removes the dichotomy of describing *either* the morphology *or* the merger-likeness of the system, should lead to a much more exact figure for the merger fraction in the near future.

4.3.4 Close-Pairs Comparison

Comparing the percentage in this strong statement with close-pairs studies is difficult because few of them present their results in terms of merger *fractions*. They also use different criteria for their volume-limiting bounds and for accounting for errors which are important in such studies (such as fiber collisions, false-pairs and non-gravitationally bound pairs). For example, Patton et al. (2000)

---

[20] Where $157{,}801$ is the denominator of (4.2).

[21] Where we use the same corrective factor $C \sim 1.5$ (Appendix A).

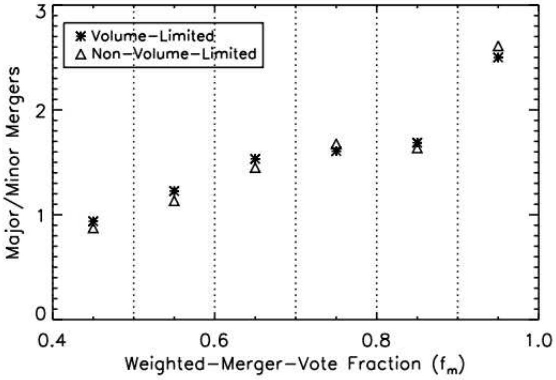


Figure 4.11: The relationship of major-to-minor-mergers ratio for the merging-pairs catalogue over the $0.4 < f_m < 1.0$ range. The trend indicates that major mergers are more likely to get merger votes than minor mergers. Minor mergers only outnumber major mergers in the $0.4 < f_m < 0.5$ bin. The effect is similar for both volume- and non-volume limited samples.

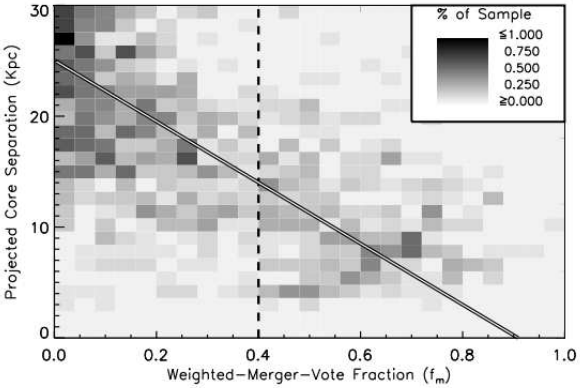


Figure 4.12: The distribution of volume-limited close-pairs objects in the MGS comparing f_m and their projected separations. The vertical broken line marks the boundary for our merger catalogue at $f_m = 0.4$. The solid diagonal line is a best-fit to the distribution of points in this f_m-separation space. The shading indicates the density of points in various regions of this space. GZ users were more likely to call a close-pairs object a merger as the projected core-separation decreased.

concluded that $\sim 1.1\%$ of nearby galaxies with $-21 < M_B < -18$ are undergoing a merger (but not necessarily a *major* merger by our definition). Our percentage is similar but the definitions are so diverse as to render comparison obsolete.

A more recent study by Patton & Atfield (2008) on SDSS close-pairs measures the number of 'close-companions' per spectral object which satisfy three constraints: physical separation (r_p; $5 < r_p < 20h^{-1}$ Kpc), rest-frame velocity ($\Delta v < 500\text{kms}^{-1}$) and absolute magnitude difference ($|\Delta M_r \leq 0.753|$). Again though, there are significant differences between their samples and ours. Their magnitude limits are $-22 < M_r < -18$ and they define a major merger by luminosity (at 1:2), not by mass as we do (at 1:3). More significantly, only $\sim$ half of the pairs satisfying their criteria are "known to exhibit morphological signs of interactions" whereas our sample is selected on the basis of visually-established interactions. So although the number of close-companions they calculate ($N_c \sim 0.02$) is similar to our major-merger fraction ($\sim 1 - 3 \times C\%$) the differences between the two techniques make claims of corroboration difficult to substantiate.

We performed our own comparison of GZ with a close-pairs catalogue of all SDSS spectral objects within a projected separation of 30kpc of each other and a line-of-sight velocity difference of $< 500\text{kms}^{-1}$. For a consistent comparison with our catalogued mergers, we examine only those objects which are within the volume-limited boundaries ($0.005 < z < 0.1; M_r < -20.55$) and the MGS. This gives 2308 individual close-pair objects. Many of these will be part of a false-pair arising from the automated deblending of a single galaxy into two or more spectral targets (see §4.1.1). Some pairs will also appear well separated (relative to their size) and show no signs of interaction. We therefore visually examined all 2308 objects in order to determine which ones are in a 'strongly-perturbed' state brought about by the galaxy represented by the other spectral object in the close pair. This led to the removal of 654 ($\sim$ 28%) of the close-pairs objects in our volume-limited MGS sample.

The 1654 remaining spectral objects are all GZ objects and so we can examine how users voted for them. We found that a significant portion ($\sim$ 64%) of these close-pair spectral objects which *are* in 'strongly-perturbed' systems (by our reckoning) had $f_m < 0.4$ and were therefore excluded from our catalogue. However, we also found that there is a strong correlation between f_m

for close-pairs objects and their *projected separation* such that the further apart close-pair objects are, the less likely users were to label it a merger (see Figure 4.12). This means that the GZ technique selects systems which are generally more advanced in the merger process and therefore undergoing more extensive interactions than a typical system in close-pairs studies. Only ~ 600 of these objects are in our catalogue of ~ 3000 pairs which fits with the claim that only $\sim 20\%$ of (relatively advanced) merging systems are spectral pairs in SDSS, the rest being systems with only a single spectral object within our magnitude-limited volume.

We conclude that, like the CAS and GM_{20} techniques, the GZ method for detecting mergers is sensitive to *different* stages of a merger compared to the close-pairs technique (Lotz et al. 2008b).

4.3.5 Estimating the Spiral to Elliptical Ratio in Merging Systems

Uncertainties and User Bias

Having established an estimate of what fraction of galaxies in the local universe are merging, we now turn to the more difficult task of estimating the spiral-to-elliptical ratio of galaxies that are merging (N_s/N_e).[22] In addition to the uncertainties associated with identifying actual mergers, there are now the uncertainties associated with varying image resolution leading to 'sure' and 'unsure' morphologies (see §4.2.4). Bamford et al. (2009) have studied extensively the dependence of GZ morphological classifications on redshift and found that the proportion of elliptical classifications increases with z. The same problem arose for our classifications: over the range $0.005 < z < 0.03$ the fraction of 'unsure' morphologies (EU, SU) to 'sure' morphologies (E, S) is $\sim 10\%$ but this fraction rises to $\sim 25\%$ as we vary over $0.03 \to 0.1$. In short, the more distant a galaxy is the more 'featureless' it appears bringing about a visual misclassification that inflates the recorded number of ellipticals. For details of the quantification and correction to this effect, see Bamford et al. (2009).

A further unknown peculiar to GZ is mass-user psychology. A natural concern of ours was that users would be more likely to call a system a 'merger' if it involves two spirals (which gen-

---

[22] Where N_s and N_e are the number of galaxies in a given sample of mergers that are spiral and elliptical respectively.

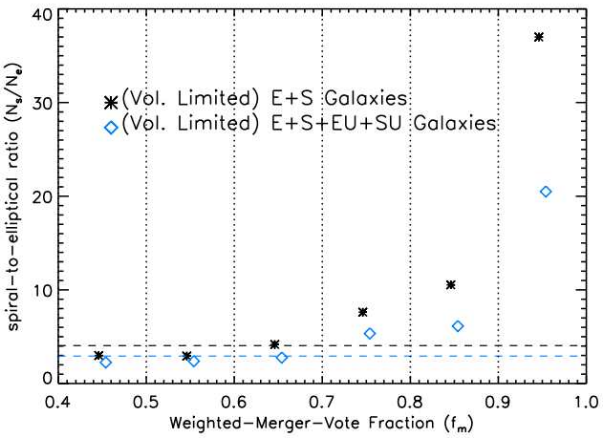


Figure 4.13: An examination of the relation between morphology and f_m. We magnitude limit our sample ($M_r < -20.55$) and measure the ratios of spiral to elliptical morphologies (N_s/N_e) of mergers for bins shown along the f_m axis. As $f_m \rightarrow 1.0$ a strong bias is seen for users to flag mergers involving *spirals*. N_s/N_e appears to converge to roughly a constant as $f_m \rightarrow 0.4$. The broken horizontal lines are the mean N_s/N_e values for the two samples over the whole range $0.4 < f_m \leq 1.0$.

erally look more dramatic) than if it involves two ellipticals. We therefore examined how the ratio of spirals to ellipticals in our merging-pairs catalogue varies with f_m, as shown in Figure 4.13. Whether we use just the ‘sure’ morphologies (E+S sets) or also include the ‘unsure’ morphologies (E+S+EU+SU sets), the N_s/N_e ratios appear to follow curves that start high for $f_m \sim 1.0$ and decay towards a constant as $f_m \rightarrow 0.4$. This confirmed the suspicion that the systems compelling users to click the merger button the most tend to involve spirals. However, the majority of mergers are located in the bins where the ratios level off at roughly a constant ($\sim 0.4 < f_m < 0.6$). Inclusion of the EU and SU categories slightly decreases N_s/N_e as expected (some ‘unsures’ are really spirals but get mistaken for ellipticals).

The horizontal lines of Figure 4.13 indicate the mean N_s/N_e ratios for the E+S and E+S+EU+SU samples over the whole range $0.4 < f_m < 1.0$. These N_s/N_e means are ~ 5 and ~ 3 respectively. The true mean over this range must surely be $N_s/N_e > 3$ therefore since the ‘unsure’ morphological categories deflate N_s/N_e through false inclusion of ellipticals as discussed earlier.

Towards an N_s/N_e Estimate for Merging Galaxies

We proceed now by extrapolating this value $N_s/N_e > 3$ (found for the range $f_m > 0.4$) to the entire range of f_m, that is, we assume $N_s/N_e > 3$ for all galaxies in mergers for our volume-limited ranges. We compare this ratio with the global spiral-to-elliptical ratio for all galaxies in our redshift range determined using the corrections of Bamford et al. (2009) to debias the high occurrence of ellipticals with increasing redshift. This debiasing leads to the estimate that there are $\sim 3:2$ spirals to ellipticals for all galaxies with $M_r < -20.55$ in our redshift range. Our extrapolated estimate of $N_s/N_e > 3$ for $f_m > 0.4$ is significantly higher in comparison, i.e. our extrapolation would suggest that spirals feature in mergers roughly twice as often as they should if selected randomly from the global population.

To test the accuracy of this extrapolation we examined the morphologies of the same 59 systems from the 100 images of $0.2 < f_m \leq 0.4$ (used in §4.3.1) that were deemed to be 'strongly-perturbed.' We found that 42/59 of these 'strongly-perturbed' galaxies were either S or SU and the remaining E or EU. Taking $N_s/N_e \sim 1.5$ for the global estimate to give null binomial probabilities $p(spiral) = 0.6$ and $p(elliptical) = 0.4$, the expected outcome of 59 galaxy morphologies would be $35.4 \pm \sigma$ spirals with standard deviation $\sigma \sim 3.8$. The observed number, 42, is just within two standard deviations of the expected value. This observation therefore supports the claim that, even in the range $0.2 < f_m < 0.4$, N_s/N_e in mergers is higher than the global mean. This also does not take into account the fact that our observations are still biased by inclusion of 'unsure' morphologies (which inflates the number of ellipticals) whereas the estimate $N_s/N_e \sim 1.5$ for the global population has been debiased.

To summarise, we find that $N_s/N_e > 3$ over the range of our merging-pairs catalogue ($f_m > 0.4$). This is at least twice the global ratio ($N_s/N_e \sim 1.5$). There is no evidence to suggest that mergers in the range $f_m < 0.4$ will compensate this effect with an excess of ellipticals relative to their global population. The high N_s/N_e ratio is especially likely to stand up to scrutiny for *major*-mergers since they have been shown to favour higher values of f_m (see Figure 4.11) where the spiral excess has been robustly confirmed.

Implications of a High N_s/N_e Ratio in Mergers

We now discuss possible reasons for a high N_s/N_e ratio in mergers. It is well established that spirals tend to occupy less-dense environments than ellipticals (established as early as Oemler 1974 and as recently as, for example, Ball et al. 2008). The discrepancy might therefore be the result of a preference for mergers to occur in field environments where spirals are more populous relative to the global population. Alternatively, the disproportionate number of spirals in our 'snapshot' of the local universe could indicate that the time-scales over which spiral galaxies remain detectable in mergers exceeds that of ellipticals.

Studies have been carried out to estimate the time-scales of mergers using dynamical-friction arguments (e.g. Conselice, 2006) and simulations (e.g. Bell et al., 2006; Conselice, 2006; Lotz et al., 2008b). Lotz et al. (2008b), in particular, focus on this question and find that the gas-fraction of galaxies in mergers is one of several factors determining the time-scale of detectability. One such simulation comparing two equal-mass mergers with different gas-fractions showed that the system with the higher gas-fraction ($f_{gas} \sim 50\%$) remained 'morphologically disturbed' (i.e. flagged as a merger by the standard criteria of G, M_{20}, C, A combinations) for $2-4$ times longer than the system with a lower gas-fraction ($f_{gas} \sim 20\%$).

In practice, any variation in N_s/N_e for merging galaxies will depend on a combination of these two explanations since, *a priori*, it seems certain that the merger frequency will have *some* dependence on environment and that the merger-time-scale of detectability will have *some* dependence on the internal characteristics that distinguish spirals from ellipticals (such as gas-content and overall mass). We examine these two effects in more detail in the following chapter and conclude that, in fact, the latter explanation seems to be the most likely, that is, that mergers involving spirals remain detectable for longer times than mergers with involving ellipticals.

4.4 Summary and Discussion

Galaxy Zoo is a new and powerful strategy for locating mergers. The technique is similar in its effect to the CAS and GM_{20} methods in that it converts images to numbers that provide a measure of how 'merger-like' a galaxy is (in this case the weighted-merger-vote fraction $f_m \in [0,1]$). The method is highly apt at locating mergers because f_m is the averaged product of human minds (which are highly adept at pattern recognition) and is therefore extremely sensitive to details while doing away with the major programming challenges associated with automated methods. It is also easier to partition merger-spaces in this method since f_m is a single parameter unlike CAS and GM_{20}, which demand more fine-tuning. The technique is also not limited to objects with spectra as the close-pairs method is (by definition), and we find in fact that only $\sim 20\%$ of our merging systems have spectra for both galaxies. This is mostly due to the large fraction of the SDSS sky that suffers from fiber-collisions ($\sim 70\%$; Strauss et al. 2002, Blanton et al. 2003). It also means that the method is effective at the broader task of finding 'strongly-perturbed' systems including minor mergers. The drawbacks to GZ are time and repeatability. The results presented in this chapter are derived from about six months of web activity.

It is worth emphasising that the results of this chapter are entirely derived from the pressing of a single button labeled 'merger.' The simplicity of this interface led to an unfortunate dichotomy whereby users were often unsure whether to emphasise the merger aspect or the morphological aspect of a given system. Now that the competence and eagerness of the public to assist in extragalactic astronomy is known and tested, so we expect greatly improved results with the Galaxy Zoo Two project - a new development that will enable finer classification of SDSS objects as well as higher redshift surveys.

Galaxy Zoo has already yielded rich results with the initial merger catalogue presented here containing 3003 merging-pairs in mergers in the range $0.005 < z < 0.1$ created from GZ objects with $f_m > 0.4$. Each has been been visually-inspected by fifty or so Galaxy-Zoo users and by one of the authors (DWD). We believe that it is the largest of its kind. Completeness, however, remains an issue as users and experts are only as accurate as the image quality allows. As redshift increases, the reduced image quality makes it difficult to identify galactic projections. Also, there will always be the problem for any merger-detection method in deciding whether or not a galaxy perturbation (such as an extended tidal tail) is great enough to warrant the term 'merger.' For these two reasons, there is a large number of 'border-line' cases in the range $0 < f_m < 0.4$ which are responsible for the error in our estimate of the merger fraction in the local universe.

To obtain this merger fraction, we first estimated the number of ‘strongly-perturbed’ galaxies with spectra in bins over the range $0 < f_m < 0.4$ plus those in our catalogue. Dividing this number by the total number of volume-limited spectral objects led us to estimate that $f_{mgs} \sim 4-6\%$. With the correction factor $C \sim 1.5$ converting f_{mgs} to f_{real} estimated in Appendix A, one can say that $\sim 4-6 \times C\%$ of all volume-limited galaxies ($0.005 < z < 0.1$ and $M_r < -20.55$) are ‘strongly-perturbed.’ We expanded upon this statement by estimating what subset of ‘strongly-perturbed’ volume-limited spectral galaxy objects are major mergers in the local universe. This led to the stronger statement that:

> $\sim 1-3 \times C\%$ of volume-limited galaxies in the local universe ($M_r < -20.55, 0.005 < f_m < 0.1$) are observed in major mergers.

We also estimated the ratio of spirals to ellipticals for merging galaxies with $M_r < -20.55$. The N_s/N_e ratio for our catalogue was highly in favour of spirals by $\sim 3:1$. We examined 100 systems in the range $0.2 < f_m < 0.4$ and found a similar result. This is large compared to the global N_s/N_e ratio ($\sim 3:2$) for this magnitude-limited volume.

We therefore concluded that more spirals are seen to be merging than ellipticals, perhaps by as much as factor ~ 2. We then discussed possible reasons for this observed spiral excess suggesting that either (1) mergers tend to occupy environments that favour spirals, or (2) the time-scale for a merger to reach a relaxed state (i.e. the time over which it is detectable) is longer for spirals than for ellipticals.[23]

We disentangle these effects in the next chapter by exploring the role of the environment and the internal properties of this merger sample. We find in fact that mergers occupy the same (if not slightly *denser*) environments as a randomly selected control sample of galaxies. We conclude there that the best explanation of an apparently high spiral-to-elliptical ratio in mergers, as we find

---

[23] The probability, p_o, of observing a galaxy merging at any general time is proportional to the probability of its merging at that time, p_m, multiplied by the time-scale, τ, over which it is detectable, $p_o \propto p_m \tau$. The probability of merging should only depend on the system’s mass and environment ($p_m = p_m(\mathrm{M}, \rho)$) whereas the time-scale of detectability, τ, must be assumed *a priori* to depend on the internal properties of the merging galaxy such as gas content and mass distribution. Our high N_s/N_e ratio therefore suggests that either $p_m(\mathrm{M}, \rho)$ or τ is large for spirals compared to ellipticals.

here, must be due to varying time scales of detectability. The properties of spirals and ellipticals that affect merger detactability are therefore an important issue that the Galaxy Zoo catalogue can help us understand.

Chapter 5

The Properties of Merging Galaxies

$z < 0.1$

5.1 Introduction

The Galaxy Zoo project[1] (Lintott et al., 2008) has helped meet the need for extensive visual classification of galaxy morphologies in a manner that does not presuppose their spectro-photometric characteristics. Prior to this, large-scale studies of morphology from surveys like SDSS required the use of proxies in place of actual morphology (e.g. as in Bernardi & al. et 2003), but this then biased what their spectro-photometric characteristics *actually* are (Schawinski et al. 2007a).

Similarly, locating mergers via structural parameters such as concentration and asymmetry (Conselice 2003b) is problematic due to the great variety of configurations of mergers (progenitor types, impact parameters and the stage at which the system is viewed) making it difficult to define a parameter space uniquely occupied by mergers. For these reasons visual examination of images of galaxies (assuming they are at redshifts low enough for a decent resolution) is the best way to identify strongly-perturbed systems and produce merger catalogues with minimal contamination.

In the previous chapter we demonstrated how the Galaxy Zoo web-interface is able to accom-

---

[1] www.galaxyzoo.org. The original site which produced the results for this chapter is preserved at http://zoo1.galaxyzoo.org.

plish this by creating a measure ($f_m \in [0,1]$) of how ‘merger-like’ an SDSS image appears to be (where an image attaining $f_m = 1.0$ is certain to be a merger and one with $f_m = 0$ is certain not to be). The f_m values were used to estimate the fraction of major mergers (where the stellar masses of the progenitors M_1^* and M_2^* satisfy $1/3 < \mathrm{M}_1^*/\mathrm{M}_2^* < 3$) in the local universe to be $1-3\times C\%$ for $M_r < -20.55$ where $C \sim 1.5$ is a correction factor for spectroscopic incompleteness.

We found that most systems with $f_m > 0.4$ can confidently be identified as mergers and used this limit to isolate 3003 merging pairs in the range $0.005 < z < 0.1$.[2] All 3003 pairs were then visually examined in order to assign morphologies to the individual galaxies in each merger. From this, we found that the spiral-to-elliptical ratio (N_s/N_e) in merging systems was higher in our sample ($N_s/N_e \gtrsim 3$ for $f_m > 0.4$) compared to the global galaxy population ($N_s/N_e \sim 1.5$) which was determined using the statistical corrections of Bamford et al. (2009) for all Galaxy Zoo morphologies. We argued that the observed spiral excess is real for major mergers, i.e., unlikely to be compensated by an excess of ellipticals in the range $f_m < 0.4$.

It is not a surprise that N_s/N_e should differ between mergers and the global population. The probability of *observing* a merger at any general time is proportional to the likelihood of it merging with another galaxy (which depends on its environment) and the time-scale over which the merger is detectable (which depends on the internal properties of the progenitors). Since spirals differ from ellipticals in both environment (Dressler, 1980) and their internal properties, it is not unreasonable to expect N_s/N_e in merger observations to deviate from that of the complete galaxy population.

Recent simulations by Lotz et al. (2008b) examined the time-scales of detectability for the merger-detection techniques of ‘close-pairs’ and combinations of non-parametric quantities (namely C, A, G & M_{20}; see Conselice et al., 2008 for discussion). These simulations found that the internal properties of the progenitors significantly affect the time-scales over which real systems would have been flagged as merging. The study also found that the physical factors that had the greatest affect on the time-scales of detectability were the gas-fractions of the progenitors, their pericentric separation and their relative orientation. Conversely, the choice of system mass and supernova-feedback prescription only slightly affected the time-scales of detectability.

---

[2] This catalogue is GZM1: Galaxy Zoo Mergers 1.

This would suggest that relative gas content is the most *morphology-specific* factor affecting the time-scales of detectability since spirals are relatively gas-rich compared to ellipticals. (Orientation and pericentric separation, on the other hand, are likely to be independent of morphology).

The internal properties of merging galaxies are also important in so far as they determine the morphological outcome of interacting galaxies. The abundance of minor mergers in the universe (e.g. Woods et al. 2006) must mean that disc galaxies survive substantial numbers of minor mergers. Furthermore, given the estimate by Conselice et al. (2008) that, on average, a galaxy in the mass range $M^* > 10^{10}M_\odot$ will have undergone $4.3^{+0.8}_{-0.8}$ major mergers since $z \sim 3$, the number of disc galaxies in the local universe should appear sizably reduced from that observed *unless* they too can survive major mergers (Hopkins et al. 2009; Hopkins et al. 2009b). Disc survival in major mergers is therefore likely to become an important principle in galaxy evolution that we aim to shed light upon in this work. The study of Hopkins et al., 2009 places great emphasis on the gas-to-stellar-mass ratio in progenitor discs which implicates the importance of feedback processes in mergers (supernovae and AGN) in so far as they can help retain gas at large radii whose angular momentum generates disc reformation after dynamical relaxation.

Star-formation histories are therefore important to study in mergers with respect to gas-retention in discs. More broadly, several matters remain unsolved regarding galactic star-formation histories (Ellis & Silk 2007; Kaviraj 2008) in which mergers play an important role as they are thought to directly trigger star formation (Schweizer 2005; Li et al. 2008), generate (Ultra-) Luminous-Infra-Red-Galaxy activity (Sanders & Mirabel 1996; Kaviraj 2009; Genzel et al. 2001) and bring about the formation of clusters (Zepf et al. 1999; Schweizer 2006). Empirical confirmation of the extent to which mergers are able to affect the luminosity function is thus an important task.

Mergers can also affect star formation and disc dynamics in so far as they trigger AGN activity. This is thought to be a natural consequence of the angular-momentum loss that can take place in galactic interactions allowing the infall of gas (Kewley et al. 2006a) that fuels the central super-massive black hole (Somerville et al. 2000; Jogee 2006). AGN feedback then controls further infall and cooling of gas leading to reduced star formation (Schawinski et al. 2006; Schawinski et al. 2007a; Khalatyan 2008; Schawinski et al. 2009a). Studies showing star-burst activity within

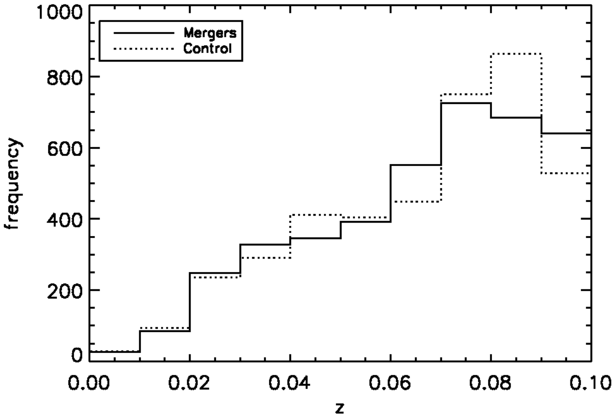


Figure 5.1: The redshift distributions of the merger and control samples appear roughly the same within counting errors as expected. Any distance-dependent aperture or deblending biases should affect both samples equally.

AGN galaxies have suggested mergers as the causal mechanism (e.g. Storchi-Bergmann et al. 2001, Kauffmann et al. 2003b). We test some of these claims by inspecting the star-formation and AGN signatures in our mergers using emission-line diagnostics.

In §5.2 we recap the catalogue conventions described earlier and describe the construction of our control sample. To disentangle the role of environment from internal properties on a galaxy's probability of being observed in a merger, we begin our investigation with a study of the environmental distributions of our samples in §5.3 which we model by a single degree of freedom. The internal properties of galaxies require many more degrees of freedom to fully capture their dynamics. We approach this task by first examining the photometry of our samples (§5.4). In section §5.5 we examine the stellar-mass distributions of our samples and how these correlate with morphologies and colours in merging systems. In §5.6 we perform spectral-line diagnostics to determine the main ionisation sources (or lack of) in our samples accompanied by star-formation-rate estimates. We summarise and discuss our results in §5.7.

5.2 The Merger and Control Samples

5.2.1 Sample Morphologies

For all 3003 merging pairs, we assigned one of the following morphologies to the constituent galaxies: ‘Elliptical’ (E), ‘Spiral’ (S), ‘Unclear but most probably Elliptical’ (EU) and ‘Unclear but most probably a Spiral’ (SU).

We then created a control sample of randomly selected spectral galaxies from the SDSS DR6 catalogue. It is from the same redshift range ($0.005 < z < 0.1$) so that the control and merger galaxies should have similar redshift distributions (qualitatively confirmed by Figure 5.1). The random nature of the selection of control objects makes them a reasonable representation of the global galaxy population whose properties can be compared and contrasted to those of our merger sample.[3]

All calculations carried out here on the merger objects are carried out in the same way for the control sample. The *only* difference is that on the few occasions where we split the control sample into spiral and elliptical categories we use the following criteria: a control galaxy is a spiral if the GZ weighted-spiral-vote fraction f_s is greater than its weighted-elliptical-vote fraction f_e (these are direct analogues to f_m but for spirals and ellipticals respectively) and with a minimum absolute difference of 0.1. Similarly, a control galaxy is taken to be an elliptical if $f_e > f_s + 0.1$. Control galaxies with $|f_e - f_s| < 0.1$ are not used when comparing morphologies to the properties of merging and non-merging galaxies since they are too hard to distinguish. It is important to note that since the merger and control morphologies were determined differently (mergers by DWD) they should only be taken as a rough guide.[4]

Figure 5.2: Example images of the visually-assigned 'stage' categories: (left) 'separated', (centre) 'interacting' & (right) 'approaching post-merger.' Of our 3003 merging pairs, 167 ($\sim$ 6%), 2526 ($\sim$ 84%) and 310 ($\sim$ 10%) were assigned to these categories respectively. (Image widths: Separated $\sim 100''$, Interacting $\sim 70''$ & approaching post-merger $\sim 50''$.)

5.2.2 Assigning Merger Stages

For each merger pair we also assigned a visually-chosen merger 'stage.' We use three categories: 'separated', 'interacting' and 'approaching post-merger.' The 'separated' stage refers to systems classified as a merger in which there is visible space between the galaxies. The 'approaching post-merger' stage refers to systems where the progenitor cores are typically within $\sim 5''$ of each other on the images. The 'interacting' stage refers to anything in between: the galaxies have coalesced to some degree with no space visible in between but the cores have not settled to $\sim 5''$ yet. Figure 5.2 shows examples of these stages. The stages of our 3003 merging pairs comprise of 167 ($\sim$ 6%) 'separated,' 2526 ($\sim$ 84%) 'interacting' and 310 ($\sim$ 10%) 'approaching post-merger' stages. The mean projected separation of the galaxy objects for these three stages are $\sim$ 27.3kpc, $\sim$ 12.8kpc and $\sim$ 5.4kpc respectively. The mean projected separation for all 3003 pairs is $\sim$ 12.5kpc.

5.3 The Environment of Merging Galaxies

To parametrise environment, we employ the method of Schawinski et al. (2007b) that takes advantage of all the spectroscopic-redshift recordings in the SDSS DR6 to obtain the dimensionless

---

[3] The control sample is arbitrarily large; we select the same number of control galaxies as are being used for the mergers depending on the specifics of the investigation. For example, if we volume-limit our merger catalogue to get a sample with x galaxies, we compare it to a volume-limited sample of x control galaxies, etc.

[4] In particular we find in §5.4 that the control ellipticals are bluer than the merger ellipticals and this will mean that stellar mass estimates will be typically lower for the control sample. It is difficult to disentangle whether this extra 'blueness' in ellipticals is physical or just a selection effect. This problem will be overcome by the Galaxy Zoo Two project.

number ρ_g (the adaptive Gaussian environment parameter) for each galaxy in our catalogue. This is a sophisticated measure of number density mapped onto $\rho_g \in \mathbb{R}^+$. The method is highly versatile and an adapted version has recently been used to locate galaxy clusters (Yoon et al., 2008). The parameter $\rho_g(ra, dec, z, \sigma)$ starts by finding close neighbours in DR6 within an initial radius of σ for each galaxy. We use $\sigma = 2.0$Mpc following Schawinski et al. (2007b). It then adapts this radius depending on the initial number return in order to compensate for the "finger-of-God" effect and is weighted such that ρ_g increases the nearer its neighbours are. Wherever we have spectra for *both* galaxies in the merger, we remove one of them from the calculation to avert a skewed result (as ρ_g is sensitive to nearby objects).

Some example values for ρ_g are useful at this point. A galaxy with the lowest value of $\rho_g = 0$ has no neighbours within a σ radius. Values up to $\rho_g = 0.1$ we call the 'field environment.' $\rho_g = 1$ roughly corresponds to the centre of a sphere of radius 3 Mpc with ten galaxies randomly distributed within. We call this the lower limit of the 'dense cluster' environment. We call galaxies with $0.1 < \rho_g < 1$ members of 'intermediate environments.'

We plot the distribution of ρ_g for our merger and control populations in Figure 5.3 with the background shading representing our different environments. The samples used are volume-limited (each galaxy must have $M_r < -20.55$) and we exclude 'unsure' type morphologies (the distributions are near identical with them). We calculate a Kolmogorov-Smirnov (K-S) statistic for the two pairs of cumulative-frequency graphs (control-ellipticals vs. E galaxies and control-spirals vs. S galaxies).

We find both merger and control samples are peaked in what we have called 'intermediate-environments.' On average, the E galaxies occupy slightly denser environments than their control counterparts ($\langle\rho_g\rangle_{\mathrm{E}} - \langle\rho_g\rangle_{\mathrm{con.\text{-}ellip.}} \sim 0.12$) with a K-S significance level of $\sim 97\%$. The S galaxies appear almost unaffected and, if anything, occupy slightly denser environments than their control counterparts ($\langle\rho_g\rangle_{\mathrm{S}} - \langle\rho_g\rangle_{\mathrm{con.\text{-}spiral}} \sim 0.02$ with a K-S significance level of $\sim 82\%$). The overall distributions are virtually unaffected if we cut by mass ($> 7 \times 10^{10}\mathrm{M}_{\odot}$) or if we use no mass/magnitude limit. When we combine morphologies, the mergers are, overall, in virtually identical environments as the control sample (Appendix A.3).

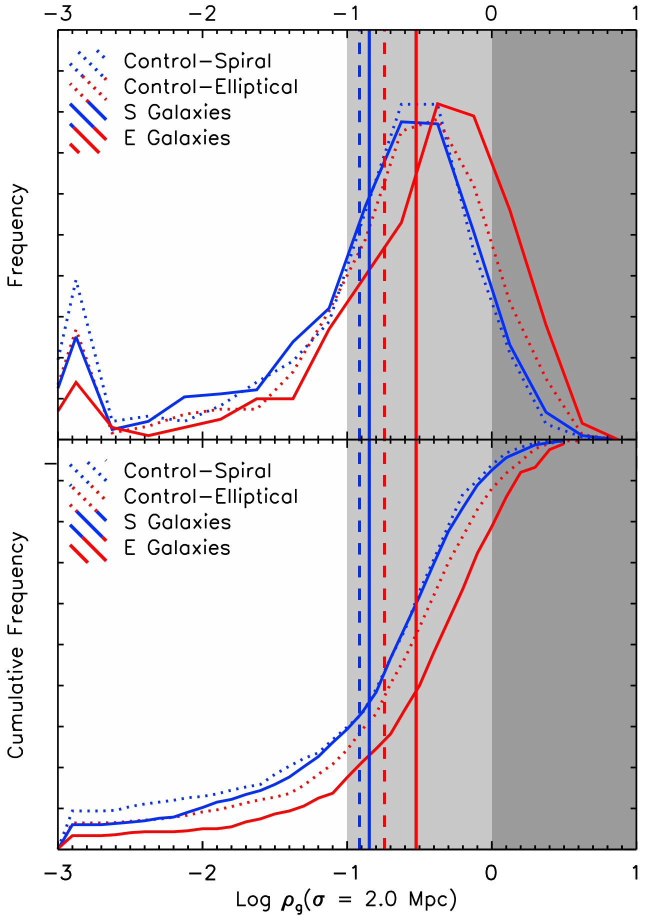


Figure 5.3: Distributions of ρ_g for merger and control populations. The distributions in the upper panel are scaled to have unitary area. We set galaxies with $\rho_g = 0$ to $\rho_g = 10^{-3}$ to avoid Log(0) errors (hence the spike near -3). The vertical lines mark the mean value $\langle\rho_g\rangle$ for the samples. The shading in the background is an indicator of environment type. The darkest shade corresponds to $\rho_g > 1.0$ - the 'cluster environment.' The unshaded-white area corresponds to $\rho_g < 0.1$ which we label the 'field' environment.' The middle shade corresponds to 'intermediate environments.'

As mergers therefore appear to occupy similar if not slightly *denser* environments (environments where ellipticals are more prevalent) we can rule out the role of environment as a means to explain the high spiral-to-elliptical ratio in mergers, as reported in the previous chapter. If anything, the tendency of mergers to occupy denser (elliptical-rich) environments ought to decrease the spiral-to-elliptical ratio in mergers. The discrepancies in the spiral-to-elliptical ratios between the merger and global populations must therefore arise from *longer time-scales of detectability* for mergers involving spirals than for mergers involving ellipticals. Thus the internal properties of galaxies that distinguish spirals from ellipticals must be such that spirals remain detectable in mergers for longer periods of time. We begin an investigation of the internal properties of galaxies by examining their colour-magnitude relations.

5.4 The Colours of Merging Galaxies

For all 3003 merging systems, at least one of the constituent galaxies has spectra. We use this spectral redshift to obtain k-corrected rest-frame magnitudes for both galaxies in each merger pair using the SDSS *ugriz* model mags as inputs into the IDL routine `k`correct 4_1_4 (Blanton & al. et, 2003b).

We examine luminosity and colour in detail for our samples (Figure 5.4) in order to gain an overview of their characteristics and to examine the qualitative effects of including the ‘unsure’ morphologies and imposing the volume-limited constraints.

The upper and lower sets of diagrams display the volume-limited and non-volume-limited samples respectively. The volume-limited sample has both redshift and absolute magnitude bounds ($M_r < -20.55$) whereas the non-volume-limited sample only has redshift bounds. For both of these sets, the colour distributions are plotted for just the ‘sure’ morphologies (E & S - top rows) and then all merger morphologies (E, S, EU & SU - bottom rows).

All samples exhibit some bi-modality though to differing degrees. The volume-limited samples show only marginal bi-modality which is not surprising since the brighter galaxies will be dominated by galaxies in the red sequence (since dimmer galaxies are, on average, bluer). The magnitude cut of $M_r < -20.55$ removes many of the bluer, low-luminosity galaxies. We see this

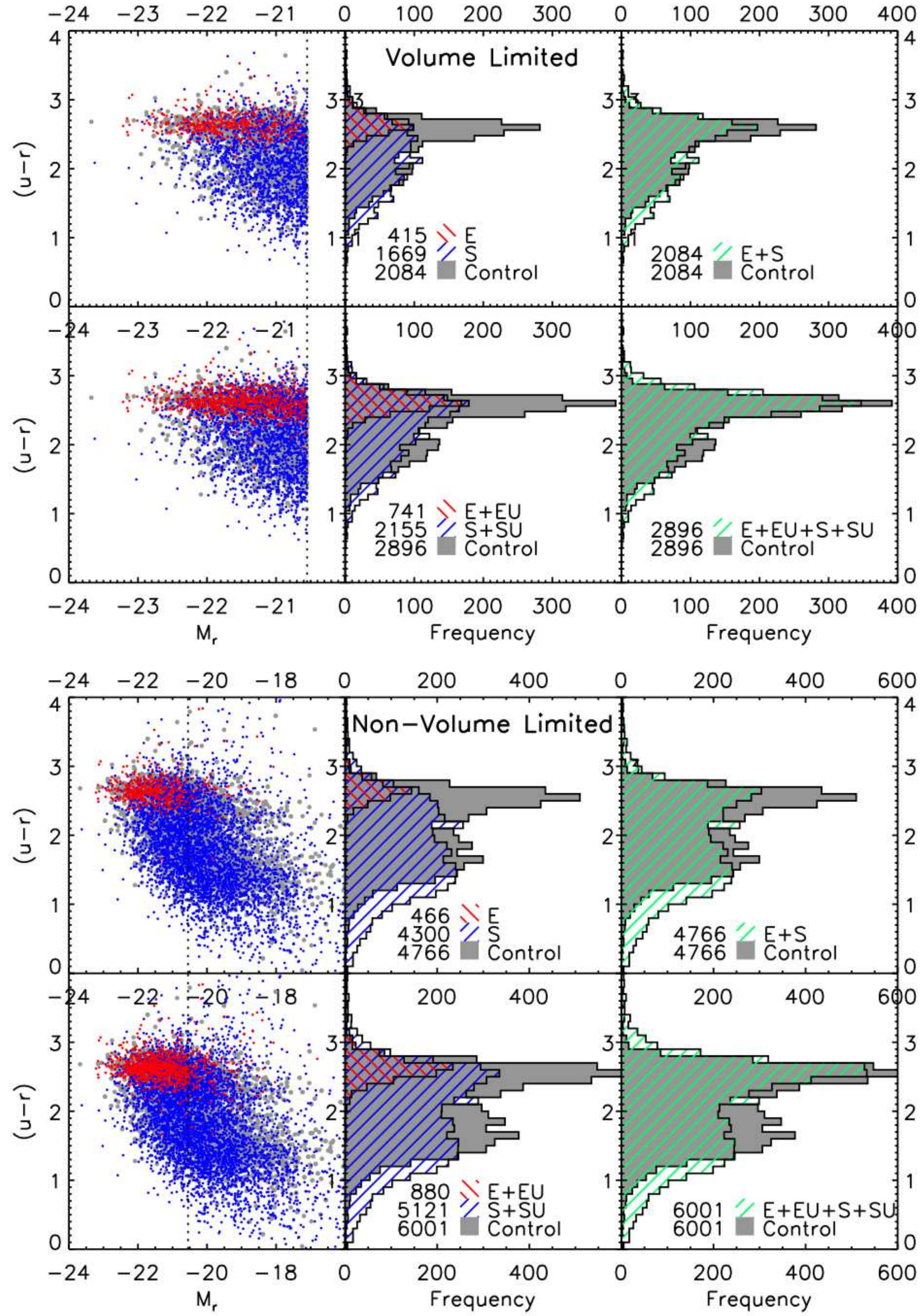


Figure 5.4: Colour-magnitude diagrams for samples of the individual galaxies involved in our mergers (coloured) and our control sample (grey). The k-corrected rest-frame magnitude limit is $M_r < -20.55$ (broken vertical line). The upper and lower sets of figures correspond to the volume-limited and non-volume-limited samples respectively.

in the non-volume-limited diagrams which include many more (relatively-dim) galaxies that are mostly blue spirals. For both the volume-limited and non-volume-limited samples, we find that inclusion of the ‘unsure’ morphologies makes the overall distributions more peaked in the red. Apart from this, the qualitative shapes of the distributions are roughly the same with or without the ‘unsure’ morphologies.

In particular we find that in all cases the mergers appear to have a higher spread in colour at both the red and blue ends compared to the control sample (see right hand columns of both the upper and lower sets of diagrams). This is in accord with early observations that ‘irregular’ morphologies have a greater spread in colour than ‘regular’ ones (Larson & Tinsley, 1978). The effect is especially strong at the blue end and a natural interpretation of this is due to strong star formation induced by the merger process. We examine this possibility using emission-line diagnostics in §5.6.2.

The slight spread at the red end might be due to increased extinction brought about by the journey of light from one galaxy core through the extra dust of the perturbing neighbour (if they lie roughly on the same line of sight). We visually examined all spirals in mergers to ensure those with $u-r > 3.5$ were not red due to an edge-on view. The blue tail is more prominent for the non-volume-limited sample which, as stated, includes more low-luminosity galaxies which are almost all S or SU morphologies. This fits well with the notion that low-mass spirals have formed recently and are rich in gas and will therefore produce high specific-star-formation rates if they undergo mergers. We show in §5.6.2 that low-mass spirals do in fact have the highest star-formation rates relative to their stellar mass.

We also compared the colours of the control morphologies to the merger morphologies. We find that, when we use volume-limited samples, the overall means for $u-r$ are very similar between the control and merger samples. Similarly, the merger-spiral (S+SU) and control-spiral subsets have similar $u-r$ means with $\Delta\langle u-r\rangle \sim 0.05$ magnitudes. However, the merger ellipticals (E+EU) have a slightly redder mean compared to the control ellipticals with $\Delta\langle u-r\rangle \sim 0.15$ magnitudes. It is difficult to disentangle whether this is due to a selection effect based upon how the morphologies were selected or whether ellipticals in mergers are genuinely observed to be

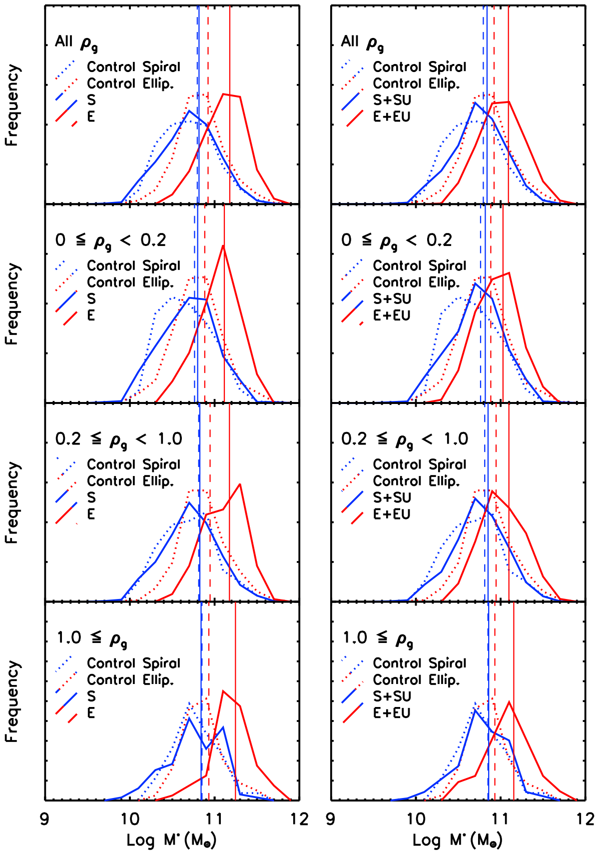


Figure 5.5: Mass distributions of the volume-limited galaxies for differing environments corresponding to (from top to bottom) 'all', 'field', 'intermediate' and 'cluster' environments. All graphs are scaled to have unitary area. The vertical lines indicate the mean masses of the samples. The right-hand panels use all morphologies, the left-hand panels only the 'sure' morphologies.

redder. As noted, the overall merger distributions have a more prominent red tail compared to the control distributions, and so we should not be surprised that the ellipticals in mergers are genuinely redder, only, the degree to which they are redder might be exaggerated by the morphological selection effects (see §5.2.1). This emphasises the fact that comparisons between *morphologies* for the merger and control samples should be taken as a rough guide only.

5.5 The Stellar Masses of Merging Galaxies

5.5.1 Merger Mass Distributions

Figure 5.5 shows the volume-limited mass distributions of galaxies in the merger and control samples. We find that across almost all environments, the spiral-galaxy distributions appear to be virtually the same for both the mergers and the control sample. By contrast, the ellipticals in mergers appear slightly more massive than their control counterparts with a difference in the means of ~ 0.2 dex. This closely parallels the previous conclusion that merger and control spirals occupy similar environments whereas ellipticals in mergers are located in slightly denser environments (which in turn host more massive galaxies on average) than their control counterparts (see §5.3). However, it is important to note that part of this affect could be connected with the different criteria used to distinguish morphologies (the mergers were decided by DWD, whereas the control morphologies are determined directly from GZ; see §5.2.1). The effect holds true even when we restrict the merger sample to 'sure' morphologies (see the left hand column of Figure 5.5) and implies that the control-galaxy morphologies allow slightly bluer systems to be classified as ellipticals.

Again though, like with the environment, we find that when we decline to split the merger and control populations by morphology, we do get very similar mass distributions for the merger and control samples while showing slight favour of merging galaxies being more massive (see Appendix A.3). This should be taken to imply that merging galaxies *are* in fact more massive on average than non-merging galaxies, especially since spirals are over-observed in mergers and, being less massive on average compared to ellipticals, should make the average mass of merging galaxies *less* than that of the global population (all else being equal). The fact that mergers favour spirals (which are generally less massive) *yet* possess an overall distribution just as massive (if not slightly more) than the control sample strongly suggests that galaxies observed in mergers really are more massive. The more tentative conclusion that this is especially true of ellipticals (by ~ 0.2dex) would corroborate the findings of Bundy et al. (2009).[5]

---

[5] Tentative because of the different methods for distinguishing morphologies employed here.

5.5.2 The Mass-Colour-Morphology Relation

Figure 5.6 shows the entire merger-pairs catalogue in mass-colour-morphology space. Both colour and morphology scale strongly and smoothly with mass: spiral-spiral mergers dominate the lower-mass end, elliptical-elliptical mergers the upper-mass end and elliptical-spiral mergers roughly in between. A sharp transition mass for galaxy properties within SDSS was noted by Kauffmann et al. (2003a) at $3\times10^{10}\mathrm{M}_{\odot}$ above which galaxies have "high surface mass densities, high concentration indices typical of bulges and predominantly old stellar populations" and below which galaxies have generally opposite characteristics. We find that below this value, ellipticals are extremely rare and above it, spirals are both reddening and diminishing in number in mergers.

The near absence of ellipticals with masses below $3\times10^{10}\mathrm{M}_{\odot}$ raises the question as to what becomes of the numerous low-mass spiral-spiral mergers we observe. Kauffmann et al. (2003a) noted this special mass with respect to galaxy properties but said little about the mechanism that drives the transition beyond suggesting relations between star formation, feedback mechanisms and halo mass. We hypothesise that this mass could represent a *merger* transition related to spiral-spiral survival in major mergers: below this stellar mass, spirals tend to survive mergers, above it they are likely to form an elliptical remnant. Why might this be so?

The relatively high gas content in low-mass spirals could be the key. The simulations studied in Hopkins et al. (2009) emphasise the role of the progenitor gas-to-stellar-mass ratio as well as feedback mechanisms that serve to retain gas at large radii during the merger process. These outer gas supplies retain angular momentum and aid the reformation of a disc in the post-merger remnant. The transition mass at $3\times10^{10}\mathrm{M}_{\odot}$ could therefore correspond to some critical gas-to-stellar-mass ratio for disc galaxies.

On this hypothesis then, galaxies with stellar mass $< 3\times10^{10}\mathrm{M}_{\odot}$ generally have sufficient gas content to bring about disc reformation after a (major-) merger. As spirals increase in stellar mass (at the general expense of gas supply) they become increasingly prone to catastrophic angular-momentum loss with respect to disc maintenance in the event of a merger. Their remaining gas supplies then plunge into the central core and transfer the angular momentum required for disc morphology into the stellar dispersion of the remnant bulge (Kewley et al. 2006a). The exhaustion

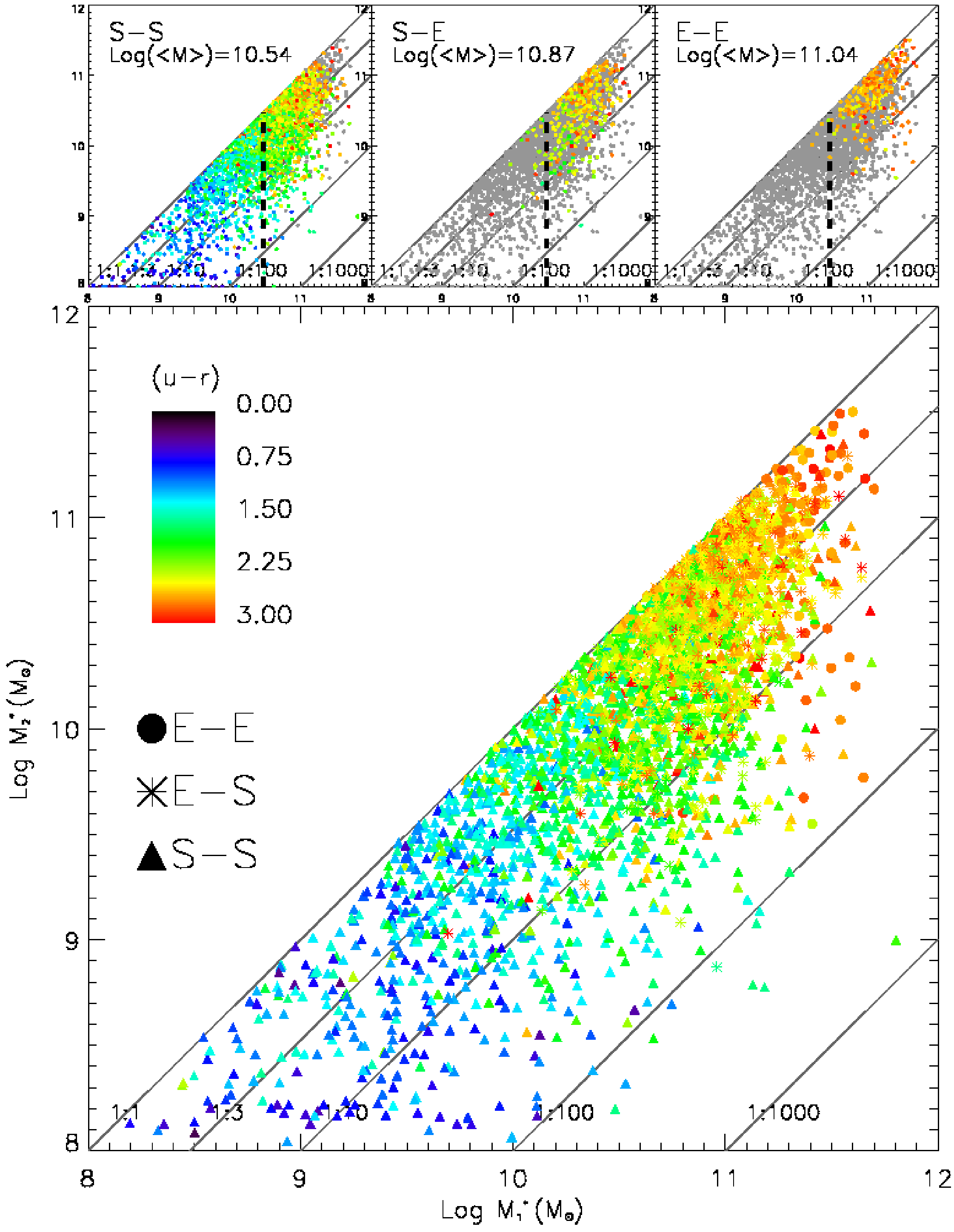


Figure 5.6: Mass-Colour-Morphology diagram. Each of the 3003 points represents a merger pair with the more massive galaxy mass plotted on the x-axis and its partner's mass along the y-axis. The colour of each point is the *mean* $(u-r)$ of the two galaxies. The width of the symbols is the same as the mean-mass error for the entire sample. The symbol represents the morphologies of the galaxies (for S-E we do not distinguish which type is the more massive). We do not impose the magnitude limit on the sample (which would exclude most points for $< 10^{10}\mathrm{M}_\odot$) in order to maximise the range of view of the mass-colour-morphology relation. The upper panels individually show the morphological categories over the total merger population (coloured grey). The broken

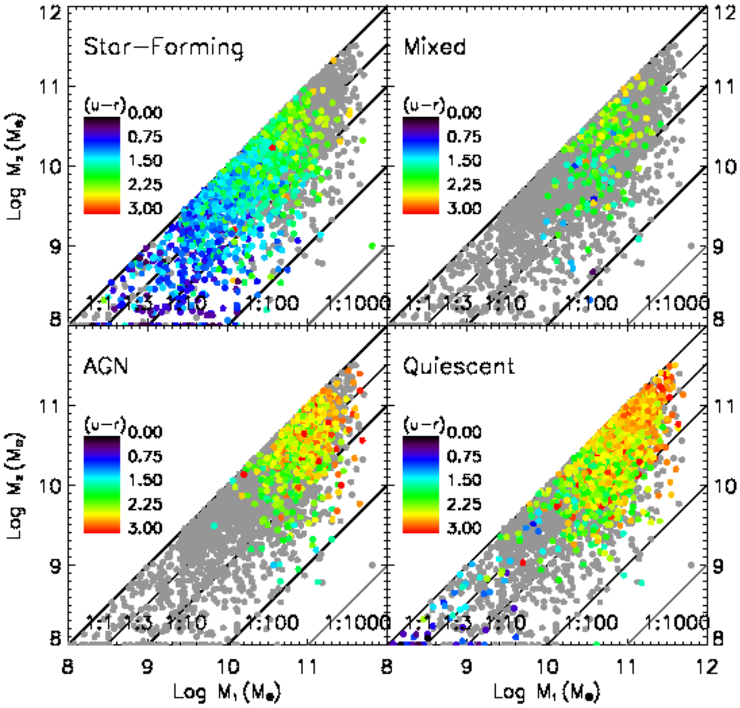


Figure 5.7: Spectral Type-Colour-Mass relations. The mass and colour are plotted the same as in figure 5.6 for all 3003 systems. The panels show the population split into its various spectral types: Quiescent, Star-Forming or AGN. No magnitude limitation is imposed for an enhanced view of mass build-up in relation to these properties.

of gas not only limits the system's capacity to retain angular momentum at high radii but also leaves little for passive star formation in the remnant. The resultant bulge-dominated galaxy is thereby destined towards an increasingly red and elliptical galaxy-type (barring further gas accumulation through accretion and gas-rich mergers).

Since feedback mechanisms are important to gas retention in this model we next examine the AGN and star-formation signatures of our mergers.

5.6 AGN, Star-Forming and Quiescent Signatures in Galaxy Mergers

5.6.1 Ionisation Processes in Mergers

We perform emission-line diagnostics in order to determine the major sources of ionisation in both the merging and control galaxies. To do this we made use of the publicly available direct fitting tools `PPXF` and `GANDALF` (from Cappellari & Emsellem 2004 and Sarzi et al. 2006, respectively) to separate the contribution of the stellar continuum and of the ionised-gas emission to the SDSS spectra, as in Schawinski et al. (2007a).

We then used the measured fluxes for the nebular emission lines of our samples to determine the most likely source of ionisation by juxtaposing a number of emission-line ratios as first suggested by Baldwin et al. (1981). Specifically, we used the reddening-insensitive diagnostic diagrams introduced by Veilleux & Osterbrock (1987), which uses the four optical line ratios [OIII]/Hβ, [NII]/Hα, [SII]/Hα, and [OI]/Hα to separate (i) Star-forming regions, (ii) Seyfert nuclei, (iii) Low-Ionisation Nuclear Emitting regions (LINERs) and (iv) the so-called Mixed/Transition objects, which display the spectral signatures of both HII regions and AGNs. We assigned these classes to all galaxies with S/N>3 in at least all the Hα, Hβ, [OIII] and [NII] lines, and further deemed as (v) Quiescent all those galaxies for which such a criterion was not met. In other words a quiescent object is defined as having *at least* one weak emission line and so an alternative label is the ‘weak emission-line’ category. To separate the different kinds of central activity in our merger galaxies we followed the demarcations between purely star-forming systems, transition objects and truly active nuclei drawn by Kauffmann et al. (2003b) and Kewley et al. (2006b). We combine AGN types into a single category for this presentation.

Thus, to each spectral object we assign one of the following classifications:

1. Star-Forming
2. Mixed (both star-formation and AGN activity)
3. AGN (either Seyfert or LINER)
4. Quiescent

We refer to these possibilities as the galaxy’s (ionisation-) ‘type.’ We obtain classifications for 1371 individual galaxies in our volume-limited merger sample. Figure 5.7 illustrates the location of these ionisation types in the same mass-colour space used in Figure 5.6 with no magnitude limitation (a proper volume-limited sample would see decreased numbers of points in the

Table 5.1: Percentages of ionisation types for volume-limited merger and control galaxies. Numbers given are rounded to nearest integer. The 'All AGN' row is the sum of the Mixed and AGN percentages. The 'All SF' row is the sum of the Mixed and Star-Forming percentages. We include the sample sizes plus Poisson-Counting errors rounded up to the nearest percent.

Type	S+E Galaxies	Control		S	E		Con.-Spirals	Con.-Ellipticals
Star-Forming	45±2	14±1		51±2	0±1		25±2	6 ±1
Mixed	7 ±1	4 ±1		8 ±1	0±1		6 ±1	2 ±1
AGN	16 ±1	20±1		15 ±1	18±3		23±2	20±2
Quiescent	32±2	62±2		26±1	81±7		46±3	73±3
All SF	52±2	18±1		59±2	0±1		31±2	8 ±1
All AGN	23±1	24±1		23±1	18±3		29±2	20±2
Galaxies in Sample	1371	1200		1219	152		600	600

$M \lesssim 10^{10} M_{\odot}$ regions). Comparing Figures 5.7 and 5.6, we see that the star-forming types occupy the smaller-mass regions which are dominated by spirals and the quiescent types occupy the higher-mass regions, which are dominated by ellipticals. The AGN categories seem to occupy the intermediate-mass regions.

The lack of star formation and AGN activity in high-mass galaxies suggests that their fuel supply has been exhausted whereas the lack of AGN activity in low-mass gas-rich galaxies suggests that either AGN do not form there (perhaps because they have insufficiently massive black-holes at their centres to generate substantial ionisation) *or* that their AGN signatures are obscured by the high gas content and star-formation rates (SFRs) (obscuration of ionisation signatures is a perennial problem of BPT-style classifications; Baldwin et al. 1981; Bamford et al. 2008).

The sample fractions with Poisson counting errors for these various ionisation types are shown in Table 5.1. We exclude 'unsure' morphologies (EU, SU). When EU and SU morphologies are included, the percentage of star-forming types decreases by $\sim 10\%$ with the quiescent and AGN categories increasing by $\sim 5\%$. This effect is to be expected since the 'unsure' morphologies include a higher proportion of ellipticals which, as the table shows, have fewer star-forming types but more AGN and quiescent. The control sample here consists of 1200 randomly selected volume-limited objects. We also looked at the percentages of the first 600 control galaxies that are deemed to be spirals according to the criteria given in §5.2.1 and likewise for the first 600 control-ellipticals.

Examining Table 5.1, we find that the fraction of AGN in mergers appears no different from the control sample ($\sim 23 \pm 1\%$ compared to $\sim 24 \pm 1\%$) for the total populations. However, splitting the merger and control samples into separate morphologies suggests that the fraction of AGN in merging *spirals* is slightly less than in their control counterparts ($\sim 23 \pm 1\%$ compared to $\sim 29 \pm 2\%$). As mentioned though, AGN signatures might be obscured by high star-formation rates (SFRs) and disrupted gas content in merging galaxies. These star-formation rates are seen to be extremely high for merging spirals ($59 \pm 2\%$) compared to control spirals ($31 \pm 2\%$). When we further split the merger populations into the three visually-allotted merger 'stages' ('separated', 'interacting' and 'approaching post-merger' see §5.2.2), we find that the percentage of star-forming spiral galaxies in mergers for these stages are $59 \pm 8\%$, $50 \pm 2\%$ and $43 \pm 7\%$ respectively. The descending percentages suggest that star-formation takes place early-on in the merger process. When we examine the fractions of AGN types in spirals for these stages we obtain $21 \pm 5\%$, $23 \pm 2\%$ and $32 \pm 6\%$ which shows slight signs of ascending AGN activity within merging spirals as they approach the post-merger stage. Alternatively, this could suggest that where SFRs are less intense, AGN signatures become easier to detect or even that we are seeing the effects of AGN feedback quenching SF.

The sample of ellipticals in mergers, by contrast, resembles that of the control ellipticals when split into ionisation types except that *none* of them are star-forming types. Both merging and control ellipticals are dominated by quiescent types ($81 \pm 7\%$ and $73 \pm 3\%$) and have the same fraction of AGN ($18 \pm 3\%$ and $20 \pm 2\%$). In short, the internal properties of ellipticals appear basically unaffected by the merger process and thus live up to the 'red-and-dead' stereotype, dominating the quiescent category.

Our results are in broad agreement with previous studies. Induced star formation in interacting galaxies was first quantified by Keel et al. (1985) and Kennicutt et al. (1987). They claimed, however, that both star formation and nuclear activity is enhanced in close-pairs. Similar studies since then have strongly confirmed that mergers induce star formation (see §5.1; Hopkins et al. 2003), though the idea that AGN are significantly induced by mergers remains tentative (Ellison et al. 2008).

Our study so far strongly confirms that mergers significantly enhance SFRs but *only* in spirals

- there appears to be no effect at all upon our visually-inspected ‘sure’ ellipticals. Our work also lends very little support to the notion that AGN activity is enhanced by the merger process, the one exception perhaps being in late-stage spirals.

5.6.2 Star-Forming Rates in Merging Galaxies

Having found the fraction of galaxies classified as ‘star-forming,’ we now wish to quantify the *rates* at which their star formation occurs. We use the integrated spectral flux of the extinction-corrected Hα lines derived by our ionisation-types assessment to obtain an absolute rest-frame flux. We scale the flux measured in the 3$''$-diameter SDSS fibre aperture to give an estimate of the total flux, using the ratio of Petrosian and 3$''$ aperture fluxes in the *r*-band photometry. We then apply the model Hα-SFR relation derived by Kennicutt (1998), Eq. 3:

$$SFR_{\mathrm{H}\alpha}\,[\mathrm{M}_{\odot} yrs^{-1}] = 7.94 \times 10^{-42} L_{\mathrm{H}\alpha}\,[\mathrm{ergs/s}]$$

to obtain estimates for the SFRs of our merging and control galaxies. We find that our (volume-limited) sample of star-forming merger galaxies has a mean SFR$_{\mathrm{H}\alpha}$ of $\sim 5.2\mathrm{M}_{\odot} yr^{-1}$. The equivalent control sample has $\sim 2.6\mathrm{M}_{\odot} yr^{-1}$, i.e. the merger process enhances our SFRs by a factor ~ 2. The highest SFR for any of our star-forming merging galaxies is $\sim 95\mathrm{M}_{\odot} yr^{-1}$.

However, our sample involves a range in masses over $3-4$ orders of magnitude and so it is not entirely appropriate to compare SFRs across such a range (one would expect larger galaxies to have a greater absolute SFR) and so we quantify the *relative* size of the SFR for each galaxy by defining the *specific*-SFR, κ, as the log of the SFR$_{\mathrm{H}\alpha}$ per stellar mass unit:

$$\kappa = \log \left[\frac{(\frac{\mathrm{dM}}{\mathrm{dt}})_{star\,formation}}{\mathrm{M}^{*}} \right] \mathrm{yr}^{-1}. \tag{5.1}$$

The upper panel of Figure 5.8 plots the value of κ against the stellar mass for each galaxy of the star-forming type. There is a negative correlation between these two quantities such that the more massive a star-forming galaxy is, the smaller its SFR$_{\mathrm{H}\alpha}$ per stellar mass (similar to the findings of Brinchmann et al. 2004 Figure 13). The star-forming control sample has a mean κ of ~ 0.25

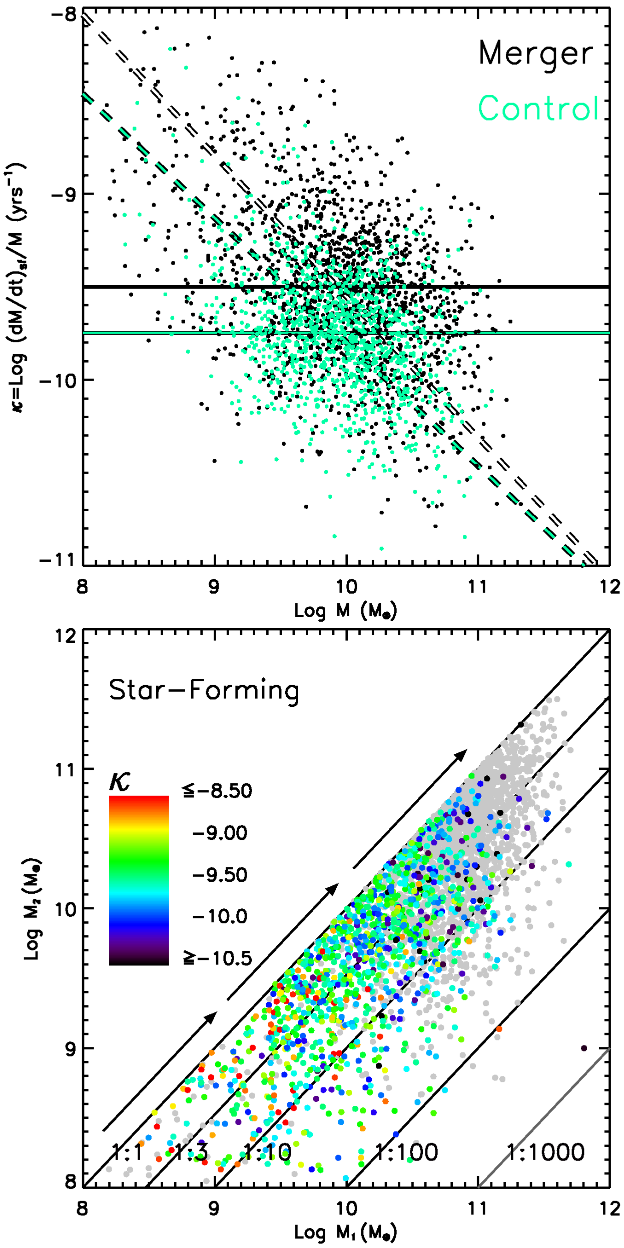


Figure 5.8: The specific-star-formation rate (κ) compared to stellar mass. The upper panel shows the relationship between stellar mass and specific-star-formation (κ) for the 1588 star-forming galaxies in mergers in our catalogue and the same number of star-forming systems taken from the control sample. The broken lines are linear best-fits to the samples. The solid horizontal lines show $< \kappa >$ for the two populations. The lower panel shows κ-mass space for the star-forming merger systems (any system with at least one galaxy of the star-forming type) where the colour scale represents κ of the galaxy which is star-forming. Neither sample is volume-limited for an enhanced general overview of κ across our stellar-mass range. The arrows indicate the gas-depletion evolution advocated in this study.

less than the star-forming mergers. The control's $\kappa - \mathrm{M}^*$ gradient is also shallower indicating that as the size of the galaxy increases, the relative star formation enhancement induced by the merger diminishes. This is not surprising since gas supply in galaxies should generally scale down with stellar mass (Noeske et al. 2007). Taking κ as a proxy for gas content (reminiscent to the Schmidt law Schmidt (1959)), we can interpret this relation to mean that the larger the star-forming galaxy becomes (with respect to stellar mass) so their merging becomes 'drier.' By the time the gas is completely exhausted, there simply is no fuel available for SF, even in a merger.

These observations therefore lend well to the hypothesis that a critical gas-to-stellar-mass ratio exists for spirals which could correspond to galaxies with the $3 \times 10^{10}\mathrm{M}_{\odot}$ mass of Kauffmann et al. (2003a). By taking κ as a proxy for relative gas abundance, one can envisage a smoothly decreasing gas supply with increasing stellar mass in the lower panel of Figure 5.8. The number of star-forming spirals then begins to diminish for those of mass beyond $3 \times 10^{10}\mathrm{M}_{\odot}$ which is roughly where elliptical galaxies begin to take over (Figure 5.6). The suggestion is that spirals with gas supply corresponding to $\kappa \lesssim 10^{-10}$ will most likely result in an elliptical remnant should they undergo a major merger, the likelihood of this result scaling up with decreasing κ.

5.7 Summary and Discussion

In the previous chapter, we found that the spiral-to-elliptical ratio in mergers (N_s/N_e) was high by a factor of at least 2 in our sample compared to the global population. The first aim of this chapter was to discern the likely cause for this discrepancy suggesting that it is either the result of an environmental preference for mergers to take place where spirals are relatively abundant *or* that the time-scales of detectability for spiral-mergers are longer than those for elliptical-mergers.

To test the role of environment we used the adaptive-Gaussian-environment parameter ρ_σ to create distributions for our samples. By comparison to the randomly selected control sample of SDSS galaxies with spectra, we found that mergers occupy similar if not *denser* environments than the control sample. This, if anything, would not favour the presence of spirals in mergers but ellipticals since it is known that denser environments are favourable to elliptical galaxies (Dressler 1980).

We concluded therefore that the high number of spirals in mergers is unlikely to be an environmental effect. On the other hand, the suggested alternative (that the time scales for a merger to reach a relaxed state vary depending on the internal properties of the galaxies) seems intrinsically plausible and has been corroborated by other studies (Bell et al. 2006; Lotz et al. 2008a; Lotz et al. 2008b). Spiral galaxies are typified by relatively large gas reservoirs, a more uniform distribution of matter along their radius and lower total mass in comparison to ellipticals. One would expect therefore that, when two ellipticals merge, they tend to produce comparatively faint tidal tails and little star formation, making their detection a more difficult observational task. The role of mass remains unclear though. The simulations of Lotz et al. (2008b) suggested that mass made little difference to these time-scales but our results suggested that very massive ellipticals in mergers were more likely to merge (§5.5.1).

This slight excess in mass is complimentary to a slight excess in environmental density. Suppose that the probability of a galaxy merging at some general time, p_m, is only a function of galaxy mass and environment, $p_m = p_m(\mathrm{M}^*, \rho)$.[6] For any given environment, ρ, a more massive galaxy exerts a stronger pull on its neighbours and so, all else being equal, a more massive galaxy should be more likely to merge.[7]

More massive galaxies are also more likely to occupy denser environments (given the morphology-environment relationship, e.g. Dressler (1980) and the mass-morphology relationship, e.g. Kauffmann et al. (2003a)) so that two galaxies of mass M_1^* and M_2^* where $\mathrm{M}_1^* > \mathrm{M}_2^*$ which have the same probability of merging, $p_1(\mathrm{M}_1^*, \rho_1) = p_2(\mathrm{M}_2^*, \rho_2)$ must occupy different environments and, since mass generally scales with environment, we must have $\rho_1 > \rho_2$. In other words, *both* the mass *and* environment distributions of galaxies in mergers should appear rightward-shifted compared to the global population as we see in Figures 5.3 and 5.5.

Since environmental factors do not provide an explanation for the high N_s/N_e observed in

---

[6] This takes into account the number density and peculiar velocities of surrounding galaxies since these are both functions (or definitions) of environmental measure.

[7] Moreover, for any environment taken as a closed system orbiting a common centre of mass where it can be assumed that it's constituent bodies are in equilibrium (having the same kinetic energy), a more massive body will have a smaller peculiar velocity with respect to the system's centre of mass making it more conducive to gravitational binding with some other orbiting body.

mergers, we conclude that mergers involving spiral galaxies remain detectable for longer periods. Whereas the study by Lotz et al. (2008b) provided theoretical evidence that this is in fact the case, this study provides empirical evidence that these time-scales of detectability do indeed vary. This should be taken into consideration by those that aim to convert an observed merger fraction to an absolute merger rate for implementation in hierarchical models.

Mergers with spirals must remain detectable for longer due to their internal properties and so we turned to investigate them, beginning with the photometric properties of mergers. We showed that the colours of merging galaxies scale strongly with mass and morphology and are more spread compared to ordinary galaxies (§5.5). In particular, mergers exhibit a strong blue tail which we concluded is due to intense star formation induced by the merger process.

Below the stellar transition mass $\sim 3 \times 10^{10} M_{\odot}$ noted by Kauffmann et al. (2003a) we found that ellipticals were rare in both the merger and the control samples though spirals were fairly common in both. What then becomes of the numerous low-mass spiral-spiral mergers? It was posited in §5.1 that at least some spiral-spiral mergers survive major mergers and this lead to the hypothesise that the transition mass of $\sim 3 \times 10^{10} M_{\odot}$ corresponds to a transition between general-disc survival and general-disc destruction in mergers.

Such a transition would be closely linked with gas dynamics in mergers. Simulations studying disc survival have placed great emphasis on the interactions between gas and stars in mergers suggesting that galaxies with high gas-to-stellar-mass ratios and reservoirs at high radii are highly capable of rapid disc-reformation after dynamical relaxation (Hopkins et al. 2009). As spiral galaxies evolve they expend gas in their disc via passive star formation and merger-induced drainage leading to an increasingly lower gas-to-stellar-mass ratio. Since the gas content in spirals generally scales down with stellar mass, there must be some average gas-to-stellar-mass ratio for spirals at $3 \times 10^{10} M_{\odot}$ and this, we hypothesise, marks a critical point beyond which spirals are unlikely to survive major mergers.

While the gas-to-stellar-mass ratio is important, it cannot be the sole determinant of disc survival. For example the distribution of gas is also an important factor meaning that feedback mechanisms that retain gas at high radii are indirectly involved in disc survival/destruction in mergers.

This prompted AGN-SFR analysis using the spectral-line widths available to our catalogue.

We found that mergers induce intense star formation but *only* in mergers involving spirals (see Table 5.1) - ellipticals are hardly affected and dominate the quiescent category. This fits with the ‘red-and-dead’ stereotype for giant ellipticals and suggests that mergers can account well for the spread towards the high-mass end of galaxies in the red-colour sequence (i.e. giant elliptical-elliptical mergers increase the luminosity of the progenitor, but negligibly affect its colour and internal properties).

By contrast, we found little overall evidence for increased AGN activity in mergers in broad agreement with several recent studies (Barton et al. 2000; Alonso et al. 2007; Li et al. 2008) though contrary to early reports such as Kennicutt et al. (1987) and, more recently, Geller & Woods (2007), Schawinski et al. (2009b). The recent study by Ellison et al. (2008) also found little evidence for increased AGN activity in their close-pairs sample and concluded that, if AGN are induced by mergers, then they must occur at stages later than close-pairs typically examine. In Figure 4.12 we did show in fact that our merger-location technique picks up mergers in later stages compared to the close-pairs technique. Furthermore, when we divided our mergers into their visually assigned stages, there appeared to be a slight increase in the proportion of merging galaxies in the ‘approaching post-merger’ stage ($32 \pm 6\%$ with mean projected core-separation $\sim$ 5kpc) in comparison to mergers at earlier stages ($23 \pm 2\%$ with mean projected core-separation $\sim$ 13kpc). Caution is urged here though since the counting errors are large and there may be obscuration affects associated with strong star formation signatures.

We found that the specific-SFRs (defined in Eq. (5.1), §5.6.2) are higher in star-forming mergers, on average, than in the star-forming control galaxies by ~ 2. For the star-forming galaxies in mergers we find that the specific-star-formation rate scales down with stellar mass. We interpreted this to mean that gas supply is being continually drained as galaxies accumulate stellar-mass. This is consistent with the hypothesis that a critical gas-to-stellar-mass ratio emerges near $3 \times 10^{10} \mathrm{M}_{\odot}$ for disc survival/destruction.

The results of this study generally imply that, where mergers do happen, their effects are powerful on spirals (eroding their gas and angular momentum supplies and strongly enhancing their SFRs) but much weaker on ellipticals. This in turn affects the time-scales of detectability for mergers which should be taken into account by studies aiming to convert merger fractions into merger rates.

Many interesting clues about galaxy evolution can be gleaned from our data and future projects such as Galaxy Zoo Two applied to SDSS and higher redshift surveys promise exciting results.

Chapter 6

Multi mergers and the Millennium Simulation

6.1 Introduction

As we have seen, the exact extent to which mergers are able to account for the observed properties and morphologies of galaxies in the Universe preoccupies much of modern research. If mergers are not sufficient to explain all observations pertaining to mass-assembly, then other modes of galaxy formation must be conjoined to the standard hierarchical scheme. If, however, mergers alone (implemented via a model of structure formation such as ΛCDM) are enough to explain what we observe in galaxies, then such additional processes can (and therefore should) be discarded. In either case, mergers are known to occur at significant rates (Conselice et al. 2008; Lotz et al. 2008a; Patton & Atfield 2008; Bertone & Conselice 2009; Stewart et al. 2009a; Robaina et al. 2010; Kaviraj et al. 2011) and are an indispensable explanatory resource with respect to galaxy evolution.

Here we examine the interesting subset of the 3003 merger pairs: 39 systems with three or more galaxies merging simultaneously, i.e. small interacting clusters (shown in Figure 6.1), and use it to estimate, for the first time, the (major) multi-merger fraction of galaxies in the local Universe. This fraction and the examined properties of these multi-merging galaxies thus provide a useful *independent* test of SAMs from the typical observables that such models are tuned to reproduce. As one of our stated interests was to eventually employ SAMs to explore the anthropic landscape about p_i' (Chapter 3.1), it is important to test SAMs, where possible, to see if they are accurate with respect to observations that were not explicitly built into their construction. We also compare the fractions and properties of the binary mergers to those of the Millennium SAMs.

As already discussed, in the ΛCDM cosmology galactic mergers are primarily driven by the coalescence of Dark Matter (DM) structures (see e.g. White & Frenk 1991; Bond et al. 1991; Rees & White 1978; Lacey & Cole 1993; Jenkins et al. 2001; Springel et al. 2005; Stewart et al. 2009b). Once DM haloes have become virialized, further growth can only occur through accretion and merging (Fakhouri & Ma 2008; Neistein & Dekel 2008; Fakhouri et al. 2010). The merger histories of DM halos can be reproduced through N-body simulations (Springel et al. 2005; De Lucia et al. 2004b; Harker et al. 2006)[1] or through analytic approximations such as Press-Schechter (Press & Schechter 1974) and its extensions (Bond et al. 1991; Bower 1991; Somerville et al. 2000).

To empirically test the accuracy of DM structure formation, semi-analytic recipes for the evolution of the visible matter within these haloes are required. These aim to capture the macro-physical processes affecting observable quantities such as the galaxy Luminosity Function (Benson et al. 2003). Each physical process typically involves one or two free parameters and so semi-analytic models (SAMs) require fine-tuning to reproduce empirical observations. The major considerations are photoionisation (Benson et al. 2002), shock heating of gas (Cattaneo et al. 2006a), gas cooling (De Lucia et al. 2010), AGN feedback (Bower et al. 2006; Croton et al. 2006), supernovae feedback (also enriching the IGM with metal; De Lucia et al. 2004a) and mergers (Springel et al. 2001). The resultant 'galaxies' that occupy the DM haloes can then be converted to observable luminosities through synthetic stellar-population models (e.g. Bruzual & Charlot 2003; Maraston 1998; Maraston 2005).

Given enough adjustment of the free-parameter values and phenomenological ingredients to represent time-dependent feedback effects, any one quantity such as the empirically determined

---

[1] While the N-body simulations are more or less 'exact' the scheme for grouping DM-particles into halos and subhalos is arbitrary to a certain extent, in other words, the merger history depends on the detailed definition of a halo.

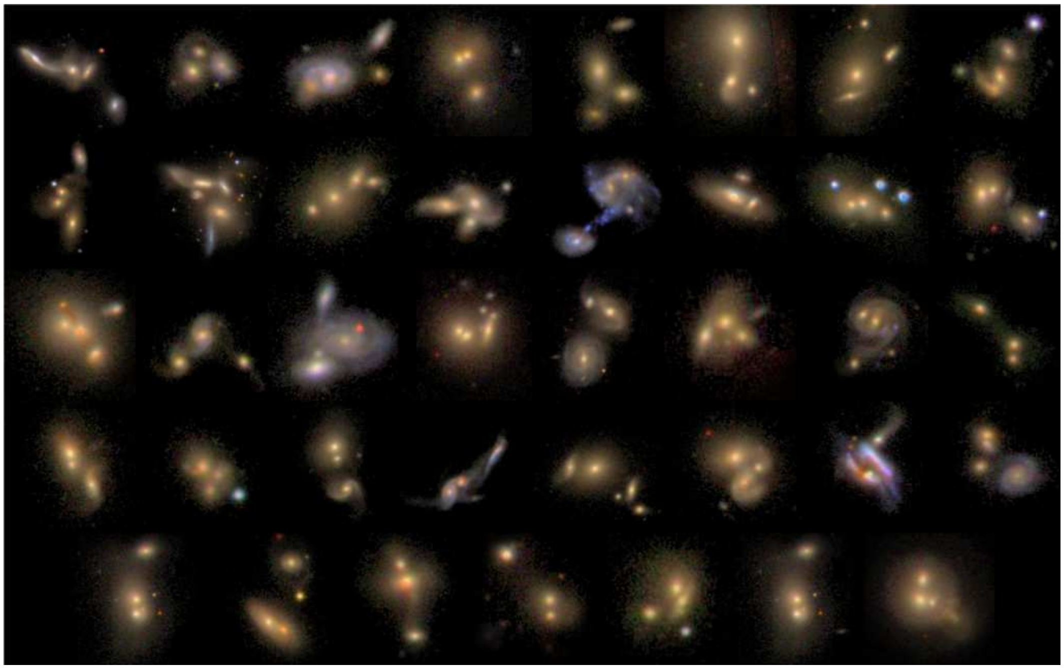


Figure 6.1: Images of the 39 multi-merger systems obtained from GZM1. Each tile has been scaled for optimal viewing, typically with sides of $\sim 50''$.

Luminosity Function (Cole et al. 2001; Norberg et al. 2002; Huang et al. 2003; Panter et al. 2004; Jones et al. 2006; Devereux et al. 2009) can be approximated arbitrarily well in principle. A major test of a model's veracity therefore rests in its capacity to reproduce observables that were *not* involved in its original calibration. One such test is to determine how well a SAM agrees with observed merger rates (or fractions). Several studies have compared the evolution of the galaxy merger rate obtained by the close-pairs technique (see §6.2.1 for description) to that of SAMs implemented in the Millennium Run (Kitzbichler & White 2008; Patton & Atfield 2008; Mateus 2008; Hopkins et al. 2010b). Bertone & Conselice (2009) more recently compared the SAM of Bertone et al. (2007) to the merger rate obtained by the CAS (concentration, asymmetry and clumpiness; Conselice 2003a; Conselice et al. 2003) method and found the two were roughly consistent for $z \lesssim 2$.

In this chapter, we introduce a new test for galaxy-evolution models that has, until now, been too difficult to find observationally: the fraction and properties of galaxies in (near simultaneous) multi-mergers (mergers of three or more galaxies of similar mass). Several individual multi-merger systems have been studied (Cui et al. 2001; Amram et al. 2007; Rines et al. 2007) and a few numerical simulations of multi-mergers carried out (Weil & Hernquist 1996; Bekki 2001; Renaud et al. 2010) but no practical method has been obtained till now that might locate multi-mergers in a near complete manner.

In §6.2 we describe how we constructed the catalogue in order to estimate the multi-merger fraction. We then compare the binary and multi-merger fractions obtained by the Galaxy Zoo project with those of the SAMs of the Millennium Run. They fall broadly into two families of models: those developed by MPA Garching in Munich (Croton et al. 2006; De Lucia et al. 2006a; Bertone et al. 2007) and those of Durham (Cole et al. 2000; Benson et al. 2002; Benson et al. 2003; Baugh et al. 2005; Bower et al. 2006; Font et al. 2008). Several implementations have been developed by both groups and we use those which are publicly available.[2] For the MPA, these are the models of De Lucia et al. 2006a, De Lucia & Blaizot 2007 (hereafter DeLucia06) and Bertone et al. 2007 (hereafter Bertone07, an extension of DeLucia06) and for Durham, the model of Bower et al. 2006 (hereafter Bower06). We describe some of their characteristics in §6.3.

By comparing the SAM merger fractions to SDSS observations made herein (§6.4), we effectively test the accuracy of the build up of clumpiness in the Universe since the main factor affecting merger rates is environment. Other properties correlate with environment such as stellar mass, colour and morphology and so we examine these in both the SAMs and Galaxy Zoo catalogues for multi-mergers, binary-mergers and single galaxy systems (§6.5). We summarise our results in §6.6.

6.2 The Multi-Merger Catalogue

6.2.1 Finding Multi-Mergers

As discussed in §4, finding mergers amongst surveys with $\sim 10^6$ galaxies is highly non-trivial. Non-parametric techniques such as CAS and GM_{20} (Gini coefficient and the second-order moment of the brightest 20% of the galaxy's light; Abraham et al. 2003; Lotz et al. 2004; Lotz et al.

---

[2] See http://www.mpa-garching.mpg.de/millennium/

2008a) that aim to identify parameter spaces uniquely occupied by mergers have thus far proved challenging and the prospect of finding even more specific sub-spaces limited solely to *multi*-mergers is unrealistic (Lisker 2008).

Likewise, modifying the close-pairs technique (locating galaxy pairs within a certain angular separation and redshift difference) to find multi-mergers within SDSS is impractical due to fibre overlaps. The apparatus within SDSS will not acquire spectra (which are needed in such ‘blind’ methods to avoid projection effects) from objects within $55''$ of each other on a single viewing. The conventional close-pairs technique is therefore only useful within tile-overlap regions. In order to find systems with *three* or more galaxies in the merger stage which are within $55''$ of each other, the system would have to rest in a part of the sky where there is a *double* tile-overlap.

We investigated the practicality of using a modified close-pairs technique to find multi-mergers using a close-pairs catalogue restricted to $0.005 < z < 0.1$ that associates spectral galaxy objects with a redshift tolerance of 0.0017 (corresponding to a velocity difference of 500 kms^{-1} as used in Patton et al. 2002) and projected separation of 30 kpc. We found that of the 4880 spectral objects in this catalogue, only 48 systems (148 objects) had three or more spectral objects. Only one of these 48 systems belonged to our catalogue indicating how incomplete this technique is for finding multi-mergers. Even when three spectral objects do fall within these limits, the close-pairs technique would not distinguish multi-mergers from normal binary-mergers that have been deblended with multiple spectral objects. Figure 4.3 shows examples of this problem - the upper images both have three spectral objects, but the left image is clearly a binary-merger (with two spectral objects on one galaxy) and the right image is a triple-merger. Likewise, without visual inspection, it would be almost impossible to know if the lower image of Figure 4.3, which has four spectral objects, contained two, three or four galaxies interacting with each other.

The only way to find multi-merging systems is therefore through visual inspection since humans can readily distinguish between features like bulges and tidal tails and can often, on this basis, tell straight away if a system is a multi-merger. The disadvantage with visual identification by individuals is that, firstly, it is time consuming in general and wholly impractical for surveys with $\sim 10^6$ galaxies and, secondly, it is subjective. Since, however, we were forced to re-examine

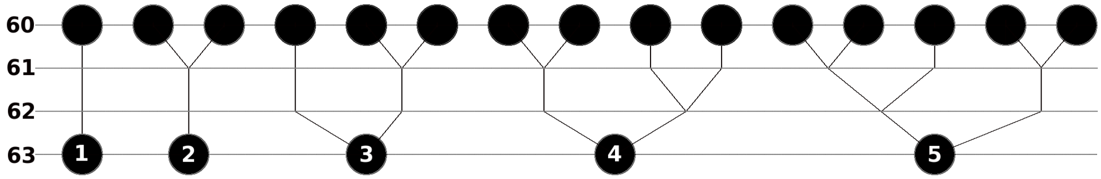


Figure 6.2: Millennium Simulation merger-tree scheme. For all descendant galaxies at snapshot number SN=63 with $M_r < -20.55$, the progenitors at SN=60 are found and counted to give the number of galaxies in single-, binary- and multi-merger systems.

a very large merger catalogue in §4, we took the opportunity to flag potential multi-mergers for just such a study. In the next chapter, we show how a greatly improved technique will allow the Galaxy Zoo approach to find all types of merger efficiently.

6.2.2 Construction of Catalogue

The creation of this catalogue required the visual re-examination of all 3003 systems to check for misclassifications and to assign morphologies to the individual galaxies. During this process, any system that appeared as though it *might* be a multi-merger was noted for future study. 78 such systems were flagged and form the parent sample for this catalogue. Closer examination of these 78 led to the conclusion that several systems were almost certainly *not* merging (but were projection effects), some were too difficult to distinguish and 39 of the original 3003 systems, which make up the catalogue, are confidently multi-mergers with signs of interaction - most of which are discernible in Figure 6.1 (simple inspection of this figure should convey just how variable multi-mergers are in appearance and therefore how challenging a pattern-recognition problem it would be to design an automated system that could reliably filter these out as such).

Having visually determined that these 39 systems of three or more galaxies (with at least one being a Galaxy Zoo spectral object associated with an f_m value > 0.4) are multi-mergers, we manually selected the two (or more) best neighbour objects available to represent the other galaxies. The 'best' object was judged according to (i) brightness in the r-band and (ii) visual common sense. Having spectra for at least one galaxy in each multi-merging system and photometric data for each individual galaxy allows us to calculate rest-frame colours and stellar-mass approximations.

6.2.3 Mass and Rest-Frame Photometry Calculations

To find a volume-limited major multi-merger fraction we need to calculate the rest-frame photometry and stellar masses of the galaxies in our catalogue and define what we mean by ‘major’ in this context.

Stellar masses are calculated as before by fitting the SDSS photometry of each individual galaxy object to a library of stellar-synthesis populations (Maraston 1998; Maraston 2005) out to the redshift given by the spectral object in the merging system. The photometric errors given by SDSS are carried through to estimate errors for the stellar masses. K-corrected rest-frame colours are calculated as before using the photometry and spectral redshifts inputted into the publicly available IDL routine `kcorrect 4_1_4` (Blanton & al. et 2003b). The rest-frame r-band magnitude (M_r) is needed to volume-limit the galaxies for our analysis.

For each system we refer to the masses of each galaxy by descending order where M_1 is the most massive galaxy, M_2 the second most massive, etc. We categorise a multi-merger as a *major* multi-merger if each galaxy of decreasing mass is within one third of the mass of the next most massive galaxy ($\mathrm{M}_1/\mathrm{M}_2 < 3$, $\mathrm{M}_2/\mathrm{M}_3 < 3$, etc.). Of the 39 systems, only 12 are major triple-mergers by this definition. A *middle* multi-merger is where the two most massive galaxies are major ($\mathrm{M}_1/\mathrm{M}_2 < 3$) but the next two are minor ($\mathrm{M}_2/\mathrm{M}_3 > 3$) and a *minor* multi-merger is where the first two most massive galaxies form a minor binary-merger ($\mathrm{M}_1/\mathrm{M}_2 > 3$). Before estimating the major multi-merger fraction of the local Universe, we now introduce the Millennium SAMs so that we can compare the fractions derived from the simulations with the empirically observed fractions (§6.4).

6.3 The Millennium Simulation SAMs

6.3.1 Dark Matter

The Millennium Run is an N-body Dark Matter simulation of a ΛCDM Universe. The original version uses $\sim 10^{10}$ particles in a cubic region of $500h^{-1}$ Mpc on a side in comoving coordinates and periodic boundary conditions. The simulation is based on the (slightly outdated) cosmological parameters $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $\Omega_b = 0.045$, $h = 0.73$ and $\sigma_8 = 0.9$ (see Springel et al. 2005 for details). 64 snapshots of the simulation were saved (from $z = 127$ to $z = 0$) and, from these, merger-trees can be constructed. However, the definition of haloes and halo substructure is a matter of convention. The MPA model defines a Friend-Of-Friend group (defined by particles linked to each other by 0.2 times the mean-particle separation) and determines substructure using the algorithm `SUBFIND` which separates bound structures from unbound particles (determined by their velocity relative to their local potential).

The Durham models, following Harker et al. (2006), carry out the same analysis with the addition of extra constraints on subhalo-definition designed to avoid tenuous ‘bridges’ that temporarily link FOF groups (but will dissipate in the near future rendering the groups distinct). The subhaloes of a FOF group are distinct haloes in their model if (i) the centre of the subhalo is outside twice the half-mass radius of the main halo or (ii) the subhalo has retained more than 75 per cent of the mass since the last output time at which it was an independent halo.

The DM build-up is the most important determinant with respect to the merging of the baryonic galaxies. When a DM (satellite) halo bound to a more massive (main) halo becomes sufficiently disrupted and falls below the 20-particle limit for a structure to be defined, the countdown begins for its central galaxy to merge with that of the main halo. The exact timing depends on the SAM details relating to dynamical friction that models the decay of the satellite orbit.

6.3.2 Baryons

It is important that the SAM accurately convert baryons to stellar populations (and thus to observable photometry) if a realistic merger fraction (or rate) is to be obtained since any sensible merger fraction must be volume-limited (in redshift and magnitude) to ensure completeness. SAM recipes ultimately relate DM haloes to galaxy magnitudes in specific bands and if the prescriptions for galaxy evolution result in unrealistic stellar populations then the volume-limited fractions will be wrong.

The Durham and MPA SAMs differ on a number of details governing the formation and evolution of galaxies. Each new model attempts to capture some extra observational feature (see Parry et al. 2009 for a summary of the differences and the original papers for details). For example, DeLucia06 concentrates on the formation of brightest cluster galaxies whereas Bertone07 develops the MPA model focussing on the treatment of metallicity production and exchange with the IGM. The model reports improvements in the suppression of star-formation in small haloes but at the expense of galaxy colour-bimodality.

6.3.3 Merger Trees

The merger catalogue is limited to the local Universe ($z < 0.1$) and, since we assume that the merger rate changes negligibly over this interval, we are only interested in local merger fractions in this chapter. The Millennium Database only outputs halos and galaxies at 64 discrete time steps (referred to as ‘snapshots’ labelled by ‘snapshot numbers’ (SN) for 0 to 63). A schematic is shown in Figure 6.2 for merger trees with the progenitors at SN=60 related to descendants at SN$=63$. We approximate that a galaxy system would ‘look like’ a merger, on average, if the progenitors of a descendant galaxy are identified as individual galaxies at a progenitor SN_{prog} with redshift corresponding to a look-back time comparable to the time-scale of merger detectability.

Of course, the vast majority of mergers will be minor-mergers whose rates are difficult to constrain observationally. Since we are interested in comparing the SAM mergers to the SDSS catalogue, we consider only progenitors with $M_r < -20.55$ and, as far as merger fractions go, we are only interested in major mergers (see §6.4). In choosing an ‘average’ or ‘typical’ time-scale of detectability we face the difficulty that they depend on the properties of the galaxies in the merger and the merger-detection technique (Lotz et al. 2008b; Lotz et al. 2010a; Lotz et al. 2010b; §5). For example, Lotz et al. 2008b found a median time-scale of $t_{merger} \approx 0.35 \pm 0.15$ Gyr for the *detectability* of the close-pairs technique whereas gas-rich spiral-mergers can remain detectable for much longer periods when using asymmetry techniques ($\gtrsim$ Gyr; Lotz et al. 2010b). If a particular population has a high proportion of spiral galaxies compared to another, the relative merger fractions will therefore appear inflated. Bertone & Conselice 2009 quote the merger time-scale range 0.4 Gyr - 1 Gyr based upon N-body simulations and dynamical-friction calculations (Conselice 2006). We choose $\mathrm{SN}_{prog} = 60$ for the fiducial snapshot since it corresponds to the

Table 6.1: Summary of merger fractions for the Millennium Run and SDSS estimated in this chapter. The Millennium merger fraction depends on the snapshot number (SN_{prog}) of the progenitors which are recorded at redshifts (z) corresponding to look-back times (Δt) as given. To contribute to the numerator of a fraction, a galaxy must be volume-limited ($M_r < -20.55$) and be part of a major merger ($\mathrm{M}_1/\mathrm{M}_2 < 3$, $\mathrm{M}_2/\mathrm{M}_3 < 3$, $\mathrm{M}_3/\mathrm{M}_4 < 3$, etc.).

SN_{prog}	z	Δt (Gyr)	Binary/Single (%)	Triple/Binary (%)	Quad/Triple (%)
DeLucia06					
58	0.116	1.0	4.0	7.1	14.5
59	0.089	0.8	3.1	5.4	12.5
60	0.064	0.6	$\underline{2.2}$	$\underline{4.1}$	$\underline{7.8}$
61	0.041	0.4	1.4	3.0	3.8
62	0.020	0.2	0.7	1.5	0
Bertone07					
58	0.116	1.0	3.0	6.9	14.2
59	0.089	0.8	2.3	5.5	11.4
60	0.064	0.6	$\underline{1.6}$	$\underline{4.0}$	$\underline{7.8}$
61	0.041	0.4	1.0	3.0	3.4
62	0.020	0.2	0.5	1.3	0
Bower06					
58	0.116	1.0	3.4	11.6	26.8
59	0.089	0.8	2.6	8.8	25.9
60	0.064	0.6	$\underline{1.8}$	$\underline{7.4}$	$\underline{16.5}$
61	0.041	0.4	1.1	4.9	10.4
62	0.020	0.2	0.6	2.7	0
This Study					
-	-	-	$1.5-4.5$	$\lesssim 2$	$0-20$*

* This estimate is based on too small a sample to reach any firm conclusions.

look-back time ($z \approx 0.064 \leftrightarrow 0.6$ Gyr) closest to the median of the range of these studies ($0.35-1$ Gyr). We also study how the merger fraction varies with SN_{prog} (see Table 6.1) and bear this uncertainty in mind in interpreting our results. As illustrated in Figure 6.2, we allow any merger history between SN_{prog} and $\mathrm{SN}_{des} = 63$.

6.4 Multi-merger fraction of the local Universe

6.4.1 SDSS Multi-Merger Fraction

Earlier we found a major merger fraction for the local Universe of $\sim 1.5-4.5\%$ for galaxies with $M_r < -20.55$.

We can estimate an upper limit for the multi-merger fraction simply by finding the ratio of volume-limited galaxies in major multi-mergers to volume-limited galaxies in binary-mergers in our catalogue. As this catalogue was constructed with $f_m > 0.4$, it is plausible to assume that multi-mergers are amongst the types of merger *more* likely to be classified as 'merging' (in the Galaxy Zoo interface) than simple binaries because multi-mergers generally appear quite dramatic, prompting the user to go for the merger button. The fraction of multi-mergers in systems with $f_m > 0.4$ is therefore likely to be greater than the fraction of multi-mergers in galaxies for all f_m. Therefore, by only considering $f_m > 0.4$, we can estimate the upper limit of the multi-merger fraction in the nearby Universe.

When we volume limit the 2×3003 galaxies in GZM1 by the constraint $M_r < -20.55$, we are left with 1634 individual galaxies in major mergers (binary or multi). Of the 39 multi-mergers we have identified, only 16 are major triple-mergers and of these systems, $38/48$ galaxies have $M_r < -20.55$. This gives a fraction of $38/1634$ and so we can approximate the upper limit of the major triple-merger fraction as $\lesssim 2\%$.[3] This number might be inflated by no more than $\sim 50\%$ if one takes into account the few systems from the original 78 (see §6.2.2) that *might* have been multi-mergers, but could not be resolved sufficiently to be sure. The multi-merger to binary-merger ratio appears to be similar, therefore, to the binary-merger to single-galaxy ratio we calculated $(1.5-4.5\%)$. We stress that this is a rough estimate for the upper boundary, since we have lost information by only considering systems for $f_m > 0.4$; but the general result is that the probability of finding a galaxy in a merger of N galaxies (for $N = 2,3$) is $\sim$ few percent of the probability of finding a galaxy in a system of $N-1$ galaxies (for these volume-limited conditions $M_r < -20.55$

---

[3] More formally: the ratio of *individual* volume-limited ($M_r < -20.55$, $z < 0.1$) galaxies in major triple-mergers to *individual* volume-limited galaxies in major binary-mergers is $\lesssim 2\%$.

and $z < 0.1$).

Extending this empirical query to systems with $N \geq 4$ galaxies suffers from small number statistics. Of the 39 systems, we visually identify only 7 systems as having 4 or more galaxies merging at once. But none of these are *major* quadruple-mergers by the appropriate definition: $\mathrm{M}_1/\mathrm{M}_2 < 3$, $\mathrm{M}_2/\mathrm{M}_3 < 3$ and $\mathrm{M}_3/\mathrm{M}_4 < 3$. However, two of the systems only just miss out on this definition by having values of $\mathrm{M}_3/\mathrm{M}_4$ slightly above 3 (with errors making < 3 possible). If both of these systems *were* to be considered as major quadruple-mergers, then the ratio of volume-limited galaxies in major quadruple-mergers to galaxies in major triple-mergers would be $(7 \pm \sqrt{7})/38$ (with $\pm\sqrt{7}$ being the Poisson-counting error). So while the *measured* quadruple-merger fraction is technically zero, it could easily have been as high as $\sim 20\%$. Our sample is therefore too small to give accurate merger-fraction estimates for systems with 4 or more galaxies of comparable size.

6.4.2 The Millennium Multi-Merger Fraction

The galaxy databases for the Millennium Run offer much larger samples that allow us to calculate merger fractions out to quadruple-major mergers. For example, in the model of DeLucia06, at $\mathrm{SN}_{desc} = 63$ ($z = 0$), there are 1,113,741 galaxies with $M_r < -20.55$ and the combined number of progenitor galaxies at $\mathrm{SN}_{prog} = 60$ is 1,121,201. As explained above, we classify each descendant galaxy at $\mathrm{SN}_{desc} = 63$ as a ‘merger remnant’ if it has two or more progenitors at a given SN_{prog} whose redshift corresponds to a look-back time comparable to a merger time-scale (we in fact vary SN_{prog} between $58 - 62$).

Of all these ‘mergers,’ we further classify them as being ‘major’ if all their progenitor masses are constrained by our working definition: $\mathrm{M}_1/\mathrm{M}_2 < 3$, $\mathrm{M}_2/\mathrm{M}_3 < 3$, etc. It is clear that our Millennium merger-fractions will depend on the choice of SN_{prog} since, the lower SN_{prog} is, the greater the number of systems there are in mergers (as the merger tree branches out with increasing redshift). We therefore calculate the merger fractions for a range of SN_{prog} values and present them in Table 6.1 referring to fractions derived from $\mathrm{SN}_{prog} = 60$ (with look-back time of ~ 0.6 Gyr) as the fiducial value for each model.

For the ratio of individual volume-limited galaxies in major binary-mergers to individual volume-limited single galaxies (labelled ‘Binary/Single’ fraction in Table 6.1), we find that all three SAMs produce a fraction within our limits ($1.5-4.5\%$). This is in agreement with similar comparisons to close-pairs (Kitzbichler & White 2008; Patton & Atfield 2008; Mateus 2008) and CAS (Bertone & Conselice 2009) for the local Universe. However, the SAMs give slightly higher percentages for the ratio of galaxies in triple-merger systems compared to binary-mergers. We estimated that this number should be no more than $\sim 2\%$ but the SAMs have at least double that fraction for $\mathrm{SN}_{prog} = 60$. Only if we use the first Millennium time-step $\mathrm{SN}_{prog} = 62$, reducing the merger-detectability time-scale to ~ 0.2 Gyr do we get agreement between the MPA models and our calculation. This might be reconciled by the fact that multi-mergers are dominated by elliptical galaxies which have shorter merger-time scales (see §6.5). The Durham model predicts roughly twice the number of multi-mergers than do the Munich models, so the latter appear closer to our observations on multi-merger fractions.

For the quadruple-triple ratio the Galaxy Zoo sample is too small to offer useful constraints. Comparing the Durham to MPA models shows that the former has a greater multi-merger fraction still (over 100% more).

6.5 Properties of Multi-Merging Galaxies

6.5.1 SDSS Multi-Merger Properties

SDSS Morphologies

One of four morphological categories was assigned to each galaxy in the multi-merger systems: S = spiral, E = elliptical, SU = ‘unsure’ spiral and EU = ‘unsure’ elliptical. Unsure morphologies are common, especially in late-stage, distant systems where structural indicators like spiral arms cannot be distinguished. The same four categories were used in earlier chapters where it was found that spirals (S and SU) outnumber ellipticals (E and EU) in volume-limited galaxies in mergers by at least 3:1. This is about twice the ratio of the global population and it was argued in §5 that this is most likely due to the fact that mergers involving spirals remain detectable for longer periods than mergers involving ellipticals. In multi-mergers, by contrast, we found that the spiral-to-elliptical

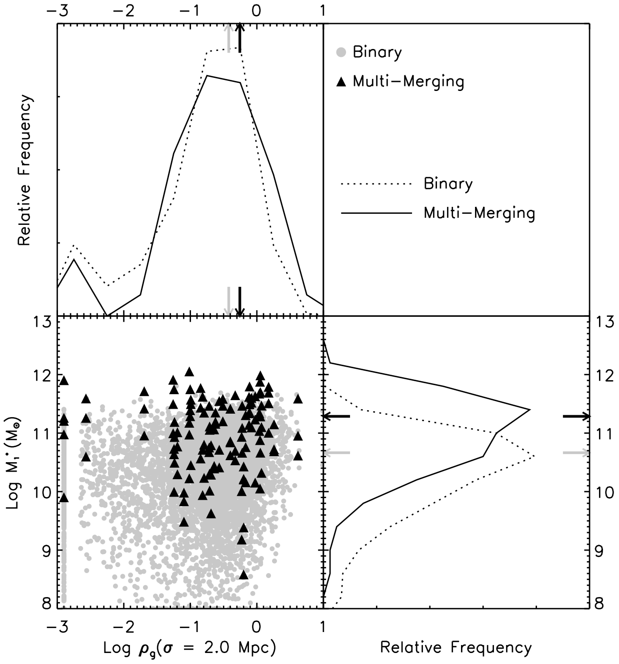


Figure 6.3: Distributions of stellar mass and environment ρ_g for galaxies in multi-mergers and galaxies in binary-mergers. The arrows point at the mean values for the distributions. The peak at $\log \rho_g = -3$ is artificial (to avoid $\log 0$ errors we set ρ_g to 10^{-3} if zero).

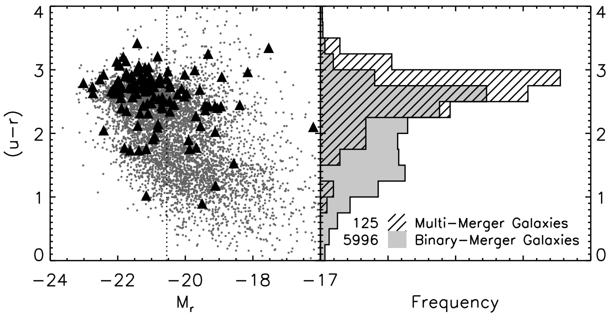


Figure 6.4: Colour-magnitude diagrams for galaxies in multi-mergers (black) and galaxies in binary-mergers (grey).

ratio for volume-limited galaxies was closer to 1:1. In other words, multi-mergers appear to favour ellipticals in our sample compared with their occurrence in binary-mergers and the global galaxy population.

SDSS Environment, Colours and Stellar Masses

It seems unlikely that this high occurrence of ellipticals in multi-mergers is entirely due to a selection effect. It is possible that bulge dominated galaxies can be visually identified in multi-mergers longer than spirals since the bulge is a key feature indicating how many galaxies were originally involved in a multi-merger; but spirals remain detectable in mergers for longer, as we concluded earlier, so the duration of detectability for multi-mergers involving spirals should be longer still than for multi-mergers involving ellipticals. Despite this, the fact that ellipticals feature so prominently in multi-mergers suggests that environment has some influence, i.e. dense environments are more likely to host multi-mergers. We found earlier that (binary) mergers tend to occupy slightly denser environments than galaxies in the global population and so it seems that the number of galaxies involved in a merger scales with environment.

We measure the environment of the multi-mergers directly using the *adaptive Gaussian environment parameter*, ρ_g, as before (see §5.3).

Figure 6.3 shows the distribution of ρ_g for the multi-merger and binary-merger systems (top-left panel). The multi-mergers on average occupy environments with slightly higher values of ρ_g. The Kolmogorov-Smirnov statistic between the binary and multi-merger data sets provides a measure of the difference between their cumulative distributions and we find them to be different with a significance level of $> 99\%$.

The observed multi-mergers are therefore found in more dense environments though the primary reason is not clear: do multi-mergers favour ellipticals because they are likely to take place in dense environments or are multi-mergers with ellipticals easier to *visually identify* and therefore make multi-mergers *appear* to favour dense environments? Probably both factors are at play and it is difficult at this stage to disentangle the effects quantitatively.

Likewise, Figure 6.3 indicates that the stellar masses of the galaxies in multi-mergers are on average greater than their binary-merger counterparts. We compare the SDSS masses directly to the Millennium SAMs in §6.5.2. Colour is yet another quantity that correlates with morphology and, as Figure 6.4 shows, the $u-r$ colours of multi-merging galaxies are redder than their binary-merger counterparts. The empirical evidence is therefore emphatically clear that galaxies *visually-*

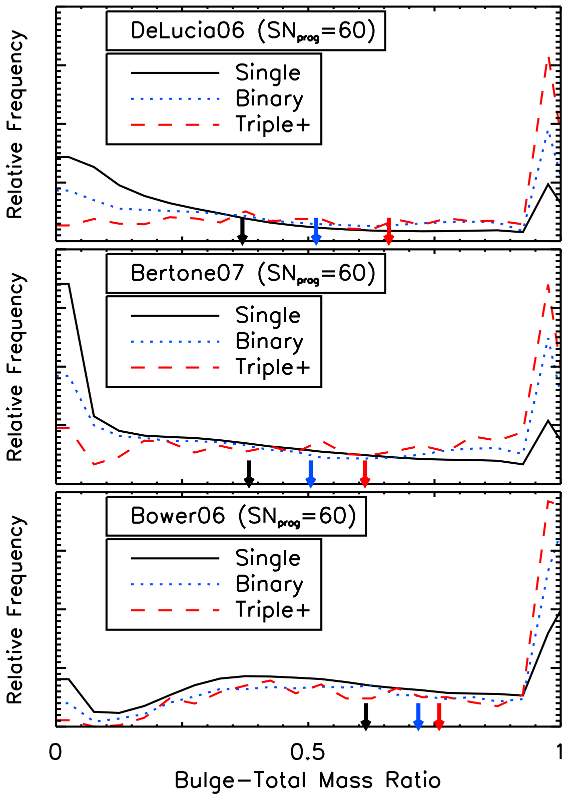


Figure 6.5: Distributions of Bulge-Total stellar mass ratio of galaxies in single-, binary- and multi-merger systems for all three SAMs at $SN_{prog} = 60$. The arrows indicate the mean values for each sample. All three predict that binary and multi-mergers have more ‘elliptical’ like morphologies compared with isolated systems - a likely concomitant of the favourability of mergers to occur in high-density environments.

observed to be in multi-mergers are more likely to be early-type than single- and binary-merger galaxies.

6.5.2 Millennium Multi-Merger Properties

Millennium Morphologies

The morphologies of the SDSS multi-mergers and the Millennium multi-mergers cannot be compared directly since the SDSS morphologies are obtained visually. However, we can determine the qualitative relationship of the Millennium galaxy morphologies using the Bulge-Total stellar mass ratio as a proxy (with a high ratio corresponding to ellipticals and low ratio to spirals). Several studies have defined morphologies this way (Khochfar & Burkert 2003; Benson et al. 2007; Bertone et al. 2007; Parry et al. 2009). Benson et al. (2007) found that the SDSS and Durham SAM produced qualitatively similar disc-bulge Luminosity Functions (see their Figure 17). The distributions of the Bulge-Total mass ratios for the galaxies of the three SAMs at $\mathrm{SN}_{prog} = 60$ are shown in Figure 6.5. All three models produce the expected qualitative result that the more galaxies there are in a (merger) system, the more bulge-dominated they will be. We find that the Durham model has systems generally more bulge-dominated than the Munich models in agreement with Parry et al. (2009).

As argued in §6.5.1, binary- and multi-mergers occur most favourably in higher-density environments and this is where interactions (inducing gravitational torques, see Hopkins et al. 2009; Hopkins et al. 2009b) causing disk instability are common. This is no doubt largely responsible for the well established morphology-environment relationship (established since at least Dressler 1980) and so mergers, taking place more favourably in denser environments, are more likely to be elliptical.

Millennium Environment, Colours and Stellar Masses

The Millennium SAM catalogues do not provide a direct measure of environment and so we decline to test this property, though it seems almost certain that multi-mergers will favour high-density environments given the bulge-dominated morphologies exhibited by the SAMs as discussed in §6.5.2.

The colours of DeLucia06 and Bertone07 were examined in Bertone et al. (2007) and it was found that the Bertone07 model did not reproduce the colour bi-modality of the local Universe as well as DeLucia06. The model of Bower06 does reproduce the local bi-modality well (see e.g. Figure 4 of Bower et al. 2006). However, since the colours are derived secondarily from the stellar populations comprising their putative galaxies (all using the stellar synthesis models of Bruzual & Charlot 2003), we analyse their stellar mass distributions as a main form of comparison.

Figure 6.6 shows the mass distributions for the SDSS and Millennium galaxies. Bertone et al. (2007) reported that both their model and that of DeLucia06 slightly underestimate the Luminosity

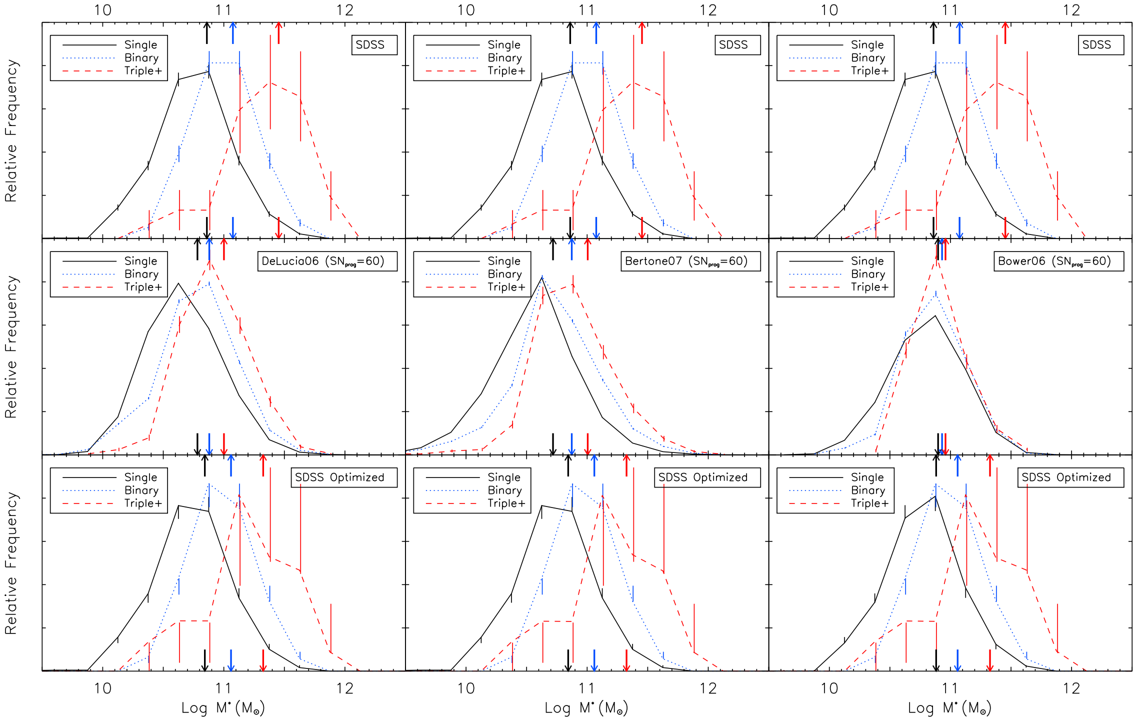


Figure 6.6: Stellar mass distributions for the single-, binary- and multi-merger systems in SDSS and Millennium. The left, middle and right columns correspond to the DeLucia06, Bertone07 and Bower06 models respectively. The top panels show the mass distributions for the SDSS systems. The bottom panels show the same (SDSS) data except the plotted points are allowed to vary along the error bars (representing the Poisson-counting errors) in order to minimise a χ^2 significance test with the Millennium model (in the middle panel). The arrows show the mean values for each distribution. All galaxies are volume-limited ($z < 0.1, M_r < -20.55$) and the progenitors are taken at SN$_{prog} = 60$. The Millennium SAM masses are determined here using $h = 0.73$.

Function as a function of stellar mass in the range $10.6 \lesssim \log \mathrm{M}^* \lesssim 11.2$. This helps explain the very slight discrepancy between the single-galaxy mass distributions for the MPA models (note the black vertical arrows show the mean masses of the SAMs are ~ 1 dex less than that of the SDSS single systems). The top and bottom panels show the SDSS distributions where the data points on the bottom are allowed to vary along the Poisson-counting error bars in order to most closely match the Millennium distributions. Also, importantly, the distributions for the binary-mergers are adjusted so as to include a spiral-elliptical ratio of 3 : 2 since it was argued in the previous chapter that spirals are over-observed by factor ~ 2 due to longer time-scales of detectability (Lotz et al. 2008b).

By contrast, it was suggested in §6.5.1 that ellipticals might be over-observed in multi-mergers but since we cannot quantify this, we cannot correct for it. It suggests that the multi-merger mass distributions might not increase at quite the rate suggested by the SDSS distributions. All this considered, the MPA models both do well in reproducing the fact (with slight underestimation) that galaxies in binary and multi-mergers increase in mass by ~ 1 dex per extra galaxy in the system (on average). By contrast, the model of Bower06 appears to reproduce the single-galaxy mass distribution to great accuracy but shows very little in the way of increasing mass with merging (see middle box of right column). With respect to predicted stellar masses, both groups of model show slight strengths and weaknesses compared to each other.

6.6 Summary

Through the Galaxy Zoo project we have assembled a catalogue of multi-merger systems in the local Universe ($z < 0.1$). Multi-mergers can only be found (at the present time) in SDSS through visual inspection since close-pairs suffer from fibre overlaps and automated methods like CAS and GM_{20} are not sensitive enough to consign a given image to a ‘multi-merger’ parameter space (distinct from binary-mergers). The original Galaxy Zoo interface was not set up specifically for the task of finding multi-mergers, but will likely be in the future based upon the improved technique we present in the next chapter.

Nonetheless, we argued that our catalogue is sufficient to provide a rough estimate of the (major) multi-merger fraction and gave an upper bound such that $\lesssim 2\%$ of all volume-limited galaxies ($M_r < -20.55$) in a major merger (most of them being binary) are specifically in a *multi*-merger. This is about the same percentage as that calculated for the (binary) major merger fraction ($1.5-4.5\%$) for the same volume-limiting constraints. However, our sample is not large enough to find the quadruple-major merger fraction (or beyond).

The Millennium SAMs gave similar merger fractions for the number of volume-limited galaxies in major binary-mergers compared to single galaxies ($\sim 2\%$). However, the next level of merger exhibited some disagreement between the SAMs and our observations (with the SAMs over predicting galaxies in multi-mergers by at least factor ~ 2). The Durham model offered a multi-merger fraction roughly twice that of the MPA model. However, since we have shown that galaxies in multi-mergers tend to be elliptical (Figure 6.5), which have shorter time-scales of detectability, this could justify taking the Millennium multi-merger step at $\mathrm{SN}_{prog} = 62$ in which case the fraction would be within our rough observational limit in the Bertone07 model.

Comparing the properties of the galaxies in these multi-mergers to those in binary-mergers and single-galaxy systems, we found that the (volume-limited) galaxies in multi-mergers have greater stellar masses (Figure 6.6), redder colours (Figure 6.4) and occupied slightly denser environments (Figure 6.3). Such properties are characteristic of elliptical galaxies and we found a high elliptical-spiral ratio (at about $1:1$) in multi-mergers compared to the single systems (at about $2:3$) and binary-mergers (at about $1:3$). We argued that this is unlikely to be entirely due to a selection effect. To corroborate this, we compared our results with the SAMs.

We found good qualitative agreement: all three models predicted that the Bulge/Total mass ratio increases with merger-number corroborating the observation that multi-mergers favour ellipticals and, implicitly, occupy denser environments on average compared to galaxies in binary-mergers and single galaxies. The MPA models also agreed qualitatively with the fact that galaxy mass increases, on average, with the number of galaxies in the system. The Durham model appeared to slightly underestimate this effect.

Chapter 7

All the SDSS Mergers ($z < 0.1$)

7.1 Introduction

In this section we present a powerful synthesis for merger-location that has the potential to become the standard method in future surveys. It is capable of finding *all* types of merger - minor, major and multi - in a near-complete manner. This is important since merger-detection techniques to date tend to struggle with minor mergers in particular and these contribute significantly to galaxy evolution being more frequent than major mergers (Hopkins et al. 2010a; Kaviraj et al. 2011; Lotz et al. 2011).

As we have seen so far, to overcome the problem of finding mergers (and galaxy morphologies more generally), there are two broad types of decision-making processes that one can use: 'automated' and 'human-visual.' Both tools possess strengths and weaknesses (computational decisions are fast and reproducible but unadaptive; assessment by human individuals is slow and subjective but highly versatile - see §7.2 for elaboration) and *all* merger-location techniques at present use a mixture of these two to varying degrees.

The 'Close-Pairs' technique (CP) for locating mergers is at the more 'automated' end of the range, finding pairs of galaxies likely to merge within a dynamical-friction timescale by calculating their separation in (*ra, dec, z*) space. But the technique gives no information as to whether the systems are interacting or not (or how many galaxies are involved; see Figure 4.3 and surrounding discussion). To find this out, a correction for contamination is required which can only be obtained through direct visual examination or techniques that rest more heavily on visual-tuning.[1]

These include the 'non-parametric' techniques (CAS and GM_{20}) that we discussed that convert pixel-arrays to numbers designed to summarise the distribution of light in galaxy images. These techniques require choices of thresholds and partitions that define the galaxy's morphological classification and which ultimately trace back to (and try to replicate) human-visual decisions. Moreover, since no technique can ever perfectly reproduce the opinions of experts, all such automated techniques will involve some contamination that can only be quantified through visual inspection of random subsets.

For this reason, many morphological studies have opted for the brute-force approach of human visualisation often averaging decisions over several experts to minimise subjectivity. Some recent examples are those of Nair & Abraham (2010), who visually examined 14,034 SDSS galaxies and the EFIGI[2] group who complemented and controlled their bulge-disc decomposition analysis of 4458 SDSS galaxies with visual classifications (Baillard et al. 2011; de Lapparent et al. 2011). The Galaxy Zoo project took this to a whole new level by treating the world-wide web as a giant neural net of sorts, averaging over the decisions of dozens of individuals per morphology-related question, and thereby ascertaining a quantitative level of confidence for each discrete decision. Of course, all visual techniques are based on parent samples that are created by automated processes, namely the data reduction pipeline from instrument to database.

In short, it is important to recognise that pattern recognition is, very generally, a synthesis between 'man and machine' and the problem we face in finding mergers and morphologies is *not* whether to use human-visual *or* automated techniques, but rather to find the technique that makes best use of both types of decision-making process. This study aims to advance the efficiency of that synthesis by combining the best aspects from the techniques that have gone before it.

We showed in previous chapters that the basic Galaxy Zoo approach was highly effective at finding mergers in large quantities but it faced several of the problems as the non-parametric and

---

[1] As discussed in Lotz et al. (2011), this correction factor can be anywhere in the region $0.4 - 1.0$. Owing to this significant contamination, non-visual studies tend to be restricted to the evolution of the merger *rate* (assuming a systematic contamination across redshift) rather than the *properties* of the galaxies in mergers.

[2] "Extraction de Formes Ideélisées de Galaxies en Imagerie."

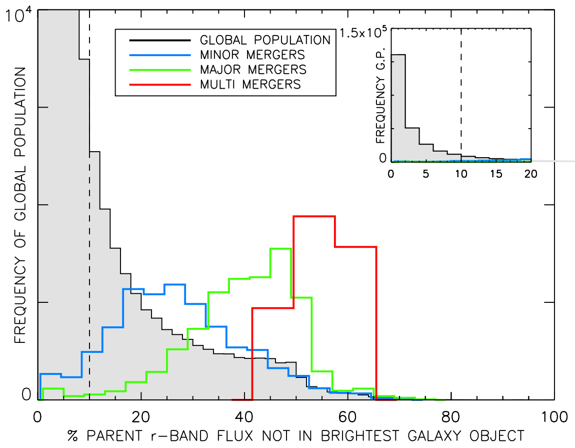


Figure 7.1: The distribution of SDSS galaxies and the percentage of flux (in the r_{petro} band) of galaxy photometric objects within deblended parent images that does *not* belong to the brightest galaxy object. The grey histogram shows all deblended SDSS parent images containing a galaxy with spectra for $z < 0.1$. The minor and major mergers are taken from the original catalogue constructed earlier and separated by stellar-mass ratio of 1:3. The multi-mergers are those from the catalogue constructed in the previous chapter. All three merger histograms are scaled to match the area of the grey histogram 10% on the x-axis - the parent sample for catalogue construction in this study guarantees inclusion of all detectable mergers with flux ratio of at least 1:9.

close-pair techniques. Firstly, the first generation of Galaxy Zoo interface (Lintott et al. 2008) asked users to decide whether the galaxy at the centre of an image (the result of an automated process) was involved in a merger or not. As expected, the weighted fraction of affirmative responses to this question, f_m, offers a useful measure of the likelihood that the central photometric object is involved in a merger, but it (like other techniques) says nothing about *what* the central galaxy is merging with (is it a minor merger? a multi-merger? etc.). To determine this, further decisions would have to be made as to which photometric object(s) represent(s) the merging partner(s).

Secondly, because mergers tend to produce clumpy and asymmetric images (prone to ‘shredding’ by the SDSS deblending routine if close-by), there was no direct way of ensuring that the central photometric object about which the image was centred represented the light of the merging galaxy accurately.

Thirdly, there was no way of directly ensuring that the body of light deemed to be merging with the central galaxy is in fact another galaxy as opposed to a star (many users were insufficiently familiar with the difference in appearance between stars and galaxies to avoid this source of contamination). These problems meant that, although the Galaxy Zoo approach substantially reduced the size of the parent sample, an extensive re-checking and refining process was required by the research group where contaminants were removed and the photometric objects best representing the galaxies in the true binary and multi-mergers were manually selected so that their properties could be studied.

Fourthly, f_m is a continuous variable such that systems with $f_m \sim 1$ are virtually certain to be involved in a merger and systems with $f_m \sim 0$ are almost certainly not. Like the non-parametric and close-pair techniques, a somewhat arbitrary 'merger-defining' threshold/partition had to be picked based upon extensive visual examination. In this case, a value $f_m > 0.4$ was chosen leaving a substantial number of mergers in the $f_m \sim 0.2 - 0.4$ interval. This number had to be estimated in calculating a final merger fraction and brought about a large error as a result (frac $\sim 1.5 - 4.5\%$ for $M_r < -20.55, z < 0.1$). It also made the sample biased against minor-mergers (which tended to score smaller f_m values than major mergers; see Figure 4.11) and, although the sample was large and representative of mergers whose properties were investigated in §5, the catalogue was substantially incomplete.

In conclusion, when it came to finding mergers, although the original Galaxy Zoo interface did prove useful in creating a very large merger catalogue, it did not put the power of human-visual pattern recognition to its best use by simply constructing a parent sample 'likely to contain mergers' that needed review and decontamination by individual researchers. This could have been done using automated processes. Rather, human-visual labour is put to better use when making more nuanced decisions beyond what the programmer can do by setting thresholds: 'this photometric object is part of a tidal tail,' 'this object is part of an irregular galaxy, not a merger', 'something has gone wrong here,' etc.

With these lessons in mind, we re-arranged the combination of automated vs human-visual tasks in the following way. We use an automated process to select the parent sample *most likely to contain mergers in a complete manner* and to remove stars. Since merger-images are always going to produce peaks of light near to each other, they should always be found within isophotes where some significant portion of the deblended flux is *not* found within a single peak (as illustrated in Figure 4.1; compare with Figure 7.2). Figure 7.1 shows a strong correlation between the percentage of flux *not* located in the brightest galaxy object within the SDSS parent isophote (demarcating source from background) and the 'size' of the merger (represented by whether a merger is 'minor,' 'major' or 'multi'). In §7.2 we describe how the SDSS deblending routine was used to achieve this task and virtually *guarantee* that all minor, major and multi-mergers will be included in a parent sample significantly smaller than the global population.

Having created a parent sample of tractable size, we direct the human-visual task to making extremely detailed decisions on a (photometric) object-by-object basis. Using a specially designed interface (described in §7.2), we group together all photometric objects belonging to the same galaxy and then decide whether the galaxies represented by these groups are interacting with each other or not. This way we neatly separate the light belonging to interacting galaxies and create a better representation of their total flux.

The result of this approach was to nearly double the size of merger catalogue from 3003 binary pairs (from DR6) to 5872 systems (from DR7) with more detailed information on the photometry constituting each galaxy in each image and with stars automatically removed.[3] We are thereby able to select near-complete samples of minor, major and multi-mergers (i.e. small clusters) with relative ease and calculate the merger-fraction of the local universe with much smaller errors than before. Additionally, we are able to "re-blend" the photometry of many galaxies with low, uniform surface-brightness which are often of irregular morphology and 'shredded' by the deblending routine (see Figure 7.5 for examples).

In §7.2 we describe in more detail how we construct the parent sample and convert it, via a visual interface, into a detailed merger catalogue of all minor, major and multi-mergers in the local Universe of SDSS ($z < 0.1$). In §7.3, we calculate and compare the minor and major merger fractions of the local Universe with those predicted by the latest publically-available Millennium Simulation semi-analytic model (SAM) (Guo et al. 2011, hereafter G10).

---

[3] Images of the merger catalogue with their separated photometries can be viewed here: `http://www-astro.physics.ox.ac.uk/~ddarg/reblending_project/`.

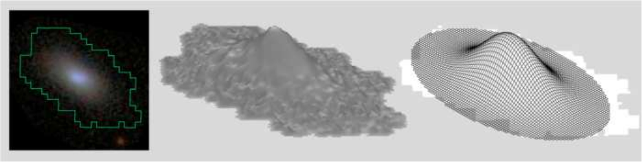


Figure 7.2: Example of unperturbed, 'blended' (parent) image to which a single model fit is sufficient. Most SDSS objects are of this sort and are omitted from the parent sample for this study.

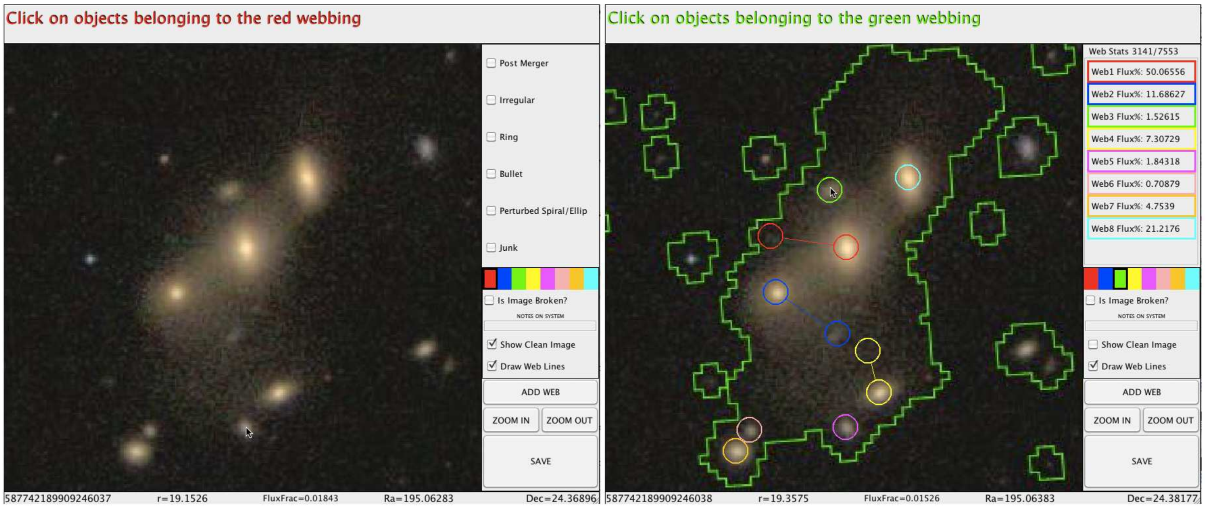
7.2 Method

To find mergers efficiently, we first use the automated deblending routine of the SDSS image-processing pipeline to find parent images likely to contain mergers that are at least minor (with flux ratios of $\sim 1:9$). We first select from an initial database of $323,032$ spectral-galaxy objects for $z < 0.1$ that are 'deblended.'[4] The flux distribution of a typical galaxy with `parentID=0` is illustrated in Figure 7.2; the fact that they are 'blended' means that the probability of hosting a merger is effectively zero. This leaves $261,895$ spectral galaxy objects in DR7. For each of these, we find all 'children' photometric objects with the same `parentID` that are deemed to be 'galaxy' according to their `phototype` - an automated assessment of the photometric object's PSF that separates stars from galaxies with $> 98\%$ reliability Strauss et al. (2002). This removes a major source of contamination and leaves $1,006,962$ child photometric galaxy objects in total.

We then process each set of galaxy photometric objects (belonging to the same parent image) to find those parent images where at least 10% of the r-band Petrosian flux of the brightest galaxy object is to be found in the remaining galaxy objects. As shown in Figure 7.1 and illustrated in Figure 4.1, this efficiently narrows down the parent sample in the hunt for mergers since these will have much of the flux of the parent image distributed beyond the brightest object. This takes the sample from $261,895$ parent images down to $47,475$ to be visually processed with an average number of ~ 6 child objects. For $z < 0.02$ we analyse all child objects but, since many of the objects contain negligible magnitudes, we make a cut for $0.02 < z < 0.1$ such that only as many objects as are needed to account for at least 99% of the galaxy flux in each parent image are

---

[4] I.e. all objects with `parentID!=0`.



Click on objects belonging to the red webbing

☐ Post Merger
☐ Irregular
☐ Ring
☐ Bullet
☐ Perturbed Spiral/Ellip
☐ Junk
☐ Is Image Broken?
NOTES ON SYSTEM
☑ Show Clean Image
☑ Draw Web Lines

587742189909246037 r=19.1526 FluxFrac=0.01843 Ra=195.06283 Dec=24.36896

Click on objects belonging to the green webbing

Web Stats 3141/7553
Web1 Flux%: 50.06556
Web2 Flux%: 11.68627
Web3 Flux%: 1.52615
Web4 Flux%: 7.30729
Web5 Flux%: 1.84318
Web6 Flux%: 0.70879
Web7 Flux%: 4.7539
Web8 Flux%: 21.2176

☐ Is Image Broken?
NOTES ON SYSTEM
☐ Show Clean Image
☑ Draw Web Lines

587742189909246038 r=19.3575 FluxFrac=0.01526 Ra=195.06383 Dec=24.38177

Figure 7.3: The interface for reblending galaxy images. The user has photometric and visual information to make informed decisions as to (i) which photometric objects belong to the same galaxy, (ii) whether these groupings ('galaxy-webs') represent irregular, post-merger, strongly-pertubed or ring/bullet galaxies or are to be discarded, and (iii) whether the galaxies represented by each web are interacting with any other galaxy-web.

analysed (this reduces the average number of child objects from ~ 6 to ~ 4).

Each parent image was analysed as follows by the interface shown in Figure 7.3. Firstly, every object is grouped into a 'web' representing a single galaxy. This is usually a very easy task for human-visualisation owing to our adept pattern recognition capacity to outline shapes based on colour-contrast. The task becomes more involved with strongly interacting systems where the galaxies are so intertwined that it can sometimes be difficult to tell which part of the image belonged to which progenitor. Nonetheless, our built in capacity to re-construct 3-dimensional trajectories is able to make such decisions much more reliably than an automated process. Each merger image tells a different story and thus requires the adaptability of the human mind to figure out, say, that two strongly perturbed galaxies within the same isophote (and nothing else around) must be interacting, or that a particular image is the result of a multi-merger, and so on.

By contrast, the computer only 'knows' where certain peaks are located but, without running an expensive suite of n-body simulations across a wide-range of impact parameters, viewing angles, etc. and matching them to the image in question, it cannot decide which objects belong to which

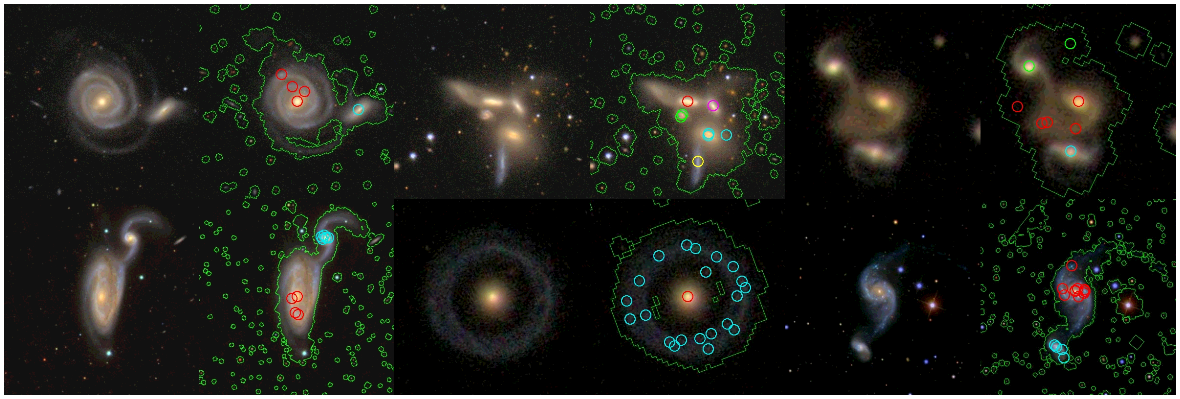


Figure 7.4: Examples of the outputs of the interface: galaxies are 'reblended' and the resultant webs are classified as interacting (or not) with each other. The result is a catalogue of 149,165 such 'galaxy-webs.'

progenitor galaxy. Even then, computational matching of this sort often faces the problem of 'false minima' usually requiring human supervision.

Examples of the effectiveness of this visual 'reblending' can be seen in Figure 7.4 and in the online catalogue.

Once all (uncut) galaxy objects in each parent-isophote have been grouped into a web, each web can be flagged as representing a galaxy that is 'strongly-perturbed,' 'irregular' (i.e. not in the Hubble sequence), 'post-merger,' 'ring' or to be discarded. If a web contains a spectral object then the spectral redshift is used to represent the whole of that galaxy-web. The magnitudes and corresponding errors of all photometric objects in each web can then be combined and, if the galaxy-web has a spectral redshift, can be used to derive combined k-corrected rest-frame magnitudes. In theory, the combined magnitudes of the 'reblended' webs will give a more complete and accurate set of magnitudes for the system. The brightest object in each web can also be used to represent the galaxy (for most galaxies there is negligible difference between the web's 'combined' magnitude and web's 'brightest-member' magnitude).

As one might expect, the exception are those galaxies that tend to be classed as 'irregular' or 'strongly perturbed.' The typical galaxy-web in the catalogue with spectral redshift has a ratio of combined flux to brightest-member flux of ~ 1.03 - a negligible difference. But those classed as

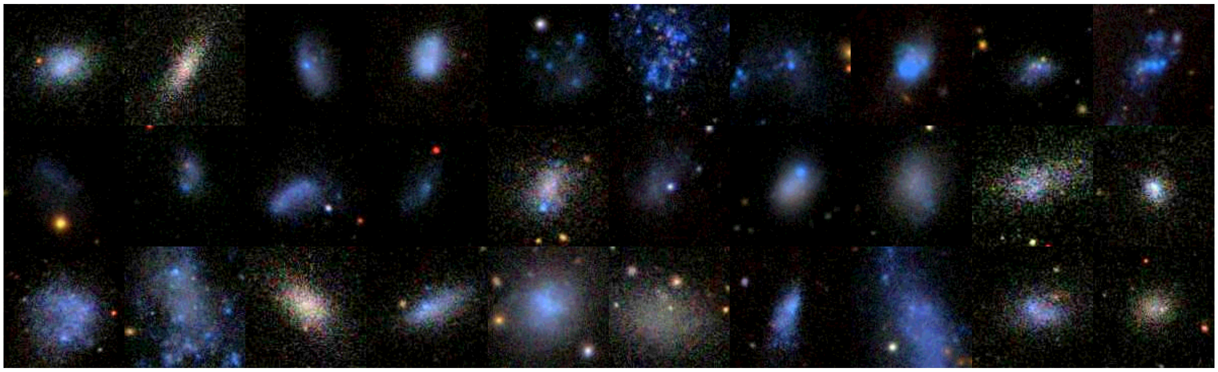


Figure 7.5: Examples of irregular galaxies - uniform, low-surface brightness galaxies that do not fit into the standard Hubble classification.

irregular have mean ratio of ~ 1.13 and 97 have over *double* the ratio. Examples of these galaxies - where the light is extremely spread out - are shown in Figure 7.5 and form an interesting catalogue in and of themselves that we shall investigate in future studies.

Each galaxy-web is then labelled as ‘interacting’ with another web if they show clear signs of morphological disturbance and no background space is visible between them. We were quite conservative in our assessments of interactions in order to avoid mistaken projections. If a galaxy-web with spectra is deemed to be interacting with a galaxy-web without spectra, then the galaxy-web without spectra inherits the redshift (which is used to calculate rest-frame magnitudes). After examining $47,475$ images, we produced a catalogue of $149,165$ galaxy-webs, $4,066$ of which were flagged to be discarded, leaving $145,099$ galaxies with reblended photometry. Of these, $49,706$ galaxy-webs have their own spectral redshifts.

The catalogue has $13,005$ galaxy-webs flagged as ‘interacting’ with at least one other galaxy-web and 601 with at least two (potentially forming part of a multi-merger or cluster). Of the interacting webs, $7,183$ have their own spectral redshift and $4,985$ have spectral redshifts inherited from the galaxy-web they are interacting with. (The systems deemed to be interacting but having no spectral redshifts were either too faint for SDSS spectral targeting or stood within $55''$ of a spectral object in a separate galaxy that prevents it from acquiring spectra due to fibre clashes).

All galaxy-webs with spectral redshifts (own or inherited through interactions) had k-corrected rest-frame magnitudes calculated using the IDL routine `kcorrect 4_1_4` (Blanton & al. et 2003b) with the Petrosian magnitudes, errors and extinction levels supplied by SDSS. These magnitudes are needed to perform the volume-limiting analysis in calculating merger fractions.

7.3 Binary Merger Fractions

As preliminary analysis, since this project is still ongoing, we shall show that we get very good agreement with the Millennium Simulation. Throughout this section, we measure the size of merger-ratio by r-band flux ratio, denoted by $0 < f_r^n \leq 1$ ($f_r = 1$ being an "equal-mass" merger), that serves as a proxy for stellar mass. In the absence of a superscript, it can be assumed that f_r represents a binary merger.

We define our merger fraction for three intervals of magnitude: $-19.5 < M_r < -17.5$, $-21.5 < M_r < -19.5$ and $M_r < -21.5$. These intervals are chosen based upon comparison to the distribution of stellar-masses in the semi-analytic galaxies of G10 (Millennium-II) that are tuned to the observed mass and luminosity functions of the local Universe. Based upon the correlation shown in Figure 7.6 (*top*), we can associate these magnitude intervals with galaxies of approximate stellar-mass $9.0 < \log \mathrm{M}^* < 10.0$, $10.0 < \log \mathrm{M}^* < 11.0$ and $11.0 < \log \mathrm{M}^*$ respectively (within the errors derived from the spread). The SAM galaxy population peaks at its lowest resolution mass of $\log \mathrm{M}^* \sim 7.0$, whereas the SDSS sample peaks at $M_r \sim -20.5$ roughly corresponding to the limit for spectroscopic detection ($r_{petro} = 17.77$) at $z \sim 0.1$ (Figure 7.6 *middle*).

When we select a subsample of the SAM galaxies to match the distribution of M_r of the SDSS sample, we find that the mean M_r of galaxies in mergers (where $f_r > 1/9$) in both samples is roughly one magnitude greater than the mean M_r of the global population (Figure 7.6 *bottom*). This agrees with what we found in Figure 6.6, that galaxies observed in mergers tend to be more massive than single-system galaxies.

The denominators of all our observational merger fractions are found by counting the total number of all galaxies with spectral redshifts within the volume-limiting definitions up to $z = 0.1$. E.g. for the low-brightness bin, this means finding all galaxies with spectral redshifts and $-19.5 < M_r < -17.5$ up to $z = 0.026$ for completeness. This makes use of the galaxy-web catalogue to avoid

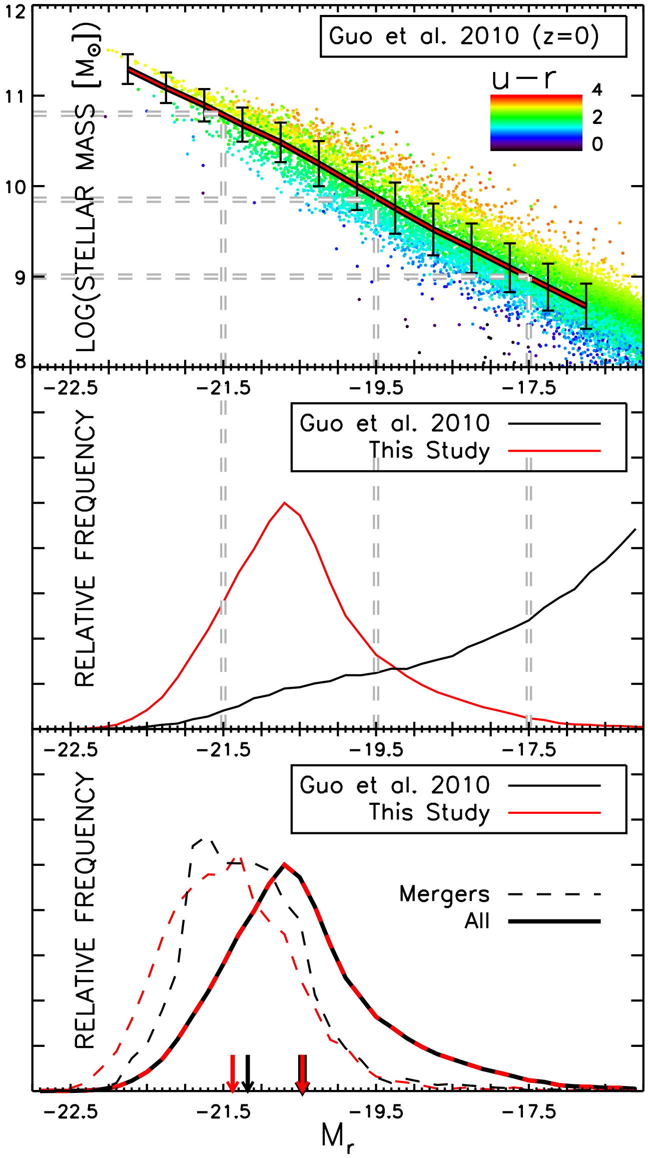


Figure 7.6: Comparison with G10 photometry. *Upper:* SAM galaxies from G10 relating SDSS M_r to stellar mass. *Middle:* unmodified samples; SDSS peaks at $M_r \sim -20.5$, G10 at resolution mass $M^* \sim 10^7 M_\odot$. *Lower:* the G10 galaxies are sampled so as to match the SDSS distribution (solid red-black line) and the broken curves show the distribution of r-band flux of the subset of galaxies in mergers that are at least minor. Arrows show the mean M_r for these samples.

double-counting by sorting out close-by galaxies with more than one spectral object. Obviously this fraction is only based upon the subset of SDSS sky where spectra have been obtained.

The numerators for the major- and minor-merger fractions are found by simply counting the total number of galaxy-webs that are deemed to be merging with a *less luminous galaxy* within the defining limits of $f_m > 1/3$ and $1/3 \leq f_m > 1/9$ respectively.[5]

These results are presented in Table 7.1 along with comparison merger fractions derived from G10. The Millennium database only releases ‘snapshots’ at time intervals of roughly ~ 200Myrs ranging from SN$= 0$ at $z = 127$ to SN$= 63$ at $z = 0$. As before, we can estimate the merger fraction at $z \sim 0$ by finding the progenitors of each descendant galaxy in the merger tree at SN$= 63$ at some earlier snapshot, SN$_{prog}$, with a look-back time corresponding to a sensible time-scale of detectability (illustrated in Figure 6.2, p. 160).

In theory, the method employed here should yield complete merger catalogues and accurate fractions. However, there are a few unavoidable sources of uncertainty. Firstly, poor image quality sometimes makes it difficult to judge whether two galaxies are interacting or not (*viz.* projection effects). Secondly, the time-scale of merger detectability, t_{obs}, depends on the galaxies’ properties and viewing angle. These two problems are somewhat related: interacting galaxies are relatively easy to identify when involving large, gas-rich spirals (with tidal-tail disruptions, etc.) even when the image quality is poor whereas small, spheroidal galaxies usually require high image quality to be classed confidently as interacting.

The time-scale of detectability also depends on merger-location technique (Lotz et al. 2008b; Lotz et al. 2010a; Lotz et al. 2010b). For example, Lotz et al. 2010a show that the asymmetry parameter, A, depends sensitively on the merger-mass ratio with t_{obs} ranging from $0.2 - 0.4$Gyr for major mergers ($M_2/M_1 < 1/3$) of moderate gas content $f_{gas} \sim 0.2$ but dropping off rapidly at $M_2/M_1 \sim 1/5$ such that minor mergers of $M_2/M_1 \sim 1/9$ have $t_{obs} \lesssim 0.06$Gyr.

---

[5] Note: this is different to the definition of the merger fraction used earlier. There, the numerator was defined by counting *all* galaxies in a major merger (defined by stellar-mass 1:3) contained by the volume-limits $M_r < -20.55$ and $0.005 < z < 0.1$. For many systems, this meant that a binary-merger contributed $+2$ to the numerator since, if the more massive is within the brightness limit then the other, being within $1/3$ of the stellar mass, will often also be. This gave a major-merger fraction of $\sim 1.5 - 4.5\%$ with the large error resulting from the need to estimate the fraction within the $f_m < 0.4$ range. If we were to adopt the same definition in this study (except using f_r instead of stellar-mass ratios), we get a major-merger fraction of $\sim 2.6\%$.

Table 7.1: Merger fractions for SDSS (this study) and the Millennium SAM galaxies of G10. Since the SAM merger fractions depend sensitively on the progenitor snapshot (SN$_{prog}$), we include a range of values from SN$_{prog} = 60$ (look-back time of $\Delta t \sim 0.6$Gyr) to SN$_{prog} = 62$ ($\Delta t \sim 0.2$Gyr) which should roughly match the time-scale of detectability for merging systems. We underline the merger fractions from G10 that most closely match the observational value. The errors are Poisson counting statistics.

	Major Merger Fraction ($1 \leq 1/f_r < 3$)			
Mag Bin	SDSS	Guo SN$_{prog}$=62 $\Delta t \sim 0.2$Gyr	Guo SN$_{prog}$=61 $\Delta t \sim 0.4$Gyr	Guo SN$_{prog}$=60 $\Delta t \sim 0.6$Gyr
$-19.5 < M_r < -17.5$	0.28 ± 0.05	0.04 ± 0.01	0.09 ± 0.02	$\underline{0.20 \pm 0.02}$
$-21.5 < M_r < -19.5$	0.65 ± 0.03	0.23 ± 0.04	$\underline{0.54 \pm 0.06}$	0.90 ± 0.07
$M_r < -21.5$	2.58 ± 0.07	0.96 ± 0.23	1.98 ± 0.33	$\underline{2.94 \pm 0.39}$
	Minor Merger Fraction ($3 \leq 1/f_r < 9$)			
Mag Bin	SDSS	Guo SN$_{prog}$=62 $\Delta t \sim 0.2$Gyr	Guo SN$_{prog}$=61 $\Delta t \sim 0.4$Gyr	Guo SN$_{prog}$=60 $\Delta t \sim 0.6$Gyr
$-19.5 < M_r < -17.5$	0.15 ± 0.03	$\underline{0.16 \pm 0.02}$	0.30 ± 0.03	0.46 ± 0.04
$-21.5 < M_r < -19.5$	0.34 ± 0.02	$\underline{0.46 \pm 0.05}$	0.83 ± 0.07	1.38 ± 0.09
$M_r < -21.5$	2.11 ± 0.06	$\underline{1.40 \pm 0.28}$	3.32 ± 0.42	5.21 ± 0.52

How sensitive is visual-detectability to the various factors affecting t_{obs}? Although it is generally easy to visually demarcate different galaxies, determining whether or not they are interacting is probably similar in its dependencies to the asymmetry parameter A. The Gini coefficient is highly sensitive to double nuclei but this means it is prone to classify projections as 'interactions.' The Asymmetry parameter, on the other hand, can yield a very low value for double nuclei[6] making it more resistant to projection effects, but it also makes it sensitive to mass ratio. Since we chose to be conservative in evaluating potential projection effects (relying on the presence of genuine morphological disturbance), visual classification is probably more in tune with A than G.

This means that the time-scale of detectability for visual-classification will depend significantly on merger mass-ratio. To get a handle on how t_{obs} varies for our sample, we compare the merger

---

[6] This is because A is calculated iteratively until the *lowest* value of mirror symmetry is obtained. Double-nuclei images can have a very symmetric distribution of light either side of the line joining the nuclei.

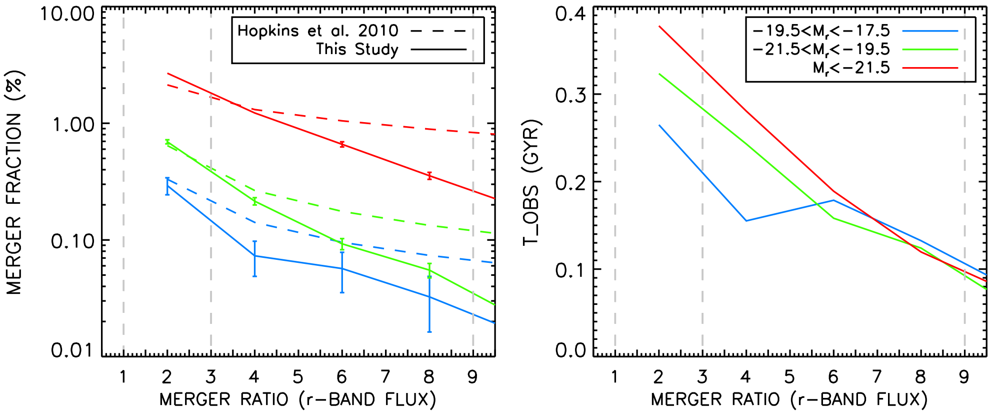


Figure 7.7: *Left panel:* a comparison of the H10 merger fractions, scaled to constant $t_{obs} = 300$Myrs across merger-mass ratio, to this study. The three H10 curves are for the stellar mass ranges $9 < \log \mathrm{M}_1^*/\mathrm{M}_\odot < 10$, $10 < \log \mathrm{M}_1^*/\mathrm{M}_\odot < 11$ and $11 < \log \mathrm{M}_1^*/\mathrm{M}_\odot$ corresponding roughly to the three r-band magnitude intervals used in this study (and merger ratio is in terms of M^* for H10). *Right panel:* t_{obs} for this study determined by matching H10 with our observations.

fraction with the semi-empirical model of Hopkins et al. (2010a) (hereafter H10).

Figure 7.7 (right panel) shows the H10 merger-fraction as a function of mass-ratio for stellar-mass ranges corresponding to the three r-band magnitude intervals used in this study. The H10 fractions are scaled for $t_{obs} = 300$Myrs putting them into close agreement with the major-merger fractions for this study for all three magnitude bins. Similar to the findings of this study, the H10 model exhibits a downward slope with increasing mass-ratio for all three magnitude bins. However, the difference in merger fraction from this study grows with merger ratio, which is not surprising since $t_{obs} = 300$Myrs is large for such marginally-perturbed systems. If we scale t_{obs} for the H10 models so that the fractions match our own (see left panel of 7.7) then we can visualise more explicitly how t_{obs} varies for our sample (assuming we are complete and H10 is accurate).

When we compare this to the models of G10, as shown in Figure 7.8, we see that we get good agreement with the fact that the brightest galaxies have larger merger fractions by factor ~ 10 than the least bright ones. There is also good qualitative agreement with the downward sloping trends in the merger fraction with increased merger-ratio for the bright and intermediate samples *if* we take into account the varying time-scales of detectability. That is, for major mergers, the snapshot(s) that generally agree closest are $SN = 60-61$; but as the merger ratio increases our fractions fall-off

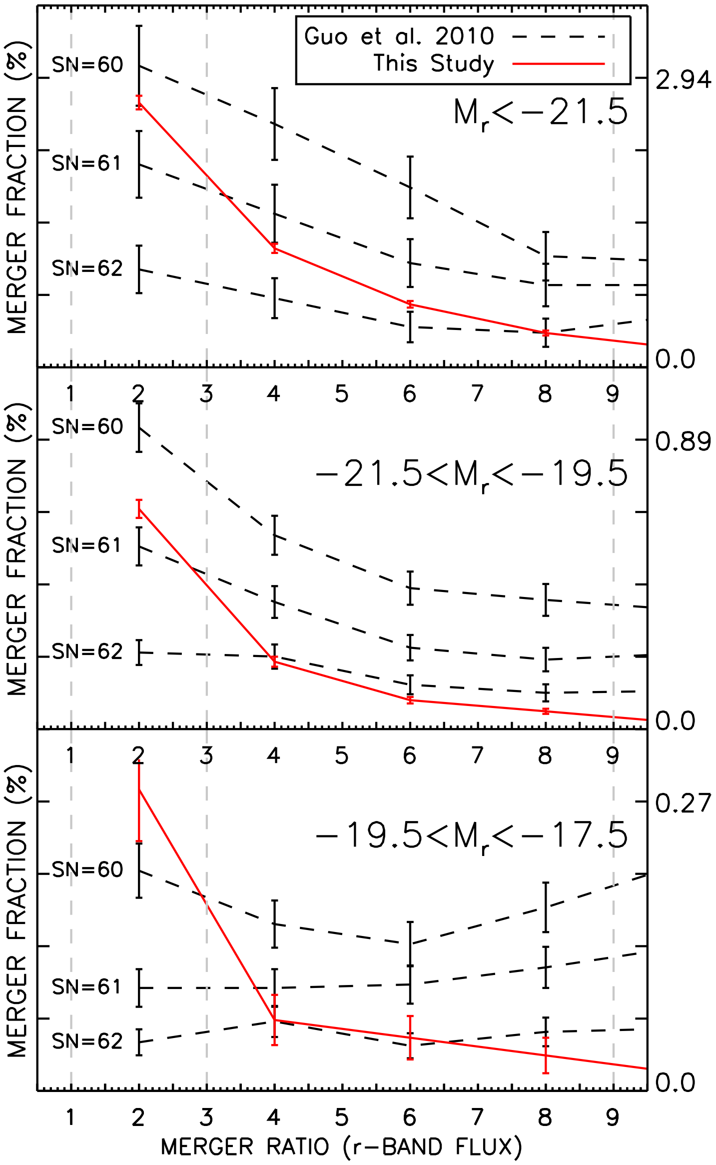


Figure 7.8: Merger-fraction versus merger-ratio distributions comparing observational merging galaxies from this study with SAM merging galaxies from G10. The errors are Poisson counting statistics.

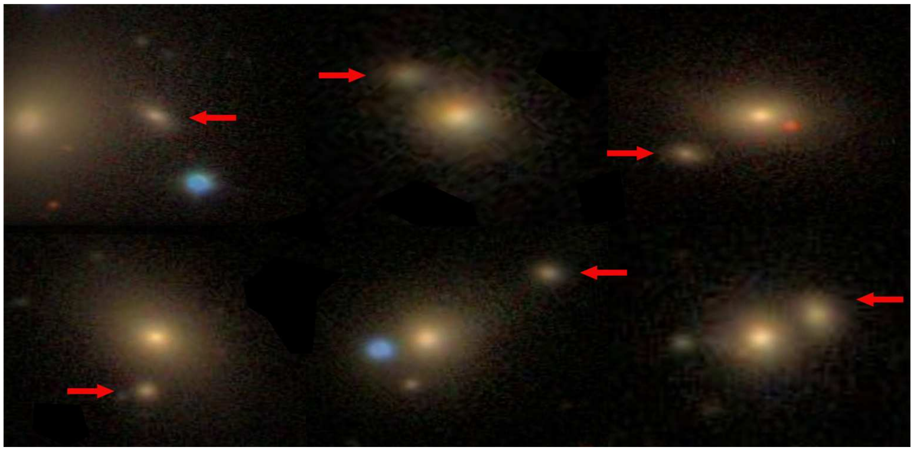


Figure 7.9: Examples demonstrating difficulty of spotting interactions of potential minor mergers with poor image quality. All the same, such difficult decisions are best left for direct visual assessment.

faster - owing to shorter time-scales of detectability - and more closely match the merger fractions derived from the Millennium $SN = 62$ snapshot. The low-brightness G10 galaxies however show a rather flat distribution with merger-ratio - in disagreement with this study and the H10 model.

As a preliminary assessment, these findings are consistent with the possibility that we have managed to locate *every* minor merger in the SDSS sky that is presently interacting though, as always, there is uncertainty stemming from the fact that the synthetic models may have errors and the visual-examination technique is only as good as the images it uses. We illustrate this fact with examples in Figure 7.9 that are borderline: some of these will be interacting, some will be projections. This is unavoidable but, still, visual examination is the closest one will come to effectively finding such systems and separating their photometry in an accurate manner.

7.4 Summary and Discussion

This project required a very large amount of visualisation at near $50,000$ images. This was *highly* time consuming, but effective nonetheless and has commended itself therefore to the larger scale visualisation technique that can only be provided by the Galaxy Zoo project. This has the added advantage of averaging over errors and freeing up research time. The interface need not use the ‘click on the object’ strategy as was used here, but users could be shown one image at a time and make decisions for two objects. For our sample, that would require $50,000 \times 4$ individual assessments, assuming the cut is performed so that each image has an average number of 4 child objects. This is comparable in scale to the first Galaxy Zoo project.

This work is ongoing and the publication to be released will analyse the properties of minor mergers in a volume that has not been accomplished before. Investigations are also underway to see if this same technique can be used with other deblending routines such as sExtractor for application to higher redshift objects. This offers many prospects to investigating the properties of mergers in the Universe that are important to the semi-analytic approach presented in Chapter 3.1 in exploring the anthropic landscape.

Chapter 8

Concluding Remarks

This thesis represents the culmination of many research activities in both philosophy and mainstream astrophysics. In summarising, I wish to draw attention to two chief difficulties to its composition. Firstly, as discussed in the preface, this DPhil was the first of its kind, to my knowledge, in its placement of a doctoral research student in an astrophysics department to work on both astrophysics and philosophy. One of the most difficult challenges of the philosophical component of the thesis had been to decide what question it is that we are trying to answer. Much has already been written on the AP and FTL and the key hypothesis that has grown in popularity out of this literature amongst cosmologists in recent years is the putative existence of infinitely-many, variegated universes that are, in effect, completely unobservable. This raises questions and difficulties that lie at the very heart of the philosophy of science (*viz.* underdetermination, realism vs. empiricism, etc.). For example, what is meant, if anything, by the claim that a generic Multiverse combined with the AP constitutes an 'explanation' of the existence of this 'finely-tuned' Universe?

As pointed out in chapter 2, the concept of 'explanation' is broad and philosophically contentious. To illustrate, some claim that 'transcendent design' is the best 'explanation' of the Universe (e.g. Swinburne) while others say that 'God' is no explanation of anything at all (c.f. Dawkins). I distinguished a form of explanation called *physical explanation* (see p. 51) and argued that the key concept to this form of explanation is *algorithmic compressibility*: does a posited entity or hypothesis serve to reduce the resources (informational? computational?) required to *de-*

scribe the phenomena in question? If so, then it is a “good” physical explanation (or better relative to rival hypotheses that are not as parsimonious in the given sense).

Although not proved herein, for such a contention is probably not amenable to formal analysis, I have suggested that neither of the ‘popular explanations’ for FTL (God or the Multiverse) are ‘explanations’ in this *physical* sense; i.e. positing the existence of an infinity of other universes does nothing to aid us in describing the physical states of *this* Universe, just as asserting ‘God did it’ does not assist in the taxonomy of the phenomena of ‘this world.’[1] Furthermore, I claimed that, plausibly, our existence places constraints (*a posteriori*) on the degree to which the trivial representation of the Universe can be algorithmically compressed; if the Universe were simpler (e.g. requiring fewer free parameters to specify its state), then complex life forms may well not be possible. If so, then we would eventually find that our empirically-adequate descriptions of all hitherto-observed physical phenomena (such as the semi-empirical formulae used in particle physics) can simply not be improved upon. We would be forever left with equations and parameters that must be taken as ‘brute-fact’ and no amount of mathematical manipulation would be able to reduce the number of free-parameters, etc. that feature therein without simultaneously increasing the number of mathematical terms, mappings, etc. needed to generate all empirical measurements.[2] If this is correct then reality, whatever that ‘is’, can only be described ultimately, not explained, and no answer to Leibniz’s question could ever be ascertained as proponents of a final ToE have long hoped.

However, it was noted in the opening chapter that there is a hierarchy of ‘fundamental ques-

---

[1] Note that this choice of word is purposefully vague and provocative, for what is meant by ‘world’ is strongly dependant on one’s preconceived view of reality (the ‘world’ means something different to to the idealist as does to the realist). See, e.g. van Fraassen (2002, p. 5ff.).

[2] A good illustration of this is given by Barrow (2003, p. 73-4) where he compiles various attempts to compute the fine-structure constant from ‘primitive’ mathematical values and functions. For example, one calculation gives $1/\alpha = 2^{19/4}3^{10/3}5^{17/4}\pi^{-2} = 137.03594...$ Suppose that we said α takes its specific value because it is ultimately given by this relation and that the digits agree as far down as experimental determination currently indicates. This would not constitute an explanation because we have not reduced the number of free parameters needed to generate what was found empirically - we needed to place many more integers in specific formulaic relationships. If, on the other hand, we found that this equation actually matched α “all the way down” to arbitrary precision then we *would* have free-parameter reduction (at some point) and thus conclude that there is a genuine ‘physical’ connection. However, there is no avoiding a qualitative decision as to how ‘ad hoc’ or contrived such trade-offs are between complexity in information content (one’s brute-fact list of numbers that the algorithms operate on) and complexity in structure (how many terms/processes are involved in one’s algorithms).

tions' linking Leibniz's ontological question to the realm of axiology and mind (c.f. the ontological, taxological and axiological questions posed on p. 2). Pursuing this connection, it was surprising to find over the course of this research that there are deep philosophical connections between the field of cosmology, especially pertaining to the AP and FTL, and the philosophy of mind. In both fields, *conceivability*, that is, counter-factual analysis, produces a deep sense of dissatisfaction with the position that the particular physical structure of our Universe and the particular mental states that appear to supervene over specific physical states (*viz.* human minds) are to be taken as brute facts. I explored this connection in some depth and showed how the Multiverse hypothesis could easily be extended to 'solve' or 'explain' the mind-body problem in a manner analogous to how it purportedly 'explains' FTL. I took this as an example of how flexible, all-encompassing and, therefore, vacuous the generic Multiverse hypothesis is an 'explanation.' By explaining everything, it really explains nothing. This work is continued in more depth elsewhere where it is argued that mental states are 'fine-tuned' in a manner quite analogous to FTL (Darg 2012b; planned book to be co-authored with J. Silk) and that selection effects parallel to the AP (what we call the 'Noological Principle') must be in operation whenever an observer makes rational deliberations.

The second major difficulty in the production of this thesis was combining these philosophical topics with the mainstream astrophysical research carried out. At first glance, there is little in common between the AP and galaxy morphologies. However, it came to my attention at an early stage of the DPhil that the latter are important for understanding the evolution and abundance of disc-dominated galaxies in the Universe. It also occurred to me that discs are probably more favourable to life as we know it compared to bulge-dominated galaxies. This allowed me to pursue a 'connecting project' using the SAM of chapter 3 in which we varied the cosmological constant. The question we examined was whether changes to this fundamental parameter would result in more or less stars in disc-dominated galaxies which we treated as our proxy for life. Although there are many caveats to this investigation, it was interesting to find that Λ does appear to be within an order of magnitude of the optimal value - keeping all other parameters constant - that would maximise the number of stars in disc galaxies. Reducing Λ results in slower spatial expansion and more accentuated gravitational collapse leading to a great universal merger rate and the conversion of disc-galaxies into bulges. Increasing Λ, on the other hand, means that galaxies don't build up quickly enough, by converting gas to stars and through hierarchical assembly, such that by the time such a universe enters into its de Sitter phase, the galaxy population is dominated by small galaxies in shallow potential wells that lose their gas through ejection and can no longer grow through accretion or merging. The proportion of stars in discs is high, but the global amount of star-formation is significantly suppressed.

This study highlighted the importance of the merging process with regard to the production of galactic habitable zones and thus ties in with the studies carried out on mergers. The first difficulty in studying mergers is the pattern-recognition problem of locating and isolating their photometry in astronomical surveys in a way amenable to scientific analysis. In chapter 4 we explored how the Galaxy Zoo project might help overcome this problem by using it to construct the largest catalogue of merging galaxies to date. It is interesting to note that there is an unavoidable problem as to who or what constitutes the final epistemic authority on such matters. Automated techniques for locating and isolating mergers rely on the ingenuity of the human programmer. All thresholds, algorithms and computational techniques must be deemed sensible (or not) by *humans*, not machines. This requires us to have powerful pattern-recognition capabilities and thus requires us to be in the sort of universe where the pre-requisite conditions for such pattern-recognition capabilities can come about. This connects with discussions as to what 'observational reference class' we fall under with regards to the PoM. Are we, according to this principle, supposed to take ourselves to be typical members of the class of 'observers of *anything*' or of the more specific class of 'scientific societies?' Questions of this nature are typically glossed over in such discussions and illustrate how vague and philosophically nuanced such 'principles' turn out to be.

Furthermore, there is the sociological question as to which *specific humans* oversee the whole pattern-recognition process. The Galaxy Zoo technique works by enlisting volunteers on the internet; but they have no choice regarding the format of the computational interface, the weighting of their decisions[3] and, of course, the many qualitative decisions that were necessary to convert the

---

[3] The decision to weight a user's vote according to how well they agree with the majority opinion (the 'democratic

outputs of the interface to published papers full of graphs and results. All of these decisions are carried out by individual researchers operating according to the sociological distinction between expert and non-expert and there is no way to make progress without this distinction. Hence, there is potential room for criticism of the term ‘citizen science.’

The construction of our mergers catalogue allowed us to carry out detailed investigations regarding the fraction, morphologies, stellar masses, colours, environment, star-formation rates and AGN signatures of galaxies in the local universe. In chapters 4 and 5 we found that spiral galaxies tended to be observed in mergers in greater proportions to their global abundance and attributed this to their longer time-scales of detectability in mergers. Galaxies in mergers tend to be bluer in colour, due to increased star-formation, have marginally greater stellar masses, inhabit slightly denser environments and we found slight evidence that AGN activity is enhanced towards the end of the merger process.

In chapter 6, we used our merger catalogue to test the accuracy of the SAMs of the Millennium Simulation regarding the production of small clusters, what we called ‘multi-mergers.’ This sort of test is important for such models because these SAMs were not ‘tuned’ beforehand to reproduce results specific to multi-mergers. Successful predictions of this sort increase one’s confidence in the use of SAMs when extrapolated to new circumstances such as we did in chapter 3 with ‘counter-factual’ universes. We found good quantitative agreement between the SAMs and our observations with regard to merger fractions (both binary and triple mergers) and good qualitative agreement with regards to their properties.

In the last chapter, we took a step back and assessed the strengths and weaknesses of the GZ approach to merger studies. We found that the original GZ interface did not deliver fully on its initial promise to remove the need for experts to sift through thousands of images and decide which were or were not part of a genuine merger. Rather, it functioned in a manner rather similar to non-parametric techniques, that is, the original GZ interface acted as an initial filter that isolated lots of systems that are *likely* to contain mergers *but* there was still significant contamination (many

---

weight’) was decided by the GZ team. An alternative weighting could have been to scale the weight of a user depending on how well he/she agrees with ‘expert opinion’ on commonly-answered questions (the ‘aristocratic weighting’).

systems were not mergers) and an arbitrary cut-off of the merger-vote fraction was required at $f_m = 0.4$ resulting in significant incompleteness. Experience with these issues lead to the development of a much better synthesis of ‘man-machine’ pattern recognition that uses the algorithms of the SDSS pipeline to first identify systems likely to contain a merger based on whether or not an image had been ‘deblended.’ A graphical interface was then designed and built that allowed individuals to manually ‘re-blend’ the dissected photometries of individual galaxies thus efficiently separating out the components of a merging system.

The result of this process was to double the size of the merger catalogue, greatly reduce the error in our merger fraction estimate, and obtain near-complete catalogues not only of major mergers, but minor as well. We found good quantitative agreement with the latest Millennium SAM and we now aim to promote this technique for future surveys in combination with citizen science projects like Galaxy Zoo. Many other philosophical and astrophysical lines of research have presented themselves over the course of this thesis and this work will hopefully mark the beginning of many projects to come.

Appendix A

Appendix

A.1 The Fine-Tuning of the Universe for Physical Life

This thesis has focussed more on the *interpretation* of the Anthropic Principle (AP) and the ‘fine-tuning’ of our Universe for the existence of physical life as we know it (FTL) rather than trying to *establish* that the Universe is in fact ‘fine-tuned’ in this way. Ideally, one might think that one can separate out these two exercises: first establish FTL according to well understood physics and simple counter-factual analysis (what would happen if we increased the strength of gravity? etc.), then interpret these facts philosophically. Unfortunately, this is too simplistic as there is not a clear distinction between these two exercises and it is worth stating some of the interpretive issues before reviewing examples of FTL.

Problems of fine-tuning are quite unlike the ‘traditional’ problems physicists used to face. In the past, the great problems of physics typically involved disagreement between theory and observation. For example, the ‘ultra-violet’ catastrophe pertaining to black-body radiation helped bring about the replacement of the former mathematical formalism of classical theory with that of quantum mechanics. Theory then matched observation, the extra parameters required by the quantum formalism were measured (namely h) and the scientific community moved on to new problems. Nowadays the formalism of quantum field theory exhibits few (if any) disagreements with observation. So why is the scientific community not content with the standard model as it is empirically adequate? One of the key reasons is that there are many free parameters (rendering these theories more ‘descriptive’ than ‘explanatory’) and, as we have discussed, there is a deep-set belief amongst physicists that some principle of paramount simplicity must connect *all* physical phenomena *qua* a putative ToE. Moreover, these parameters seem (as a first gloss) to be too specifically ‘life-friendly’ to be attributable to chance alone.

How this latter judgment is reached is no trivial issue as no one has found a convincing formal basis on which to speak of ‘chance’ in this context. In particular, a key dispute in the philosophical literature is the issue of “coarse-tuning”: how, if at all, can one interpret examples of parameter-sensitivity in a probabilistic manner? Suppose that some dimensionless constant, such as α, is subject to anthropic bounds such that its value must lie within the interval $\alpha_{lower} < \alpha < \alpha_{upper}$ in order for life to be possible.[1] What is meant by the claim that the real-line segment $(\alpha_{lower}, \alpha_{upper})$ is small? Compared to what is it small? If compared to the infinite real line then *any* finite interval - even one billions of orders of magnitude larger than the parameter itself - would measure infinitesimally in probability space. From this, McGrew et al. (2001) conclude that probabilistic interpretations are meaningless while Koperski, on the other hand, suggests we “bite the bullet, stand by the mathematics, and say that a coarse-tuned universe *would* require an explanation” (Koperski (2005, p. 312)) and attribute as infinitesimally improbable *any* occurrence of a parameter with an anthropic bound.

We mention this in order to show that ‘giving examples of FTL’ is *not* a straightforward application of counter-factual physics. The physics may be sound (vary α by factor x and life is inhibited), but whether the reader admits any such example into the category of ‘fine-tuning’ that ‘requires explanation’ is, as we have discussed in this thesis, a matter of considerable personal psychology. For what appears ‘natural’ to the reader and ‘cries out for explanation’ will depend on one’s view of the world, their acquaintance with physics, their philosophical perspectives on the importance and nature of simplicity, ‘naturalness,’ Ockham’s Razor, their willingness to hold out for some hitherto-unknown dynamical principle that would remove any appearance of anthropic contrivance (as inflation has to the flatness problem), etc.

As an example of the subtle issues involved, consider Penrose’s calculation that the entropy

---

[1] According to Barrow (2003, p. 166) the specific values are $1/180 < \alpha \approx 1/137 < 1/85$.

of the very early Universe corresponds to a phase space some $10^{10^{123}}$ times smaller than the phase space of a black hole having the same number of particles (see Penrose 1999, p. 440-7). If one were to take this ratio as a straight-forward probability, it would *easily* constitute the most impressive example of 'fine-tuning' in the literature. However, it rarely is regarded in this way - why not? The answer is probably connected to the fact that this constraint was necessary for the early Universe to be (near) perfectly smooth and uniform and something *feels* 'simple' or 'natural' about the Universe starting off in this way. (It also corresponds to the Weyl curvature tensor equalling zero, and zero is usually considered to be a 'natural' number for Nature to work around.)

Having laid out these subtle caveats, it remains the case, nonetheless, that all that is needed to establish fine-tuning is to make plausible the claim that the volume in parameter-space of fundamental parameters (constants and universal boundary conditions) that is amenable to life is significantly *smaller* than the volume in which life is prohibited for one reason or another. (See discussion in §3 where this parameter space is represented by the 31-element vector p_i.) Here are a few examples. (For an in depth review of all examples of fine-tuning in the literature, see Barnes 2011.)

The Cosmological Constant:

The fine-tuning problem that has received the most attention concern's Einstein's constant that appears to be set to cancel out the vacuum energy arising from particle interactions - in the low energy limit after the Universe has cooled and undergone phase transitions through symmetry breaking - to some $\sim 60-120$ orders of magnitude (depending on what cut off one chooses for contributing modes of energy to each field; see Weinberg 1987b; Bousso 2008 for reviews). If inflation is correct, then disparities between Einstein's constant λ and that arising from the vacuum $8\pi G < \rho >$ would have helped drive the expansion. Unlike the case of Penrose's entropy calculation, zero does not feature in this problem. A non-zero value of the effective cosmological constant $\Lambda = \lambda + 8\pi G < \rho >$ has been effectively measured (see §3) and results in a Universe which is only now entering the vacuum-dominated phase. How it is that λ happens to be set to *such* a precise value so that *we* happen to be able to exist *and* to detect it (thus enabling us to learn about the Multiverse?) appears to be a staggering pair of coincidences that has fuelled much debate and given motivation to the development of mechanisms that would generate eternal inflation with a wide-range of cosmological constants sprouting forth in bubble universes (c.f. the String landscape).

The Strong and Electromagnetic Force:

Whatever one may glean from counterfactual analysis, one thing is undoubtedly clear - the stability of atoms and molecules depends upon the balancing of several forces of different strengths and ranges and these could easily have been disrupted by altering the values of the coupling constants. For example, the stability of nuclei depends on the counterbalancing of electromagnetic and strong forces such that, in order for biologically useful nuclei above $Z = 5$ to be stable, the strong force could not be reduced by any more than 50% of its actual value (Barrow & Tipler 1996, p. 327). In order to produce both Carbon and Oxygen - elements essential to life - the strong force could not have been increased by more than a 0.5% or stellar nucleosynthesis would have been significantly altered (Oberhummer et al. 2000). Also, if the strong force were increased by a few percent, two protons would bind (Barrow & Tipler 1996, p. 321) and all of the hydrogen in the Universe would have burnt to helium in the early stages of the Big Bang. Without hydrogen, stars would burn too fast stable planetary life to evolve and no complex molecular compounds involving hydrogen would have existed.

Q - the standard deviation of the amplitude of primordial density perturbations:

As discussed in §3.1, the amplitude of primordial fluctuations is tied in with Λ. However, keeping Λ and all other parameters constant, Tegmark (1998) found that deviations from the observed value of $Q \sim 10^{-5}$ by an order of magnitude results in either no galaxy formation or structures that are dangerously clumpy for stable planets to survive the billions of years that are required.

Baryon-Anti Baryon Asymmetry:

At the earliest moments of the Universe, an asymmetry came about whereby baryons outnumbered anti-baryons by one part in 10^9. All but this small fraction annihilated leaving 10^9 photons for

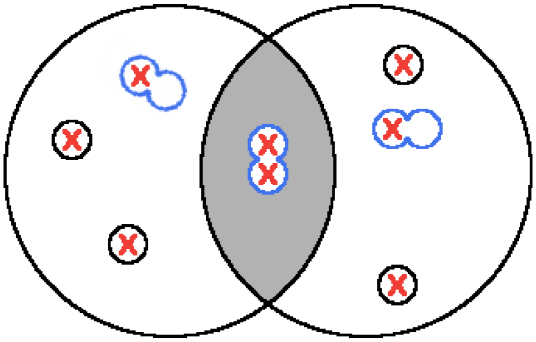


Figure A.1: An illustration of the SDSS spectroscopic tiling scheme. The overlap region shaded grey covers a fraction k_{sky} of the area. Strongly-perturbed systems are coloured with blue outlines and single galaxies black. Those targets which receive spectra are marked with a red cross. Here we only consider systems where some strongly-perturbed spectral objects are merging with spectral targets.

every baryon left over. Had the symmetry been more precise, then fewer baryons would have been left over and galaxies would not have been able to form. If significantly more baryons had been left over (and the abundance DM remained constant), then Silk Damping would have smoothed out the inhomogeneities needed for galaxies to form (Tegmark et al. 2006 suggest an order of magnitude difference would have been sufficient for this disaster).

A.2 Estimating the Merger Fraction Using Spectral Objects

Here we clarify some of the subtle issues that arise when attempting to estimate the merger fraction of the universe. It was claimed in §4.3.1 that one could use spectral objects alone to obtain an accurate estimate of the merger fraction. This is true even though a sizable number of galaxies in the universe are strongly-perturbed but do not have spectra due to fiber collisions (two spectral targets within $55''$ cannot both obtain spectra in regions with only a single tiling). In overlap regions, there is near spectral completeness for spectral targets (Strauss et al. 2002; Blanton et al. 2003; see Figure A.1).

In calculating the merger fraction, we only use spectral objects belonging to the Main-Galaxy-Spectroscopic sample (MGS) in SDSS. This is the collection of targets identified photometrically as galaxies (but not quasars or luminous red-galaxies; Stoughton et al., 2002; Strauss et al., 2002) with $r < 17.77$ and is intended for statistical sampling of galaxies from a uniform population

(Strauss et al., 2002).

Figure A.1 depicts a simple tiling scheme analogous to that employed by SDSS (Blanton et al., 2003). The shaded area represents the overlap which we say covers a fraction k_{sky} of the tiled area (for SDSS $k_{sky} \sim 30\%$). Two objects within $55''$ in non-overlap regions suffer from fiber-collision so that only one can get measured. Within overlap regions virtually all targets get measured due to multiple tiling opportunities. Altogether about 6% of all MGS targets do not obtain spectral measurements due to fiber collisions (Strauss et al., 2002). These are, of course, the objects most likely to be of interest in a mergers study though many might be projections, so one cannot assume they are part of a perturbed system.

We argue now that our estimate for the fraction of ‘strongly-perturbed’ volume-limited MGS objects (f_{mgs}) is, upto a correction factor close to unity, a good approximation to the ‘real’ fraction of volume-limited galaxies (f_{real}). For simplicity, let us begin with a sky as depicted in Figure A.1 involving only galaxies which are bright enough to be spectral targets and where some of these might be in the process of a binary merger such that they are within $55''$ of another spectral target. We assume that mergers are randomly distributed with respect to tile-overlap regions. Let the number of single (i.e. non-perturbed) galaxies be N_s and the number of binary-merger *pairs* be N_m. The merger fraction that we calculated, f_{mgs}, would therefore be

$$\begin{aligned} f_{mgs} &= \frac{2k_{sky}N_m + (1-k_{sky})N_m}{2k_{sky}N_m + (1-k_{sky})N_m + N_s} \qquad (A.1) \\ &= \frac{N_m(1+k_{sky})}{N_m(1+k_{sky}) + N_s}. \qquad (A.2) \end{aligned}$$

The real merger fraction, (f_{real}) should take account of everything regardless of overlap regions so that the fraction of strongly perturbed spectral targets is

$$f_{real} = \frac{2N_m}{2N_m + N_s}. \qquad (A.3)$$

Now we let the ratio of binary-merger pairs N_m to single galaxies in the local universe equal p. Taking the ratio of (A.2) and (A.3) and substituting $N_m = pN_s$ will give the corrective factor, C, relating our fraction to the real fraction:

$$C(k_{sky}, p) = \frac{f_{real}}{f_{mgs}} = \frac{2(1 + pk_{sky} + p)}{(2p+1)(1+k_{sky})}. \quad \text{(A.4)}$$

When $k_{sky} = 1$ (i.e. when the whole sky is an overlap region) we get $f_{real} = f_{mgs}$. For realistic values like $k_{sky} \sim 30\%$, $p \sim 5\%$ we get a ratio $C(k_{sky} = 0.3, p = 0.05) \sim 1.5$ and we find that (A.4) is not very sensitive to changes in p. Multi-mergers have the affect of increasing C but are rare enough to be ignored (only comprising $\sim 1\%$ of the merging-pairs catalogue) and so we can take our corrective factor to be $C = 1.5$.

A.3 Environment and Masses of Combined Morphologies for Merger and Control Sample

It was claimed in §5.3 with reference to Figure 5.3 that merging galaxies appeared to occupy very similar, if not, denser environments for both ellipticals and spirals compared to their control counterparts. A very similar set of results was claimed in §4.3.2 with reference to Figure 5.5 suggesting that merging galaxies possessed very similar, if not, more massive stellar masses than their control counterparts. In both cases, the excesses appeared slightly higher for ellipticals, though still only with a ~ 2dex difference in the means for both ρ_g and M*.

However, the morphologies for the two samples were selected by different means (the mergers visually by DWD and the control sample by GZ data as described in §5.2.1). In particular the control sample, when divided into ellipticals and spirals, was rendered incomplete by the stipulation that $|f_e - f_s| < 0.1$. We therefore reproduce Figures 5.3 and 5.5 in Figures A.2 and A.3 without distinguishing morphologies.

These figures confirm the basic result that for both environment and stellar masses, the merger and control distributions are very similar with the mergers exhibiting a very slight excess in both cases with respect to their mean values. However this is significant since, as argued in D09a, the merger sample has a high spiral-to-elliptical ratio compared to the global population which is represented here by the control sample. This should decrease the mean-values of the mergers for

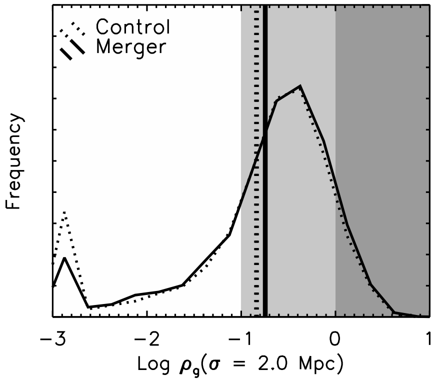


Figure A.2: Combined-morphologies version of Figure 5.3.

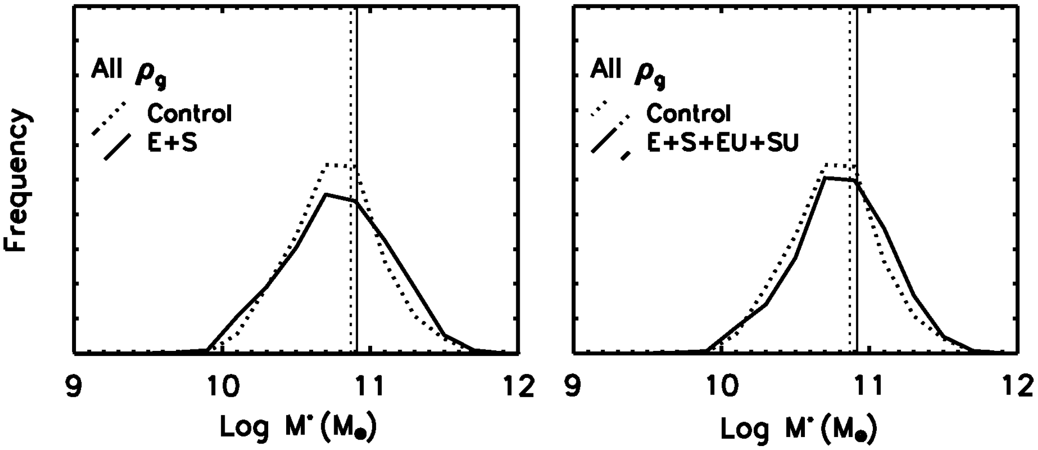


Figure A.3: Combined-morphologies version of Figure 5.5.

both environment and stellar mass since spirals are known to be less massive and occupy less dense environments than ellipticals. To put this in other words, the mergers manage to ‘keep up’ with the control sample despite the handicap of a high spiral population which strengthens the claim that mergers do in fact have a slight excess in mass and environmental density compared with the global population.

Bibliography

Abraham, R., denBerghS. van, Nair, P. & al. et, 2003. ApJ, **588**, 218A.

Adams, R. M., 1982. Leibniz's Theories of Contingency. In M. Hooker, ed., Leibniz: Critical and Interpretive Essays, 225–40. University of Minnesota Press, Minneapolis.

Aguirre, A., 2007. Making predictions in a multiverse: conundrums, dangers coincidences. In B. Carr, ed., Universe or Multiverse?, 367. Cambridge University Press, Cambridge.

Aguirre, A., Johnson, M. C. & Shomer, A., 2007. Towards observable signatures of other bubble universes. Phys. Rev. D, **76**, 063509.

Alonso, M., Lambas, D., Tissera, P. & Coldwell, G., 2007. MNRAS, **375**, 1017.

Amram, P., Mendes de Oliveira, C., Plana, H., Balkowski, C. & Hernandez, O., 2007. A&A, **471**, 753.

Ashok, S. K. & Douglas, M. R., 2004. JHEP, **01**, 060.

Atkins, P. W., 1995. The limitless power of science. In J. Cornwell, ed., Nature's Imagination: The Frontiers of Scientific Vision, 122–32. Oxford University Press, New York.

Baillard, A. et al., 2011. A&A, **532**, 74.

Baldwin, A. J., Phillips, M. M. & Terlevich, R., 1981. PASP, **93**, 5B.

Ball, N., Loveday, J. & Brunner, R., 2008. MNRAS, **383**, 907B.

Ball, N., Loveday, J., Fukugita, N., Nakamura, O., Okamura, S., Brinkmann, J. & Brunner, R., 2004. MNRAS, **348**, 1038.

Bamford, S. et al., 2009. MNRAS, **393**, 1324.

Bamford, S. P., Rojas, A. L., Nichol, R. C., Miller, C. J., Wasserman, L., Genovese, C. R. & Freeman, P. E., 2008. MNRAS, **391**, 607.

Barbour, J., 2011. Bit from It. `http://platonia.com/bit_from_it.pdf`.

Barnes, L., 2011. The Fine-Tuning of the Universe for Intelligent Life. Arxiv:1112.4647.

Barrau, A., 2007. Physics in the multiverse. Cern Courier, (20).

Barrow, J. D., 1991. Theories of Everything. Oxford University Press, Oxford.

Barrow, J. D., 2003. From Alpha to Omega The Constants of Nature. Vintage Press, London. First Published 2002.

BARROW, J. D., 2007. Living in a simulated universe. In B. Carr, ed., Universe or Multiverse?, 481–6. Cambridge University Press, Cambridge.

BARROW, J. D. & TIPLER, F. J., 1996. The Anthropic Cosmological Principle. Oxford University Press, New York. First Published 1988.

BARTON, E., ARNOLD, J., ZENTNER, A., BULLOCK, J. & WECHSLER, R., 2007. AJ, **671**, 538.

BARTON, E. J., GELLER, M. J. & KENYON, S. J., 2000. ApJ, **530**, 660.

BAUGH, C., LACEY, C., FRENK, C., GRANATO, G., SILVA, L., BRESSAN, A., BENSON, A. & COLE, S., 2005. MNRAS, **356**, 1191.

BAUGH, C. M., 2006. Rep. Prog. Phys., **69**, 3101.

BEKKI, K., 2001. ApJ, **546**, 189.

BELL, E., PHLEPS, S., SOMERVILLE, R., WOLF, C., BORCH, A. & MEISENHEIMER, K., 2006. ApJ, **652**, 270B.

BENSON, A., BOWER, R., FRENK, C., LACEY, C., BAUGH, C. & COLE, S., 2003. ApJ, **599**, 38.

BENSON, A., DŽANOVIĆ, D., FRENK, C. & SHARPLES, R., 2007. MNRAS, **379**, 841.

BENSON, A., LACEY, C., BAUGH, C., COLE, S. & FRENK, C., 2002. MNRAS, **333**, 156.

BERKELEY, G., 1710. A Treatise Concerning the Principles of Human Knowledge.

BERNARDI, M. & AL. ET, 2003. AJ, **125**, 1817B.

BERTONE, S. & CONSELICE, C., 2009. MNRAS, **396**, 2345.

BERTONE, S., DE LUCIA, G. & THOMAS, P. A., 2007. MNRAS, **379**, 1143.

BLACKBURN, S., 1990. Filling in Space. Analysis, **50**(2), 62–5.

BLANTON, M. & AL. ET, 2003b. AJ, **125**, 2348.

BLANTON, M., LIN, H., LUPTON, R., MALEY, F., YOUNG, N., ZEHAVI, I. & LOVEDAY, J., 2003. AJ, **125**, 2276.

BLAU, S. K. & GUTH, A. H., 1987. Inflationary Cosmology. Cambridge University Press, Cambridge.

BOND, J., COLE, S., EFSTATHIOU, G. & KAISER, N., 1991. ApJ, **379**, 440.

BORDE, A., GUTH, A. H. & VILENKIN, A., 2003. Inflationary Spacetimes Are Incomplete in Past Directions. PhRvL, **90**, 1301–4.

BOSTROM, N., 2003a. Anthopric Bias. Routledge Press, New York.

BOSTROM, N., 2003b. Are We Living in a Computer Simulation? Philosophical Quarterly, **53**(211), 243Ð12.

BOURGET, D. & CHALMERS, D. J., 2009. The PhilPapers Surveys.

BOUSSO, R., 2008. The cosmological constant. Gen Relativ Gravit, **40**, 607–37.

BOUSSO, R. & POLCHINSKI, J., 2000. Quantization of four-form fluxes and dynamical neutralization of the cosmological constant. JHEP, **6**, 6.

BOWER, R., 1991. MNRAS, **248**, 332.

BOWER, R., BENSON, A., MALBON, R., HELLY, J., FRENK, C., BAUGH, C., COLE, S. & LACEY, C., 2006. MNRAS, **370**, 645.

BOYLE, L. A., STEINHARDT, P. J. & TUROK, N., 2006. Phys. Rev. Lett., **96**, 111301.

BRINCHMANN, J., CHARLOT, S., WHITE, S., TREMONTI, C., KAUFFMANN, G., HECKMAN, T. & BRINKMANN, J., 2004. MNRAS, **351**, 1151.

BRUZUAL, G. & CHARLOT, S., 2003. MNRAS, **344**, 1000.

BUNDY, K., ELLIS, R. & CONSELICE, C., 2005. AJ, **625**, 621.

BUNDY, K., FUKUGITA, M., ELLIS, R., TARGETT, T., BELLI, S. & KODAMA, T., 2009. ApJ, **697**, 1369.

BURKERT, A. & KHOCHFAR, S., 2003. AJ, **597**, 117.

CALZETTI, D., ARMUS, L., BOHLIN, R., KINNEY, A., KOORNNEEF, J. & STORCHI-BERGMANN, T., 2000. ApJ, **533**, 682.

CAPAK, P., ABRAHAM, R., ELLIS, R., MOBASHER, B., SCOVILLE, N., SHETH, K. & KOEKEMOER, A., 2007. ApJS, **172**, 84.

CAPPELLARI, M. & EMSELLEM, E., 2004. PASP, **116**, 138.

CARDAMONE, C. ET AL., 2009. MNRAS, **399**, 1191C.

CARLBERG, R. ET AL., 2000. ApJ, **532**, 1.

CARR, B. J. & REES, M. J., 1979. The anthropic principles and the structure of the physical world. Nature, **278**, 605–612.

CARROLL, S. M., PRESS, W. H. & TURNER, E. L., 1992. ARA&A, **30**, 499.

CARTER, B., 1974. Large Number Coincidences and the Anthropic Principle in Cosmology. In M. S. Longair, ed., Confrontation of Cosmological Theories with Observational Data, vol. 63 of IAU Symposium.

CARTER, B. & MCCREA, W. H., 1983. The Anthropic Principle and its Implications for Biological Evolution. Phil. Trans. R. Soc. Lond. A, **310**, 347–363.

CARTWRIGHT, N., 2002. Where The Laws of Physics Lie. Oxford University Press, New York. First Published 1983.

CATTANEO, A., DEKEL, A., DEVRIENDT, J., GUIDERDONI, B. & BLAIZOT, J., 2006a. MNRAS, **370**, 1651.

CATTANEO, A. ET AL., 2006b. MNRAS, **377**, 17.

CHALMERS, D. J., 1995. The Puzzle of Conscious Experience. Scientific American, **273**, 80–6.

CHALMERS, D. J., 1996. The Conscious Mind. Oxford University Press, USA. Reprint 1997.

CHALMERS, D. J., 2010. The Character of Consciousness. Oxford University Press, New York.

CHISHOLM, R. M., 1991. Mind. In H. Burkhart & B. Smith, eds., Handbook of Metaphysics and Ontology, vol. II. Philosophia Verlag, Munich.

CHURCHLAND, P. M., 1995. MIT Press, USA.

CHURCHLAND, P. M., 2000. A new Approach to Human Cognition and its Significance for the Philosophy of Science. In E. Agazzi & M. Pauri, eds., The Reality of the Unobservable, 59–86. Kluwer Academic Publishers, The Netherlands.

CHURCHLAND, P. S., 1987. Epistemology in the Age of Neuroscience. Journal of Philosophy, **84**, 548–49.

CHURCHLAND, P. S., 1998. The Hornswoggle Problem. In J. Shear, ed., Explaining Consciousness - The 'Hard Problem'. MIT Press, USA.

COLE, G., 1991. Theological Utilitarianism and the Eclipse of the Theistic Sanction. Tyndale Bulletin, **42**(2), 226–244.

COLE, S., LACEY, C., BAUGH, C. & FRENK, C., 2000. MNRAS, **319**, 168.

COLE, S. ET AL., 2001. MNRAS, **326**, 255.

COLLINS, R., 2009. Teleological argument: an exploration of the fine-tuning of the universe. In W. L. Craig & J. P. Moreland, eds., Blackwell Companion to Natural Theology, ??? Wiley-Blackwell, UK.

CONSELICE, C., 2003a. ApJS, **147**, 1.

CONSELICE, C., 2003b. ApJS, **147**, 1.

CONSELICE, C., 2006. AJ, **638**, 686.

CONSELICE, C., 2006b. AJ, **638**, 686.

CONSELICE, C., BERSHADY, M., DICKINSON, M. & PAPOVICH, C., 2003. ApJS, **126**, 1183.

CONSELICE, C., RAJGOR, S. & MYERS, R., 2008. MNRAS, **386**, 909.

COX, T., JONSSON, P., SOMERVILLE, R., PRIMACK, J. & DEKEL, A., 2008. MNRAS, **384**, 386.

COX, T. & LOEB, A., 2008. MNRAS, **386**, 461.

CROTON ET AL., 2006. MNRAS, **365**, 11.

CUI, J., XIA, X., DENG, Z., MAO, S. & ZOU, Z.-L., 2001. IAUS, **205**, 172.

DARG, D. W., 2012. Cosmic If-Statements. In C. C. Knight, ed., God and Physics - Exploring the work of John Polkinghorne. Ashgate Publishers. Forthcoming, 2012.

DARG, D. W., 2012b. The Fine Tuning of Consciousness. Forthcoming.

DARWIN, C. R., 1989. The Expression of the Emotions in Man and Animals. William Pickering, London. First edition published in 1872. Second edition edited by Francis Darwin and published in 1890.

DARWIN, C. R., 1998. The Origin of Species. Oxford University Press, Oxford. First published 1859.

DAVIES, P., 1993. The Mind of God. Penguin Books, St Ives, England.

DAVIES, P. C. W., 1991. Why is the world so comprehensible. In W. H. Zurek, ed., Complexity, Entropy and the Physics of Information, vol. VIII, 61–70. Addison-Wesley Publishing Company, USA. The proceedings of the 1988 workshop on complexity, entropy and the physics of information, Santa Fe New Mexico, 1989.

DAVIES, P. C. W., 1995. Algorithmic compressibility, fundamental and phenomenological laws. In F. Weinert, ed., The Laws of Nature, 248–67. Walter de Gruyter, Berlin.

DAVIES, P. C. W., 2003. The Appearance of Design in Physics and Cosmology. In N. A. Manson, ed., God and Design, 147–154. Routledge, London.

DAVIES, P. C. W., 2007. Universes galore: Where will it all end? In B. Carr, ed., Universe or Multiverse?, 487–505. Cambridge University Press, Cambridge.

DE LAPPARENT, V., BAILLARD, A. & BERTIN, E., 2011. A&A, **532**, 75.

DE LUCIA, G. & BLAIZOT, J., 2007. MNRAS, **375**, 2.

DE LUCIA, G., BOYLAN-KOLCHIN, M., BENSON, A., FONTANOT, F. & MONACO, P., 2010. MNRAS, **406**, 1533.

DE LUCIA, G., KAUFFMANN, G., SPRINGEL, V., WHITE, S., LANZONI, B., STOEHR, F., TORMEN, G. & YOSHIDA, N., 2004b. MNRAS, **348**, 333.

DE LUCIA, G., KAUFFMANN, G. & WHITE, S. D. M., 2004a. MNRAS, **349**, 1101.

DE LUCIA, G., SPRINGEL, V., WHITE, S., CROTON, D. & KAUFFMANN, G., 2006a. MNRAS, **366**, 499.

DE LUCIA, G., SPRINGEL, V., WHITE, S. D. M., CROTON, D. & KAUFFMANN, G., 2006b. MNRAS, **366**, 499.

DE SIMONE, A., GUTH, A. H., LINDE, A., NOORBALA, M., SALEM, M. P. & VILENKIN, A., 2010. Boltzmann brains and the scale-factor cutoff measure of the multiverse. Physical Review D, **82**(063520).

DEKEL, A. & BIRNBOIM, Y., 2008. MNRAS, **383**, 119.

D'ESPAGNAT, B., 1983. In Search of Reality. Springer-Verlag, New York.

D'ESPAGNAT, B., 2006. On Physics and Philosophy. Princeton University Press, Princeton.

DEVEREUX, N., WILLNER, S., ASHBY, M., WILLMER, C. & HRILJAC, P., 2009. ApJ, **702**, 955.

DI MATTEO, T., SPRINGEL, V. & HERNQUIST, L., 2005. Nature, **433**, 604.

DRESSLER, A., 1980. AJ, **236**, 351.

DUHEM, P. M. M., 2003. Sauver les apparences. Librairie Philosophique J. Vrin, Paris, France. 2nd Edition. First edition published 1908.

EDDY, M. D. & KNIGHT, D., 2008. Introduction. In Natural Theology. Oxford University Press, New York.

EINSTEIN, A., archives. In Einstein Archives.

ELLIS, G. F. R., 1999. In J. Leslie, ed., Modern Cosmology & Philosophy. Prometheus Books, New York.

ELLIS, G. F. R., 2008. Issues in the Philosophy of Cosmology. Arxiv:0602280.

ELLIS, G. F. R., 2011. Cosmology: The untestable multiverse. Nature, **469**, 294–5.

ELLIS, G. F. R., KIRCHNER, U. & STOEGER, W. R., 2004. Multiverses and physical cosmology. MNRAS, **347**, 921.

ELLIS, G. F. R. & STOEGER, W. R., 2009. A Note on Infinities in Eternal Inflation. GReGr, **41**.

ELLIS, J., 1986. The Superstring: Theory of Everything, or of Nothing? Nature, **323**, 595–598.

ELLIS, R. & SILK, J., 2007. arXiv:0712.2865, **xx**, xx.

ELLISON, S., PATTON, D., SIMARD, L. & MCCONNACHIE, A., 2008. AJ, **135**, 1877.

FAKHOURI, O. & MA, C.-P., 2008. MNRAS, **386**, 577.

FAKHOURI, O., MA, C.-P. & BOYLAN-KOLCHIN, M., 2010. MNRAS, **406**, 2267.

FONT, A., BOWER, R., MCCARTHY, I., BENSON, A., FRENK, C. S., HELLY, J., LACEY, C., BAUGH, C. & COLE, S., 2008. MNRAS, **389**, 1619.

FORGAN, D. H. & RICE, K., 2010. IJAsB, **9**, 73.

FUKUGITA, M. ET AL., 2007. AJ, **134**, 579.

GARFINKEL, A., 1981. Forms of Explanation. Yale University, USA.

GARRIGA, J. & VILENKIN, A., 2006. Anthropic Prediction for ? and the Q Catastrophe. PThPS., **163**, 245.

GEARY, D. C., 1998. Male, Female: the evolution of human sex differences. American Psychological Association.

GELLER, M. J. & WOODS, D. F., 2007. AJ, **134**, 527.

GENZEL, R., TACCONI, L., RIGOPOULOU, D., LUTZ, D. & TECZA, M., 2001. ApJ, **563**, 527.

GLEISER, M., 2004. The three origins: cosmos, life, and mind. In J. D. Barrow, P. C. W. Davies & C. L. H. Jr., eds., Science and Ultimate Reality: Quantum Theory, Cosmology, and Complexity, 637–653. Cambridge University Press, Cambridge.

GONZALEZ, G., BROWNLEE, D. & WARD, P., 2001. The Galactic Habitable Zone: Galactic Chemical Evolution. Icar, **152**, 185.

GOULD, S., 1987. The Flamingo's Smile. Penguin, London.

GOWANLOCK, M. G., PATTON, D. R. & MCCONNELL, S. M., 2011. A Model of Habitability Within the Milky Way Galaxy.

GRAESSER, M. L., HSU, S. D. H., JENKINS, A. & WISE, M. B., 2004. Anthropic Distribution for Cosmological Constant and Primordial Density Perturbations. Physics Letters B, **600**, 15.

GREENE, B., 2011. The Hidden Reality. Allen Lane, Penguin Group, UK.

GUO, Q. ET AL., 2011. MNRAS, **413**, 101.

HALDANE, J. B. S., 1927. Possible worlds and other essays. Chatto & Windus, London.

HAMILTON, A. J. S., 2001, vol. 322.

HARKER, G., COLE, S., HELLY, J., FRENK, C. & JENKINS, A., 2006. MNRAS, **367**, 1039.

HART, M. H., 1999. Atmospheric Evolution, the Drake Equation, and DNA: Sparse Life in an Infinite Universe. In J. Leslie, ed., Modern Cosmology & Philosophy, 262–72. Prometheus Books, New York.

HARTLE, J., 2007. Anthropic Reasoning and Quantum Cosmology. In B. Carr, ed., Universe or Multiverse?, 275–84. Cambridge University Press, Cambridge.

HAWKING, S. & ISRAEL, W., 1979. General Relativity: An Einstein Centenary Survey. Cambridge University Press, Cambridge. Introduction.

HAWKING, S. & MLODINOW, L., 2010. The Grand Design. Bantam Books, ???

HEISENBERG, W., 1949. The Physical Principles of the Quantum Theory. Dover Publications, USA. First Published in 1930 by University of Chicago Press.

HEMPEL, C. G., 1969. Reduction: Ontological and Linguistic Facets. In S. Morgenbesser, P. Suppes & M. White, eds., Philosophy, science, and method: essays in honor of Ernest Nagel, ??? St. Martin's Press, New York.

HICKS, W. M., 1895. Presidential address to the section of mathematical and physical science. British Association for the Advancement of Science, 596–606.

HOLDER, R. D., 2004. God, the multiverse, and everything: modern cosmology and the argument from design. Ashgate Publishers, Aldershot.

HOLMAN, R., MERSINI-HOUGHTON, L. & TAKAHASHI, T., 2008. PhRvD, **77**, 3510.

HOPKINS, A. ET AL., 2003. ApJ, **599**, 971.

HOPKINS, P., COX, T., YOUNGER, J. & HERNQUIST, L., 2009. ApJ, **691**, 1168.

HOPKINS, P. ET AL., 2009b. MNRAS, **397**, 802.

HOPKINS, P. ET AL., 2010a. ApJ, **715**, 202.

HOPKINS, P. ET AL., 2010b. ApJ, **724**, 915.

HSIEH, B. C., YEE, H. K. C., LIN, H., GLADDERS, M. D. & GILBANK, D. G., 2008. ApJ, **683**, 33.

HUANG, J.-S., GLAZEBROOK, K., COWIE, L. & TINNEY, C., 2003. ApJ, **584**, 203.

HUME, D., 1962. A Treatise Concerning Human Understanding. Collier Macmillan, USA.

HUXLEY, T. H., 1874. On the Hypothesis that Animals are Automata, and its History. The Fortnightly Review, **16**, 555–580.

ISHAM, C. J., 2008. Lectures on Quantum Theory. Imperial College Press, London.

JACKSON, F., 1982. Epiphenomenal Qualia. Philosophical Quarterly, **32**, 127Ð136.

JAKI, S. L., 2008. Impassable Divide. Real Review Books, New Hope.

JAMES, W., 1990. The Principles of Psychology. Encyclopaedia Britannica Inc., USA. First Published 1890.

JENKINS, A., FRENK, C., WHITE, S., COLBERG, J., COLE, S., EVRARD, A., COUCHMAN, H. & YOSHIDA, N., 2001. MNRAS, **321**, 372.

JOGEE, S., 2006. LNP, **693**, 143.

JOGEE, S. ET AL., 2008. ASPC, **396**, 337.

JONES, D., PETERSON, B., COLLESS, M. & SAUNDERS, W., 2006. MNRAS, **369**, 25.

KANG, H. ET AL., 1994. ApJ, **430**, 83.

KAUFFMANN, G. ET AL., 2003a. MNRAS, **341**, 54.

KAUFFMANN, G. ET AL., 2003b. MNRAS, **346**, 1055.

KAVIRAJ, S., 2008. MPLA, **23**, 153.

KAVIRAJ, S., 2009. MNRAS, **394**, 1167.

KAVIRAJ, S., TAN, K.-M., ELLIS, R. & SILK, J., 2011. MNRAS, **411**, 2148.

KEEL, W., KENNICUTT, R., HUMMEL, E. & VAN DER HULST, J., 1985. AJ, **90**, 708.

KENNICUTT, R., 1998. ApJ, **498**, 541.

KENNICUTT, R. C. J., ROETTIGER, K. A., KEEL, W. C., VAN DER HULST, J. M. & HUMMEL, E., 1987. AJ, **93**, 1011.

KEWLEY, L., GELLER, M. & BARTON, E., 2006a. AJ, **131**, 2004

KEWLEY, L., GROVES, B., KAUFFMANN, G. & HECKMAN, T., 2006b. MNRAS, **372**, 961.

KHALATYAN, A., 2008. MNRAS, **387**, 13.

KHOCHFAR, S. & BURKERT, A., 2003. AJ, **597**, 117.

KHOCHFAR, S. ET AL., 2011. MNRAS. Temp:1500.

KITZBICHLER, M. & WHITE, S., 2008. MNRAS, **391**, 1489.

KOMATSU, E. ET AL., 2009. ApJS, **180**, 330.

KOPERSKI, J., 2005. Should We Care About Fine-Tuning? Brit. J. Phil., **56**, 303–19.

KRAGH, H., 2011. Higher Speculations. Oxford University Press, New York.

KRAUSS, L., 2004. Questions that Plague Physics. Scientific American, 82–5. Article by M. Jenkinson.

KRIPKE, S. A., 2001. Naming and Necessity. Harvard University Press, Cambridge MA. First Published 1972, 1980.

KRUGLINSKI, S., 2004. When Even Mathematicians Don't Understand the Math. New York Times.

KUHN, T. S., 1996. The Structure of Scientific Revolutions. University of Chicago Press, Chicago USA. 3rd Edition; First Published 1962.

LACEY, C. & COLE, S., 1993. MNRAS, **262**, 627.

LACEY, C. & SILK, J., 1991. AJ, **381**, 14.

LAHAV, O., NAIM, A., SODRE, L. J. & STORRIE-LOMBARDI, M. C., 1996. MNRAS, **283**, 207.

LAND, K. ET AL., 2008. MNRAS, **388**, 1686.

LARSON, R. & TINSLEY, B., 1978. ApJ, **219**, 46.

LAWS, C. ET AL., 2003. AJ, **125**, 2664.

Le Fevre, O. et al., 2000. *MNRAS*, **311**, 565.

Leibniz, G. W., 1951. The Principles of Nature and of Grace, Based on Reason. In P. P. Wiener, ed., *Leibniz Selections*. Charles Scribner's Sons, New York.

Leslie, J., 1996. *Universes*. Routledge Press, London.

Li, C., Kauffmann, G., Heckman, T., White, S. & Jing, Y., 2008. *MNRAS*, **385**, 1915.

Lin, L. et al., 2008. *ApJ*, **681**, 232.

Linde, A., 1986. *MPLA*, **1**, 81.

Linde, A., 1994. The Self-Reproducing Inflationary Universe. *Scientific American*, **271**(5), 32. Reprinted in 1998, p.98-104.

Linde, A., 2004. Inflation, Quantum Cosmology and the Anthropic Principle. In P. C. W. D. J. D. Barrow & C. L. H. Jr., eds., *Science and Ultimate Reality: Quantum Theory, Cosmology, and Complexity*, 426–58. Cambridge University Press, Cambridge.

Linde, A., 2007. The inflationary multiverse. In B. Carr, ed., *Universe or Multiverse?*, 127–49. Cambridge University Press, Cambridge.

Linde, A. & Noorbala, M., 2010. *JCAP*, **09**, 008.

Lineweaver, C. H., Fenner, Y. & Gibson, B. K., 2004. The Galactic Habitable Zone and the Age Distribution of Complex Life in the Milky Way. *Science*, **303**, 59.

Lintott, C. et al., 2008. *MNRAS*, **389**, 1179.

Lintott, C. et al., 2009. *MNRAS*, **399**, 129.

Lisker, T., 2008. *ApJS*, **179**, 319.

Lloyd, S., 2002. Computational capacity of the universe. *Phys. Rev. Letters*, **88**(237901).

Lloyd, S., 2010. The computational universe. In P. C. W. Davies & N. H. Gregersen, eds., *Information and the Nature of Reality*, 92–103. Cambridge University Press, Cambridge.

Lockwood, M., 1990. *Mind, Brain & the Quantum Ð The Compound ÔIÕ*. Basil Blackwell, Worcester.

Loeb, A., 2006. An observational test for the anthropic origin of the cosmological constant. *JCAP*, **05**, 009.

Lotz, J., Jonsson, P., Cox, T. & Primack, J., 2010a. *MNRAS*, **404**, 575.

Lotz, J., Jonsson, P., Cox, T. & Primack, J., 2010b. *MNRAS*, **404**, 590.

Lotz, J., Madau, P. & Primack, J., 2004. *AJ*, **128**, 163.

Lotz, J. M., Jonsson, P., Cox, T. & Primack, J., 2011. *ApJ forthcoming*, arXiv:1108.2508.

Lotz, J. M., Jonsson, P., Cox, T. J. & Primack, J., 2008b. *MNRAS*, **391**, 1137.

Lotz, J. M. et al., 2008a. *ApJ*, **672**, 177.

Lycan, W. G., 2003. Cosmology and the multiverse. In L. Antony & N. Hornstein, eds., *Chomsky and his Critics*, 11–28. Basil Blackwell, Oxford.

MACKAY, D. J. C., 2009. Information Theory, Inference, and Learning Algorithms. Cambridge University Press, Cambridge.

MALCOLM, N., 1958. Ludwig Wittgenstein: A Memoir. Oxford University Press, London.

MAOR, I., KRAUSS, L. & STARKMAN, G., 2008. Anthropic Arguments and the Cosmological Constant, with and without the Assumption of Typicality. PhRvL, **100**, 1301.

MARASTON, C., 1998. MNRAS, **300**, 872.

MARASTON, C., 2005. MNRAS, **362**, 799.

MARTEL, H., SHAPIRO, P. R. & WEINBERG, S., 1998. AJ, **492**, 40.

MASTERS, K. L. ET AL., 2010. MNRAS, **405**, 783.

MATEUS, A., 2008. arXiv:0802.2720, **NA**, NA.

MCGINN, C., 1989. Can We Solve the Mind-Body Problem? Mind, **98**, 349–66.

MCGINN, C., 1999. The Mysterious Flame. Basic Books, New York.

MCGREW, T., MCGREW, L. & VESTRUP, E., 2001. Probabilities and the Fine-Tuning Argument: A Sceptical View. Mind, **110**, 1027–37.

MERSINI-HOUGHTON, L., 2007. The void: Imprint of another universe? New Scientist, **2631**.

MERSINI-HOUGHTON, L. & ADAMS, F. C., 2008. Limitations of anthropic predictions for the cosmological constant ?: cosmic heat death of anthropic observers. CQGra, **25**, 5002.

MUTCH, S. J., CROTON, D. J. & POOLE, G. B., 2011. The Mid-life Crisis of the Milky Way and M31. ApJ, **736**, 84.

NAGEL, T., 1974. What Is It Like to Be a Bat? The Philosophical Review, **83**(4), 435–50.

NAIR, P. B. & ABRAHAM, R. G., 2010. A Catalog of Detailed Visual Morphological Classifications for 14,034 Galaxies in the Sloan Digital Sky Survey. ApJS, **186**, 427.

NAKAMURA, O., FUKUGITA, M., YASUDA, N., LOVEDAY, J., BRINKMANN, J., SCHNEIDER, D. P., SHIMASAKU, K. & SUBBARAO, M., 2003. AJ, **125**, 1682.

NEISTEIN, E. & DEKEL, A., 2008. MNRAS, **388**, 1792.

NEISTEIN, E. & WEINMANN, S. M., 2010. The degeneracy of galaxy formation models. MNRAS, **405**, 2717.

NOESKE, K. ET AL., 2007. AJ, **660**, L47.

NORBERG, P. ET AL., 2002. MNRAS, **336**, 907.

OBERHUMMER, H., CSOTO, A. & SCHLATTL, H., 2000. Science, **289**, 5,476.

OEMLER, A., 1974. ApJ, **194**, 1.

PAGE, D., 2006. The Lifetime of the Universe. Journal of the Korean Physical Society, **49**, 711–14. ArXiv:hep-th/0510003.

PAGE, D., 2008c. See article `http://ctp.berkeley.edu/BigBrainTheory.pdf` retrieved 3rd Oct 2011.

Paley, W. S., 2008. Natural Theology. Oxford University Press, New York. First Published in 1802.

Panter, B., Heavens, A. & Jimenez, R., 2004. MNRAS, **355**, 764.

Parfit, D., 1992. The puzzle of reality. TLS, 3–5.

Parfit, D., 1998. Why anything? Why this? LRB, **20**(2), 24–7.

Park, C., Choi, Y.-Y., Vogeley, M., Gott, J. R. I. & Blanton, M. R., 2007. ApJ, **658**, 898.

Parry, O., Eke, V. & Frenck, C., 2009. MNRAS, **396**, 1972.

Patton, D., Carlberg, R., Marzke, R., Pritchet, C., da Costa, L. & Pellegrini, P. S., 2000. ApJ, **536**, 153.

Patton, D. R. & Atfield, J. E., 2008. ApJ, **685**, 235.

Patton, D. R. et al., 2002. ApJ, **565**, 208.

Penrose, R., 1999. The Emperor's New Mind. Oxford University Press, Oxford. First Published 1989.

Penrose, R., 2000. The Large, the Small and the Human Mind. Cambridge University Press (Canto edition), USA. First Published 1997.

Perlmutter, S., 2005. PhST, **117**, 17.

Perlmutter, S. et al., 1999. ApJ, **517**, 565.

Poincaré, H., 1905. Science and Hypothesis. The Walter Scott Publishing Co. Ltd., New York.

Polanyi, M., 1973. Personal Knowledge: Towards a Post-Critical Philosophy. Routledge & Kegan Paul, London. First Published 1958.

Press, W. & Schechter, P., 1974. ApJ, **187**, 425.

Psillos, S., 2009. Causation & Explanation. Acumen Publishing Limited, UK. First published in 2002.

Rees, M. J., 2003. Numerical Coincidences and 'Tuning' in Cosmology. Ap&SS, **285**, 375.

Rees, M. J., 2007. Cosmology and the multiverse. In B. Carr, ed., Universe or Multiverse?, 57–74. Cambridge University Press, Cambridge.

Rees, M. J. & White, S. D. M., 1978. MNRAS, **183**, 341.

Renaud, F., Appleton, P. & Xu, C., 2010. ApJ, **724**, 80.

Richards, R. J., 1987. Darwin and the Emergence of Evolutionary Theories of Mind and Behavior. University of Chicago Press, Chicago.

Richards, R. J., 2005. DarwinÕs Metaphysics of Mind. In V. Hoesle & C. Illies, eds., Darwin and Philosophy, 166–80. Notre Dame University Press, Notre Dame.

Riess, A. G. et al., 1998. AJ, **116**, 1009.

Rines, K., Finn, R. & Vikhlinin, A., 2007. ApJ, **665**, 9.

Robaina, A., Bell, E., derWelA. van, Somerville, R., Skelton, R., McIntosh, D., Meisenheimer, K. & Wolf, C., 2010. ApJ, **719**, 844.

ROBINSON, D., 2008. Consciousness and Mental Life. Columbia University Press, New York.

RUCKER, R., 1997. Infinity and the Mind. Penguin Books, St Ives, England. First published in 1982.

RUGH, S. E. & ZINKERNAGEL, H., 2001. The Quantum Vacuum and the Cosmological Constant Problem. Studies in History and Philosophy of Modern Physics, **33**(4), 663.

RUSSELL, B., 1912. On the Notion of Cause. Proceedings of the Aristotelian Society, **13**.

RUSSELL, B., 1927. An Outline of Philosophy. George Allen & Unwin Ltd., London.

RUSSELL, B., 2007. The Analysis of Matter. Russell Press Limited, Nottingham. First published in 1927.

SALPETER, E., 1955. ApJ, **121**, 161.

SANDERS, D. & MIRABEL, I., 1996. ARA&A, **34**, 749.

SANTOS, N. C., ISRAELIAN, G., MAYOR, M., REBOLO, R. & UDRY, S., 2003. Astron. Astrophys., **398**, 363.

SARZI, M. ET AL., 2006. MNRAS, **366**, 1151.

SCALO, J. & WHEELER, J. C., 2002. ApJ, **566**, 723.

SCARLATA, C. ET AL., 2007. ApJS, **172**, 406.

SCHAWINSKI, K., THOMAS, D., SARZI, M., MARASTON, C., KAVIRAJ, S., JOO, S.-J., YI, S. & SILK, J., 2007a. MNRAS, **382**, 1415.

SCHAWINSKI, K., VIRANI, S., SIMMONS, B., URRY, C., TREISTER, E., KAVIRAJ, S. & KUSHKULEY, B., 2009b. ApJL, **692**, 19.

SCHAWINSKI, K. ET AL., 2006. Nature, **442**, Issue: 7105, 888.

SCHAWINSKI, K. ET AL., 2007b. ApJS, **173**, 512.

SCHAWINSKI, K. ET AL., 2009. MNRAS, **396**, 818S.

SCHAWINSKI, K. ET AL., 2009a. ApJ, **690**, 1672.

SCHELLEKENS, A. N., 2008. The emperor's last clothes? Overlooking the string theory landscape. Rep. Prog. Phys., **71**(072201).

SCHMIDT, M., 1959. ApJ, **129**, 243.

SCHRODINGER, E., 1996. Nature and the Greeks and Science and Humanism. Cambridge University Press, Cambridge. First Published 1954.

SCHWEIZER, F., 2005. ASSL, **329**, 143.

SCHWEIZER, F., 2006. arXiv:0606036, **xx**, xx.

SCOTT, D., 2006. CaJPh, **84**, 419.

SEARLE, J. R., 1998. The Mystery of Consciousness. Granta Books, London.

SEARLE, J. R., 2004a. Mind: a Brief Introduction. Oxford University Press, New York.

SKIBBA, R., BAMFORD, S., NICHOL, R., LINTOTT, C. ET AL., 2009. MNRAS, **399**, 966.

SLOSAR, A. ET AL., 2009. MNRAS, **392**, 1225.

SMART, J. J. C., 1963. Philosophy and scientific realism. Routledge & Kegan Paul, London.

SMOLIN, L., 1997. The Life of the Cosmos. Orion Publishing Group, London.

SOBER, E., 2008. Parsimony Arguments in Science and Philosophy - a Test Case for Naturalism. Proceedings and Addresses of the American Philosophical Association, **83**(2), 117–55.

SOMERVILLE, R., LEMSON, G., KOLATT, T. & DEKEL, A., 2000. MNRAS, **316**, 479.

SOMERVILLE, R. S. & KOLATT, T. S., 1999. MNRAS, **305**, 1.

SPERGEL, D. N. ET AL., 2003. ApJS, **148**, 175.

SPITZER, R. J., 2010. Eerdmans Pub., Grand Rapids, USA.

SPRINGEL, V., WHITE, S., TORMEN, G. & KAUFFMANN, G., 2001. MNRAS, **328**, 726.

SPRINGEL, V. ET AL., 2005. Nature, **435**, 629.

STAFFORD BETTY, L. & CORDELL, B., 1987. God and Modern Science: New Life for the Teleological Argument. International Philosophical Quarterly, **27**, 416.

STARKMAN, G. D. & TROTTA, R., 2006. Why anthropic reasoning cannot predict Lambda. PRL, **97**(201301).

STEINHARDT, P. J., 2011. Sci. Am., 37–43.

STEWART, K., BULLOCK, J., BARTON, E. & WECHSLER, R., 2009b. ApJ, **702**, 1005.

STEWART, K., BULLOCK, J., WECHSLER, R. & MALLER, A., 2009a. ApJ, **702**, 307.

STEWART, K. R. ET AL., 2008. ApJ, **683**, 597.

STORCHI-BERGMANN, T., GONZALEZ, D., SCHMITT, H., CID, F. & HECKMAN, T., 2001. ApJ, **559**, 147.

STOUGHTON, C. ET AL., 2002. AJ, **123**, 485.

STRAUSS, M. A. ET AL., 2002. AJ, **124**, 1810.

SUSKIND, L., 2007. The anthropic landscape of string theory. In B. Carr, ed., Universe or Multiverse?, 247–66. Cambridge University Press, Cambridge.

SUSSKIND, L., 2003.

SWINBURNE, R., 2004. The Existence of God. Clarendon Press, Oxford. First edition published in 1979.

TAYLOR, S. R., 1998. Destiny or Chance: our solar system and its place in the cosmos. Cambridge University Press, Cambridge.

TEGMARK, M., 1998. Is “the Theory of Everything” Merely the Ultimate Ensemble Theory? Annals of Physics, **270**, 1–51.

TEGMARK, M., 2004. Parallel Universes. In J. D. Barrow, P. C. W. Davies & C. L. Harper Jr, eds., Science and ultimate reality: quantum theory, cosmology, and complexity, 459–491. Cambridge University Press, Cambridge. Cited copy obtained from: `http://space.mit.edu/home/tegmark/multiverse.pdf`.

Tegmark, M., 2007. The multiverse hierarchy. In B. Carr, ed., Universe or Multiverse?, 99–125. Cambridge University Press, Cambridge.

Tegmark, M., 2008. The Mathematical Universe. Found Phys, **38**, 101–150.

Tegmark, M., Aguirre, A., Rees, M. J. & Wilczek, F., 2006. Dimensionless constants, cosmology, and other dark matters. Phys. Rev. D, **73**(023505).

Tegmark, M. & Rees, M. J., 1998. AJ, **499**, 526.

Tesla, N., 1934. Radio Power will Revolutionize the World. Modern Mechanix and Inventions, 40–2, 117–9.

Tipler, F. J., 1994. The Physics of Immortality. Doubleday, USA.

Tipler, F. J., 2007. The Physics of Christianity. Doubleday, New York.

Toomre, A. & Toomre, J., 1972. ApJ, **178**, 623.

van der Wel, A., 2008. ApJ, **13**, 675.

van Fraassen, B. C., 1980. The Scientific Image. Yale University Press, London.

van Fraassen, B. C., 2002. The Empirical Stance. Yale University Press, London.

Veilleux, S. & Osterbrock, D., 1987. ApJS, **63**, 295.

Vilenkin, A., 1983. Birth of inflationary universes. PhysRevD, **27**, 2848–2855.

Vilenkin, A., 1995. Predictions from Quantum Cosmology. Phys. Rev. Lett., **74**, 846–849.

Vilenkin, A., 2006. Many Worlds in One. Hill and Wang, New York.

Vilenkin, A. & Garriga, J., 2011. Many worlds in one. Phys. Rev. D, **64**, 043511.

Wallace, A. R., 1869. Sir Charles Lyell on Geological Climates and the Origin of Species. Quarterly Review, **126**(254), 359–394. Although this book review was written anomonously, it is widely considered to have.

Ward, K., 2010. God as the ultimate informational principle. In P. C. W. Davies & N. H. Gregersen, eds., Information and the Nature of Reality, 282–300. Cambridge University Press, Cambridge.

Weil, M. & Hernquist, L., 1996. ApJ, **460**, 101.

Weinberg, S., 1987a. Anthropic bound on the cosmological constant. Phys. Rev. Lett., **59**, 2607.

Weinberg, S., 1987b. The cosmological constant problem. Rev Mod. Phys., **61**, 1.

Weinberg, S., 1993. Dreams of a Final Theory. Vintage Books, New York.

Weinberg, S., 2000. A priori probability distribution of the cosmological constant. PhRvD, **61**, 3505.

Weinberg, S., 2007. Living in the multiverse. In B. Carr, ed., Universe or Multiverse?, 29–41. Cambridge University Press, Cambridge.

Wheeler, J. A., 2004. The Creation of the Universe. PBS documentary.

White, S. & Frenk, C., 1991. ApJ, **379**, 52.

WHITEHEAD, A. N., 1929. Process and Reality.

WIGNER, E. P., 1950. The Limits of Science. Proceedings of the American Philosophical Society, **94**(5).

WILCZEK, F., 2007a. Enlightment, knowledge, ignorance, temptation. In B. Carr, ed., Universe or Multiverse?, 43–54. Cambridge University Press, Cambridge.

WILCZEK, F., 2007b. A model of anthropic reasoning: the dark to ordinary matter ratio. In B. Carr, ed., Universe or Multiverse?, 151–62. Cambridge University Press, Cambridge.

WITTGENSTEIN, L. J. J., 2009. Tractatus Logico-Philosophicus. Routledge, UK. First published in *Annalen der Naturphilosophie*, 1921. Translated by D. F. Pears and B. F. McGuinness.

WOODS, D., GELLER, M. & BARTON, E., 2006. AJ, **132**, 197.

YOON, J. H., SCHAWINSKI, K., SHEEN, Y.-K., REE, C. H. & YI, S., 2008. ApJS, **176**, 414.

YORK, D. G. ET AL., 2000. AJ, **120**, 1579.

ZEPF, S., ASHMAN, K., ENGLISH, J., FREEMAN, K. & SHARPLES, R., 1999. AJ, **118**, 752.