(Toward) Discovery of Life beyond Earth and its Impact
Proceedings IAU Symposium No. 387, 2026
H. Landt, M. Dominik & C. Oliver, eds.
doi:10.1017/S1743921324001352

The Great Filter – Is it just a matter of time?

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Abstract. The discussion on the second day of the symposium centred on the Great Filter, a concept proposed by Robin Hanson as a way to reframe the analysis of the Fermi Paradox. It asserts that there must be a least one Great Filter – an evolutionary step that is extremely improbable – somewhere along a chain which starts from a lifeless Earth-like planet, followed by the sequential development of simple, complex, intelligent/technological life, and culminating in an explosive phase of readily-detectable galactic colonization. Some 25 years on from Hanson's proposal, we examine the Great Filter's continuing usefulness as a concept and current thinking on whether any such filter lies in our past (Early Great Filter), or is waiting in our future (Late Great Filter), and what this means for us and our search for life in the Universe.

Keywords. Astrobiology, Gaia, Earth history, biosignatures, technosignatures, Great Filter, futures studies

1. Introduction

The second day of the symposium – entitled *Can we detect 'life' beyond Earth? – Uncertainty: Medium* – was perhaps the broadest of the entire week in terms of topical coverage. The session opened with a review of the Fermi Paradox which served to remind us of its role as an implicit foundation for the talks which followed. These covered the nature of exotic life from evolutionary and philosophical standpoints, Gaian regulation in the early history of life, contested evidence for alien technological artifacts and life on Mars, as well the future of our own Earth-based civilization based on projections for population and energy use and its implications for the search for technosignatures. Further presentations covered the technosignatures arising from the construction of alien megastructures beyond the planetary scale, models for the characteristics of extraterrestrial civilizations which encounter Earth, and the possibility of searching for the actions of intelligent alien life in gravitational wave signals.

The discussion at the end of the day sought to bring together these past and future perspectives through the prism of the Great Filter. The latter concept, first proposed by economist and futurist Robin Hanson just over 25 years ago (Hanson (1998a)), is essentially a reframing of the Fermi Paradox, and an economical one at that, as it abstracts away from the details of the specific mechanisms which might underlie it. It asserts that there must be at least one Great Filter – an evolutionary step that is extremely improbable – somewhere along the chain leading from a habitable but lifeless Earth-like planet, through the sequential development of simple life, complex life and intelligent/technological life (approximately our current state) and thereafter to an explosive phase of readily-detectable galactic colonization, as illustrated in Fig. 1.

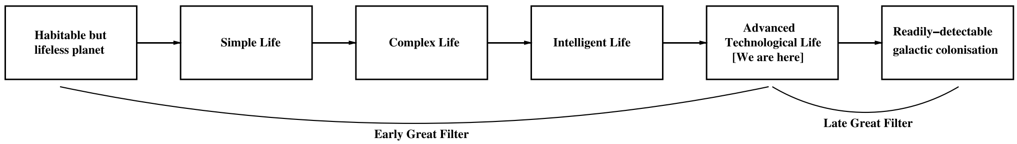

Figure 1. Schematic of the Great Filter, showing evolution from a habitable lifeless planet, through the sequential development of life, leading finally to a colonization explosion. The Early or Late Great Filters would break the development chain prior to, or after, our current position, respectively. Note that Hanson (1998a) identifies a greater number of steps in the early evolution of life.

The long-term fate of humanity and the optimum strategy for the search for life in the Universe revolve around whether any such filter is in our past (Early Great Filter) or still lies ahead of us (Late Great Filter). For the Early Great Filter, the evolution of life to our current stage would have already negotiated the most improbable step, suggesting that our future development as a space-faring civilization will not be as difficult or improbable. This implies that the search for life elsewhere, if it exists (i.e. if any life elsewhere has also passed through the Early Great Filter), should expect to find both planetary biosignatures from less evolved life and technosignatures from more advanced phases of development, as there would be no significant impediments to its long-term evolution, once started.

Conversely, a Late Great Filter would suggest that our further development as a technological civilization will ultimately reach a tight bottleneck, most likely curtailing our future before our descendants can colonize the galaxy. Under this scenario, we would expect planetary biosignatures from all prior stages in the evolution of life to be abundant, along with technosignatures from civilizations at our own stage of development and those more advanced, up to the point – as yet undefined – at which they disappear by whatever process enacts the Late Great Filter. However, Earth's present-day technosignatures are difficult to detect and short-lived over astronomical distances and timescales, respectively. Hence, the closer the Late Great Filter is to our current epoch, the more abundant we would expect biosignatures to be relative to technosignatures, the latter being rare or non-existent as far as observational detectability is concerned.

Such considerations inspired the philosopher Nick Bostrom to pen a provocative article (Bostrom (2008)) subtitled "Why I hope the search for life finds nothing", when referring to the possibility that robotic Martian probes might find evidence for independently-evolved life on the red planet. Such a discovery would suggest that the Great Filter does not lie in the past development of life, but waits ominously in our future. Therefore, according to Bostrom "It would be good news if we find Mars to be completely sterile. Dead rocks and lifeless sands would lift my spirit."

A quarter of a century on from Hanson's proposal, the Fermi Paradox has been placed on firmer scientific and philosophical foundations, with systematic classification of the many possible solutions (Ćirković (2018), Forgan (2019)). The Great Filter nevertheless continues to provide a powerful and concise narrative for many – but not all – of these possibilities, especially in areas of heightened current interest such as artifical intelligence (AI) (e.g. Garrett (2024)) and the large array of other potential threats which could destroy humanity in the coming centuries (Jiang et al. (2023), Ord (2020)).

The structure of this article is as follows. We begin with some background on relevant technical aspects of the original works of Hanson (1998a) and Hanson (1998b) which have been overlooked as the Great Filter concept has diffused to a wider audience in recent years. We also review work by Ćirković (2018) situating the Great Filter in the broader taxonomy of solutions to the Fermi Paradox, along with discussion on its continuing relevance. Thereafter, we consider mechanisms which might cause an Early Great Filter,

https://doi.org/10.1017/S1743921324001352 Published online by Cambridge University Press

focussing on the Gaian regulation of early life (Nicholson, this volume), alongside the role of astrophysical hazards such as gamma-ray bursts (GRBs). For the Late Great Filter, we consider limits to future growth based on projections for Earth's energy consumption and population, and how these might affect the longevity of our technological era and hence our prospects for becoming a space-faring civilization colonizing the galaxy. We also review how the observational search for biosignatures and technosignatures may provide constraints on such future developmental trajectories and the nature of the Great Filter. As part of this, we consider the role of AI as a mechanism for the Late Great Filter and its relevance to the 'deadly probes' hypothesis.

2. What's in a name? The Great Filter in context

2.1. *By trial and error: Hanson's hard biological steps*

The original scheme of Hanson (1998a) contains approximately nine 'hard' biological steps, with more granularity than depicted in Fig 1. These steps are assumed to operate independently and sequentially on a 'trial and error' basis, with the probability of completing step i within a time t_i being given by $1 - \exp(-f_i t_i) \simeq f_i t_i$ for $f_i t_i \ll 1$, where $1/f_i$ is the typical step completion timescale. If we select on condition of the successful completion of *all* steps within a total time window T, and if all $f_i T$ are small, Hanson (1998a) showed that the joint probability density function over all steps is the product of the f_i terms, and hence that all the hard steps have the same time distribution and take roughly the same amount of time (for a fuller treatment see Hanson (1998b)). In that case (i.e. conditioning on success), the actual time taken for each hard step is not indicative of the difficulty of the step. He argues that the latter is consistent with the roughly equally-spaced periods in the history of life on Earth, with each step taking ~ 0.3 Gyr.

In addition to these 9 hard trial and error biological steps, Hanson (1998a) proposed a further 2 non-biological 'discrete' steps, denoting the probabilities of starting off with a suitable host star-planet configuration (astronomical factors) and of a civilization not destroying itself as the 'end game' of Fig 1 is reached (sociological factors). If each of these steps has a 1% probability, and if each of the 9 biological trial and error steps has a logarithmic average completion time of 30 Gyr (versus an actual completion time in the history of life on Earth of 0.3 Gyr, giving an average $f_i t_i \simeq 0.01$), the overall probability of a given star system giving rise to a galactic colonizing civilization by the current epoch would be roughly the product of 11 factors of 0.01 which is 10^{-22}. Given that there are of order 10^{22} stars in the observable Universe, this would solve the Fermi Paradox at a stroke – we are alone in the Universe, our existence an outrageously improbable fluke. In this case, the term Great Filter would be a misnomer: rather than the filter serving to *stop* the inevitable evolutionary flow (i.e. from left to right in Fig. 1) through a series of steps which otherwise proceed rapidly, the filter would signify the inherent difficulty of the steps themselves, each typically taking much longer than the age of the Universe. The Great Filter would be time.

The challenge would then be to establish why each step in the chain ordinarily takes so long, and hence whether there are other, more likely outcomes apart from those shown in Fig 1. Indeed, Fig 1 may be very incomplete, reflecting just our own evolutionary history; in general, there may be many other ways for life to develop and become complex, many other branches and forks in the evolutionary road which do not culminate in readily-detectable galactic colonization. These other unseen and unimagined pathways may themselves act as the filter, diverting most realisations of life away at one or more steps of Fig 1. The latter possibilities would fit within the category of 'adaptationist' or 'rare mind' solutions to the Fermi Paradox as defined by Ćirković (2018), in which traits such as consciousness and technological toolmaking are temporary 'adaptive' traits

https://doi.org/10.1017/S1743921324001352 Published online by Cambridge University Press

which disappear once they cease to offer selective advantage under altered environmental conditions.

2.2. *The Great Filter and the broader landscape of the Fermi Paradox*

Looking to the broader classification landscape of Ćirković (2018), the Early Great Filter shares many features with 'Rare Earth' solutions. The latter are named after the book of the same title by Ward and Brownlee (2000), who proposed that whilst simple microbial life may be widespread in the galaxy, complex biospheres such as our own are rare because they require such an exacting combination of factors (e.g. being in a circumstellar habitable zone, having a large Moon, a Jupiter-mass planet to hoover up comets, to name but three such factors). Individually, each factor may be moderately rare and if the various factors are independent of one another, this leads to an overall very low probability for the development of a complex Earth-like biosphere. The concept of the Gaian Bottleneck (see next section and Nicholson, this volume) is a further development within this framework. As discussed by Ćirković (2018), Rare Earth solutions have been criticised as being anti-Copernican, and also on the grounds of the ceteris paribus fallacy, the erroneous notion that the various factors in the chain could be selected, à la carte, independently of each other (the issue of whether Earth would have been able to form without the presence of Jupiter being one pertinent example- see Ćirković (2017) for a fuller discussion on this point.)

In contrast, the Late Great Filter admits no single monolithic classification, and in the words of Ćirković (2018) it is "whatever can prevent the ascent of an extraterrestrial civilization along Kardashev's scale once the civilization emerges". The options we will consider broadly fall into two silos, namely logistic and neocatastrophic solutions in his terminology. The former reflect inherent and fundamental limitations – be they technological or energetic, biological or sociological – which render readily-detectable galactic colonization unfeasible or vastly more difficult than we might suppose; examples include the energy consumption and induced climate change bottlenecks facing Earth within just a few centuries, to be discussed in section 4 (see also Haqq-Misra, this volume). The neocatastrophic category includes all the familiar 'home grown' threats which could destroy humanity in the coming centuries (nuclear war, climate change, pandemics, unaligned AI to name but a few– see e.g. Ord (2020) who estimates a 1 in 6 probability that humanity will be destroyed within the next century); it also includes natural hazards both terrestrial and cosmic which reset the developmental clock on longer timescales, in terms of biological and/or technological evolution. As discussed by Ćirković (2018), natural hazards may be both random and limited in scope to an individual planet or star, or have a wider reach (e.g. due to gamma-ray bursts) and perform a synchronized reset over a large portion of the galaxy; the latter could ultimately effect what has been termed an 'astrobiological phase transition' and apply equally well as a mechanism for the Early Great Filter, as we discuss below. The final mechanism for the Late Great Filter within the neocatastrophic category, which we will discuss in section 4, is the threat from 'deadly probes'; in some ways, this is an offshoot of the aforementioned threat from unaligned AI, but elevated in scope beyond a geocentric focus to consider the role of superintelligent AI in the postbiological Universe (Schneider (2017).

The above is clearly not an exhaustive review of the Fermi Paradox, nor of mechanisms for the Great Filter, but in keeping with the astronomical focus of the symposium we do not venture into the realm of more exotic possibilities which dispense with aspects of astrophysical naturalism or physical realism. There are critics – including some at this symposium – who object that the whole concept of the Great Filter is flawed, as it is based on the Fermi Paradox which is far from being a paradox as the search has barely begun. But given that the last step in Hanson's chain is a colonization explosion which would have been readily detected by now, the key premise remains intact: one of more of the steps envisaged in Fig. 1, or perhaps the whole scheme, is much more improbable than we might naively suppose. In the words of Hanson (1998a): "Someone's story is wrong" and "It matters who's wrong".

3. The Early Great Filter

An Early Great Filter would place a highly improbable step along the road to complex intelligent life in our past. This hypothesis is related to the aforementioned Rare Earth hypothesis that predicts that complex life will be vanishingly rare in the galaxy due to the very specific conditions needed for it to arise that have come together to allow complex life to evolve on Earth (Ward and Brownlee 2000). These conditions include Earth's location in the galaxy and within our solar-system; the type of star Earth orbits; Earth's size; the presence of Earth's moon; the planetary arrangement of our solar system; and the presence of plate tectonics on Earth. Proponents of the Rare Earth hypothesis argue that each of these requirements alone appear to be rare and so finding them combined in a planetary system will be incredibly rare. Critics of the hypothesis counter that with only one data-point of an inhabited planet, all we know is how complex life evolved *on Earth*. On other planets life might take other pathways (Darling 2001). The role of Jupiter as protecting inner planets from bombardments has been questioned (Horner & Jones 2010) and as astronomers find more and more exoplanets, including rocky planets within the habitable zone of their stars, the conditions for life are looking less rare. Scientists have also identified metabolic pathways life might make use of for planets with very different atmosphere's to Earth (Seager, Bains & Hu 2013) and orbiting stars of different stellar classes to our own (Eager-Nash et al. 2024).

There are several key evolutionary steps that occurred on Earth between life emerging and evolving into humans. These steps include the emergence of life itself, the evolution of simple single-celled life, complex (eukaryotic) single-celled life, sexual reproduction, multicellular life, intelligent tool using animals, and the development of civilisations. If the Great Filter is in our past then this would imply that one of these steps is highly improbable meaning that life on other planets is unlikely to develop past that point. With only a single known inhabited planet – Earth – calculating the probability of any of these steps is impossible. However examining the timings and circumstances of these events in Earth's history can allow us to make educated guesses as to how easy or hard these steps might be.

Geological evidence for conditions on Earth get sparser the further back in time we look as rocks are recycled through Earth's mantle via planet tectonics destroying much of the evidence they contain. The evidence we have suggests that liquid water has been present in large quantities on Earth's surface for over 4 billion years (Lin-gun 2004), and that life emerged on Earth over 3.8 billion years ago (Nisbet & Sleep 2001). Therefore it appears that once conditions for life were established on Earth, life emerged and took hold quite quickly (on geological timescales!). This could make abiogenesis an unlikely candidate for the early great filter. Similarly, an important step in developing complex life on Earth was the evolution of photosynthesis. All photosynthetic life shares a common ancestor, indicating that the machinery key to photosynthesis only evolved once (Olson 1981). This could indicate photosynthesis as a difficult step to navigate on the path to complex life, however there is evidence that photosynthesis is an ancient metabolism, nearly as old as life itself (Blankenship 2010). This rapid evolution could instead suggest that perhaps photosynthesis was not so tricky after all.

Of the evolutionary steps to reach intelligent complex life, Eukaryogenesis – the evolution of eukaryotic life – is most commonly suggested as a candidate for an early great filter.

Eukaryogensis was not a singular event but involved many steps (Dacks et al. 2016). The well accepted theory of simbiogenesis posits that chloroplasts, mitochondria and other cell organelles descended from free living organisms (Margulis 1991) and primary endosymbiosis appears to be a rare event in Earth history (Stephens et al. 2021). All eukaryotic life, which includes all plants, animals and fungi, share a common ancestor (Makarova et al. 2005) and without their evolution it is thought life on Earth would have remained restricted to simple mostly single-celled organisms. Oxygen accumulated in Earth's atmosphere approximately 2.4 billion years ago (Gumsley et al. 2017) (although it would not accumulate to near modern day levels until around 400 million years ago (Lenton et al. 2016)) and this transformed Earth into an environment suitable for the evolution of complex cells. However the earliest fossilised evidence for eukaryotes dates from around 1.78 billion years ago (Knoll et al. 2006). The complexity of eukaryotic cells combined with the time it took for eukaryotes to evolve suggests that this might be a rare process. However the improbability of Eukaryogenesis and its uniqueness as an evolutionary process has been questioned (Booth & Doolittle 2015).

3.1. *Gaian Regulation and the Gaian Bottleneck*

Earth has had life and continuous habitable conditions for most of its existence. While there have been some deviations in Earth's climate where Earth has been frozen, Earth has otherwise maintained conditions at its surface that allow for liquid water. This long uninterrupted habitability has allowed life on Earth to evolve into intelligent life capable of contact with other worlds. The likelihood of such conditions persisting on other planets is therefore of direct relevance to the search for alien life and is an ongoing question in planetary formation and climate research.

Earth has been inhabited for roughly 4 billion years (Dodd et al. 2017) and over this time our planet has been dramatically transformed by life. The Earth-biosphere coupled system is known as 'Gaia', and this system has self-regulatory mechanisms that regulate Earth's atmosphere and ocean chemistry, and Earth's climate Lovelock (1965); Lovelock & Margulis (1974); Lovelock (1990) in the face of perturbations (Becker et al. 2001; Kaiho et al. 2001; Goldblatt & Zahnle 2011; Liu et al. 2020). Earth's carbon cycle acts as Earth's 'thermometer' and is an example of Gaian regulation on Earth (Lenton 2002; Kasting 2019). Over geological timescales carbon is recycled through Earth's atmosphere, oceans and lithosphere in feedback loops that heavily involve life processes. The climate sensitive chemical process 'weathering' removes carbon dioxide from the atmosphere and in warmer wetter conditions the rate of weathering increases, acting to cool the planet over long timescales due to the removal of CO_2 (Berner 1992). The products of weathering then wash into the oceans and become buried on the sea-floor where over long timescales they are recycled back into the atmosphere via plate tectonic movement and volcanic activity. Life accelerates the rate of weathering and acts as a reservoir for atmospheric carbon and thus plays a large role in determining Earth's climate. Models predict a lifeless Earth would be much hotter than today's climate (Schwartzman & Volk 1989).

The carbon cycle that regulates Earth's climate today has changed over time. When the earliest life was on Earth, it is thought that there may have been very little land-surface exposed to the atmosphere (Flament, Coltice & Rey 2008; Dhuime, Wuestefeld & Hawkesworth 2015), which would have made rates of terrestrial weathering, a crucial part of regulating our climate, incredibly low. Similarly Earth's current mode of mobile-lid plate tectonics is not thought to have been active until roughly 3 billion years ago (Condie & Kröner 2008) (although estimates vary hugely (Rollinson 2007)). This would have left early Earth without some of the key processes for climate regulation, during a time where Earth was experiencing numerous impacts, volatile evolution, and thermal instability from Earth cooling after its own accretion. The 'Gaian Bottleneck' hypothesis (Chopra & Lineweaver 2016; Nicholson et al. 2018) posits that this early window of abiotic habitability on a planet is likely to be short lived unless life quickly emerges and 'catches' this window of habitability and establishes climate regulation feedbacks. The Gaian Bottleneck hypothesis would predict that we would find either inhabited habitable planets, or inhospitable planets in our search for life in the galaxy and would place this step as the 'Great Filter' in our past. This prediction differs from an abiogenesis bottleneck as if the emergence of life was rare this would allow for the presence of habitable but uninhabited worlds. The Gaian Bottleneck instead predicts that planets will not remain habitable for long unless life emerges and establishes itself on a planet. If inhabitance is required for the long term maintenance of habitable conditions on a planet this leads to an 'inhabitance paradox' (Goldblatt 2016).

It is suggested that life might have an even greater impact on Earth's climate by influencing the continental coverage of our planet (Höning et al. 2014) (which impacts the rate of weathering) and playing a role in the establishment / maintenance of plate tectonics (Lenardic et al. 2016) which are a vital part of Earth's climate regulation. If life has such a strong influence on its planet's climate evolution then we would predict that any planet detected with habitable surface conditions will have a very high likelihood of being inhabited. Understanding Gaian systems will inform our search for inhabited planets and equally the search for life in the galaxy will provide data to test these hypotheses about Gaia.

3.2. *Natural cosmic hazards & The Great Filter*

Once life has taken hold by successfully negotiating the Gaian Bottleneck, we now consider whether evolutionary 'resets' due to natural cosmic hazards could serve to arrest its development and complexification, and thereby act as a Great Filter. Clearly any such filter could operate either before or after our current location in Fig. 1, and hence be 'Early' or 'Late' in our terminology.

There have been five mass extinctions since the Cambrian Explosion of land-based life circa. 500 million years ago, in which large fractions – but crucially not all – life went extinct (Benton 2023). The most recent of these, the end-Cretaceous mass extinction (66 Mya) which killed off the dinosaurs, has been ascribed to the impact of a ~ 10 km asteroid or comet. Although impacts of this size and severity are thought to strike the Earth roughly every 100 million years – comparable to the typical time interval between these mass extinctions – there is no evidence that any of the others were triggered in this manner. Smaller objects ~ 1 km in size – above which the climatic consequences of the impact become global – strike Earth roughly every 100,000 years (see Bailey (2018) for a review of the asteroid and cometary impact hazard). Whilst such an event would be a major setback for our civilization and could kill perhaps a quarter of the world's population through ecological and food chain collapse, the extent to which it would halt or significantly reverse our technological development is uncertain. In the consideration of such consequences, we should further distinguish between a 'one-off', isolated asteroid impact and an extended episode of multiple large impacts spread over thousands of years. The latter could be caused by the break up of a giant (> 50 km) comet, which enters the inner Solar System every 100,000 years and fragments into a multitude of smaller impactors; the most recent episode of such 'coherent catastrophism' may have occurred as recently as 10-20 thousand years ago (see Bailey (2018); Asher et al. (1994)).

Balancing the hazard posed by impacts are the benefits they offer in terms of creating new niches for the evolution of life and in delivering water (Martin & Livio 2021).

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Generalising beyond the case of the Earth to exoplanetary systems, one must consider the extent to which the existence of asteroid belts and asteroid impacts are a universal feature of different systems. Simulations by Martin & Livio (2022) show that this requires that the system contain two suitably located giant planets, but does not require excessive fine tuning of the planetary architecture. Smallwood et al. (2018) assessed the consequences for the rate of asteroid impacts of introducing a Super-Earth (10 $M_\oplus$) in the vicinity of the Earth's orbit, finding that the impact rate increases the closer the super-Earth orbit is to the Earth's orbit when interior to it, but decreases significantly when it is moved further out beyond the Earth. Childs et al. (2022) examined the incidence of giant planets beyond the snow-line in M dwarf exoplanet systems – a requirement for asteroid belt formation – and found that, although the giant planet distribution peaks there, none existed in those systems with a planet in the habitable zone. In summary, the picture is mixed concerning whether asteroid impacts could serve as an effective Great Filter mechanism of wide applicability to exoplanetary systems, even if their destructiveness can be shown to outweigh their positive benefits for the development of life.

An arguably more promising Great Filter mechanism lies in the radiative hazard from supernovae and GRBs. The former have a destructive reach of 10 pc whilst the latter can be lethal over kiloparsec scales and hence perform a synchronised reset over a much larger linear extent of the Galaxy. GRBs are, however, highly beamed, with jet opening angles of typically a few degrees, so multiple events would be required to perform a global reset over a large continuous volume of space. Wilman et al. (2018) review this hazard in general terms and estimate that at the present epoch the rate at which 'catastrophic' supernovae and GRBs strike the Earth is approximately 1 event per Gyr, with the current rate dominated by supernovae. Abrevaya & Thomas (2018) review the physics of radiation from such sources in so far as it constrains the development of life in the Universe; for the case of GRBs, the dominant effect on present-day Earth is through the destruction of atmospheric ozone and the consequent increase in surface UVB radiation.

The rates at which such destructive events affect exoplanetary systems clearly depend on the spatio-temporal evolution of star formation over the course of galactic history, with the additional complication that 'long' GRBs tend to occur preferentially in regions of low metallicity star formation. Taking this into account using the Naab & Ostriker (2004) model for the build up of the Milky Way, Wilman et al. (2018) found that the rate at which catastrophic GRBs strike Earth increases from ~ 0.2 events per Gyr at the present epoch to 1 event per Gyr when the Earth formed; the extinction rates are generally higher in the lower metallicity outskirts of the Galaxy (see also the results of Gowanlock (2016) based on largely similar assumptions). It should, however, be noted that these estimates do not take into account that the Earth's atmospheric oxygen composition was substantially below its present level more than 400 Myr in the past, and that in the absence of ozone shielding the direct radiative effects of the GRB may instead dominate. In consequence, any land-based life at such times may already have evolved in a higher-radiation environment, and sea-based life would in any case benefit from higher levels of shielding. Using slightly different assumptions, Piran & Jimenez (2014) estimate that there is a 50% chance that a catastrophic GRB has struck Earth in the past 500 Myr, causing a mass extinction. Melott & Thomas (2009) argue that this could be the late-Ordivian mass extinction some 440 Mya.

To assess whether the decline in the catastrophic GRB rate as the Galaxy evolves could be sufficient to bring about an 'astrobiological phase transition' in which the timescale for the development of sufficiently advanced life drops below the interval between successive GRB extinction events, requires new simulations. These should combine the latest hydrodynamic models for the formation of the galaxies resembling the Milky Way, tracking the evolution of star formation, metallicity and galactic satellite mergers (e.g. using

https://doi.org/10.1017/S1743921324001352 Published online by Cambridge University Press

the EAGLE simulations and others of its kind; Schaye et al. (2015), Sawala et al. (2016)), with models for the impact of GRBs on planetary atmospheres at different points in their evolutionary history.

4. The Late Great Filter

4.1. *Technosignatures and Limits to Growth*

The Rare Earth explanation for the Great Filter remains a possibility, and observations of exoplanetary systems to search for biosignatures or technosignatures is one of the only ways to experimentally test the Rare Earth hypothesis. Versions of the Rare Earth hypothesis, including some of the arguments by Ward and Brownlee (2000), may focus too narrowly on conditions that have contributed to the development of life, intelligence, or technology on Earth but may not necessarily be limiting factors if not present. But another important consideration is the "degree of rareness" that is implied by any version of the Rare Earth hypothesis. One possibility is that the universe itself could be teeming with life, but each galaxy may have only one inhabited planet on average. In this case, human civilization could be alone in the Milky Way but in a universe full of life and even technology, which may suggest that the best way to find life is to search for evidence of Kardashev Type II or Type III civilizations that would be detectable at intergalactic distances (Sagan 1973). Another possibility is that life or technology is unique to Earth, even in the entire universe, which would imply that the search for biosignatures or technosignatures will find nothing. In both cases, any null results that are obtained in the the search for life will at least provide statistical constraints on the Rare Earth hypothesis; however, search strategies should consider a wider range of possibilities than Rare Earth alone.

Searching for technosignatures can help to provide constraints on the Late Great Filter. If technosignatures are found to be abundant, then this would suggest that the Great Filter is in the past, such as biogenesis or a Gaian bottleneck. But if no technosignatures are found, this does not necessarily mean that extraterrestrial technology is nonexistent. The framework of the Drake equation (see, e.g., Vakoch & Dowd 2015) considers the number of presently communicative civilizations in the galaxy in terms of several factors, some of which are observable quantities. Factors such as rate of star formation, fraction of stars with planets, and number of habitable planets per system are now known from observations; however, factors such as the fraction of planets that develop life or the fraction of inhabited planets that develop technology are generally unconstrained and may be difficult to resolve through remote observation (Haqq-Misra & Kopparapu 2018). The most advanced fleet of telescopes could observe a potentially habitable planet and find no biosignatures or technosignatures, but this would not logically imply that the planet is devoid of life or technology. The search for biosignatures and technosignatures not only requires observers to recognize signs of life if they are observed but also requires life itself to manifest in ways that are remotely detectable. If the galaxy is teeming with life that is impossible to detect, then the observational consequences would be identical to some versions of the Rare Earth hypothesis.

The statistical sense of the Great Filter is also important to consider when searching for technosignatures and biosignatures. The analogy of the Great Filter describes the hardest steps in evolutionary trajectories in general, with possible bottlenecks or other risks that may be commonplace or frequent for any planet in the galaxy or universe in which the conditions for life are present. But the Great Filter does not necessarily imply the existence of any specific hard steps in the evolutionary trajectory of individual species on Earth; there is no "filter" that could be invoked to explain the concentration of tool use, for example, among a subset of animals on Earth. Instead, the Great Filter analogy applies to evolution at a planetary scale, and describes limitations to hypothetical populations of habitable and inhabited planets. It could also be possible that there are multiple filters of equal "greatness," perhaps with both an Early and Late Great Filter of comparable difficulty. Any limitations on the evolutionary trajectory of a biosphere or technosphere that apply as general principles to life beyond Earth would correspond to limitations on any observations of biosignatures or technosignatures in the search for life.

Conducting a statistically meaningful search for biosignatures and technosignatures to constrain the Great Filter could also provide insight for thinking about the future of human civilization. One possibility is that such a search reveals that technosignatures are about as prevalent as biosignatures—such as all habitable planets tend to have both biosignatures and technosignatures—or perhaps even more prevalent than biosignatures—such as a case involving the migration of technology to other star systems. This would serve as evidence that the Great Filter is in Earth's past, which could serve as a source of confidence for human civilization to continue striving toward survival for geological or astronomical timescales. The knowledge that no Great Filter awaits in the future, and that other civilizations have already demonstrated the potential for long-lived technospheres, could help to inspire continued problem-solving on Earth to ensure a sustainable future. Such a discovery might help to remedy feelings of nihilism or helplessness toward global problems, as it would demonstrate the existence of viable trajectories for managing problems like climate change, sustainable development, and other planetary-scale issues. But another possibility is that a comprehensive search for life finds neither biosignatures nor technosignatures, or only biosignatures. The latter scenario would serve as evidence of a Late Great Filter. This would not necessarily imply that human civilization is is doomed to extinction in the near-term future, but it does mean that managing this future trajectory may be even more challenging given the lack of observable precedent to demonstrate that it can be done. If human civilization is the first in the galaxy or universe to embark on such a trajectory toward a long-lived technosphere, then a search for life will find no technosignatures, and the sustainability of this trajectory will remain unknown.

The assumption of exponential growth is a feature of many projections of Earth's future and contributes to speculation about possible technosignatures that could be detectable elsewhere (Haqq-Misra, this volume). If current exponential energy use were to continue increasing on Earth at 2.6% per year, then this energy use itself would begin to exert direct heating on the planet via the second law of thermodynamics by the year 2250 and would reach the threshold of a Kardashev Type I civilization by 2350 (Fig. 1, Haqq-Misra, this volume). The timing of these transitions would differ if the rate in energy use were to decrease, and a net-zero trajectory even remains plausible in which the rate in energy use continues to decrease to an eventual constant energy consumption per person with a stable global population. A study by Kopparapu et al. (2024) noted that these exponential energy trajectories would require the energy-generation equivalent of covering over 20% of Earth's land with solar panels within about 100 years; this is not to imply that other energy sources should not be used but simply illustrates the scale at which energy infrastucture would need to grow to meet exponentially increasing demands. However, if global population were to stabilize (even at several times greater than today) with a constant per person energy consumption of 75 GJ per year (enough to live a high quality life), then global energy demands could be met with the energy-generation equivalent of less than 10% solar coverage. This suggests the possibility that exponential extrapolations of future growth or energy use may overestimate the extent to which humans will continue along recent growth trajectories. Perhaps human civilization, and even civilizations in general, will tend to optimize energy consumption rather than maximizing it, which may prevent any technosphere from reaching even the threshold of

https://doi.org/10.1017/S1743921324001352 Published online by Cambridge University Press

a Kardashev Type I civilization. Stability in both population and energy consumption may be a requirement for any long-term technosphere, and any challenges in achieving such stability could be one reason for a Late Great Filter.

Exponential growth itself cannot continue unbounded for any spacefaring civilization, and if not limited at the planetary scale, then an expanding civilization would most likely be forced to halt its growth rate (or collapse) upon settling across an entire galaxy. This is the "sustainability solution" to the Fermi paradox, which suggests that any extraterrestrial civilization that has attempted to grow exponentially across the galaxy has overextended and collapsed before they could be detected (Haqq-Misra & Baum 2009). This would be an even later Great Filter and would suggest that any existing civilizations that are attempting to expand would be growing at a much slower rate that remains within the limits of their environmental carrying capacity. A civilization could also choose to expand across the galaxy and then cease growing, so as to avoid collapse (Haqq-Misra & Fauchez 2022). In any of these cases, the physical limitations of having no nearby places for expansion would inevitably halt any exponential growth trajectories at the galactic scale.

4.2. *AI and Deadly Probes*

Although not addressed in detail during the Great Filter discussion segment at the conference due to time limitations, an issue which naturally follows on from the considerations of energy and population growth is the role of AI and that of 'post biological' intelligence more generally.

Quite apart from any dangers posed by AI, we must the confront the impact of its voracious energy demands. As reviewed by Ammanath (2024), the computational power used by AI is currently doubling every 100 days, leading to an annualised growth rate in its energy needs of 26–36%. If sustained, this alone will ultimately push energy consumption trends beyond the upper end of those considered in section 4.1, absent major breakthroughs in quantum computing.

Turning to the dangers of AI itself, Garrett (2024) has argued that its rapid rise contrasts starkly with the much slower pace of development in space-faring technology. As a result, he argues that we are likely to witness the emergence of Artificial Superintelligence (ASI) before we have managed to establish a sustained multi-planetary presence as a civilization. The entire future of humanity would therefore be at stake if the ASI destroys its biological parent, an event which he suggests could limit our longevity as a technological civilization to $100 - 200$ years, and therefore serve as a mechanism for the Great Filter. Applying this figure to the Drake Equation as the lifetime of the radio communicative civilization, along with optimistic assumptions for the other parameters, implies that the number, N, of radio-communicating civilizations in the galaxy at the present time is $\sim 1 - 2$. We would thus be essentially alone in the galaxy, resolving the Fermi Paradox. That said, any of the other 'home grown' threats covered in section 2.2, or a combination of them (see also Ord (2020)), could have much the same result.

Whilst Garrett (2024) is correct in highlighting the possibility of an existential threat to biological humanity posed by the rise of ASI within a few centuries, the implications for SETI, the Great Filter and the Fermi Paradox are less clear-cut. As reviewed by Schneider (2017), it has been suggested frequently that any alien life we encounter, via SETI programmes, technosignatures or other manifestations, is likely to be some form of post-biological ASI. This stems from: (i) the short timescales for ASI development; (ii) the fact that there are habitable planets billions of years older than the Earth; (iii) the superiority of silicon and other as-yet-unknown mediums for ASI computation compared with the human brain; (iv) the superior fitness of artificial postbiological entities for long-duration interstellar space travel, relative to biological creatures. Yet the issue of whether such post-biological ASI would pose an existential threat to itself, or other independently-developed ASI on other planets, in addition to the biological parent that created it, is a more speculative matter. The implications of the discovery of AI or ASI technosignatures for the Great Filter hinge on the extent of the technological leap from our present-day capabilities. If this technological leap is not far into the future of human civilization, then the discovery of AI technosignatures would be essentially the same as for other technosignatures and would provide confidence that the Great Filter is in Earth's past, or a long-way into our future.

But if the development of ASI requires a major technological leap from present-day technology, then this transition itself could be the Great Filter; in this case, the discovery of ASI technosignatures, especially those *not* associated with biosignatures, would be evidence of a Late Great Filter along the lines suggested by Garrett (2024) and perhaps indicative of the high risk involved in managing generalized AI. Distinguishing between these two possible AI-based technosignatures may not be immediately obvious, but further research may help to understand possible observable properties that could arise from postbiological technospheres.

This brings us to the discussion of 'deadly probes'. As reviewed extensively by Ćirković (2018), this is a dystopian post-biological scenario in which galaxies come under the hegemony of malignant, probably stealthy, self-replicating von Neumann probes. By accident or design, such probes seek to destroy emergent civilizations at an early stage of their development, explaining the lack of evidence for galactic colonization. It would thus only be a matter of time until Earth is destroyed in this way. Noting that this scenario is consistent with all the evidence but has received remarkably little attention since the seminal work of Brin (1983), Ćirković (2018) refers to the possibility that – absent an enforced universal prohibition on their construction – our galaxy might become forever infected by one or more populations of such probes, which would become subject to their own complex ecosystem dynamics.

5. Conclusions

In summary, for more than a quarter of a century the Great Filter has provided a valuable conceptual framework for the analysis of the Fermi Paradox. Its utility stems from its conciseness and essential simplicity, in its ability to encompass in a single arc both the ancient past and far future development of life in the Universe, as well as the multitude of existential threats facing humanity at the current epoch. Yet, there are limitations in its approach. There may not be a single Great Filter evolutionary step, but rather multiple steps of comparable difficulty. Moreover, the proposed evolutionary 'flow' from simple life to our current state and onwards to a spare-faring civilization capable of galactic colonization may be just one imagined trajectory out of many, perhaps more likely, possibilities.

Only the search for technosignatures and biosignatures can provide observational constraints on the Great Filter. But actually finding any evidence of life depends on some extent of serendipity in space and time between human civilization and any others that might be observed. If biospheres or technospheres are commonplace but are too far away, then they will be almost impossible to discover. The emergence of life and technology could also occur sporadically across time, so that the probability of any two biosphere or technospheres co-existing at the same time is nearly zero. In such scenarios, even the most comprehensive search for life would find nothing and would be unable to place any constraints on the Great Filter. But a data-driven approach by searching for signatures of life and technology provide the only path toward a scientific resolution to this problem.

Acknowledgments

RJW acknowledges financial support via a Fellowship in 2023 at the Centre for Apocalyptic & Post-Apocalyptic Studies (CAPAS), Heidelberg University, which was instrumental in shaping the background to this work. JHM acknowledges support from the NASA Exobiology program under grant 80NSSC22K1009. AEN acknowledges financial support from a Leverhulme Trust research project grant: RPG-2020-82.

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