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French Newtonianism

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This article examines the intellectual contexts in France that facilitated the reception between 1670 and 1790 of Newton's work in optics and celestial mechanics—it deals with his early optical work, and the content of the *Principia*, along with the various adaptations and interpretations of this work in France and Switzerland.

This article is part of the theme issue 'Newton, *Principia*, Newton Geneva Edition (17th–19th) and modern Newtonian mechanics: heritage, past & present'.

1. Introduction

By the time Isaac Newton died in March 1727, his work had attracted interest from French scholars for over half a century. From as early as 1672, they paid serious attention both to his successful construction of a reflecting telescope and his pioneering work on light and colour. Thereafter, they engaged with the publication of the *Principia Mathematica* (in 1687), *Opticks* (1704) and their successive editions, along with the release of key tracts from Newton's mathematical archive. Although the reception of his religious ideas does not form part of this article, an abridged version of his work on historical chronology briefly caused a sensation in the 1720s. Newton's optical doctrines were largely accepted in France by the time French editions of *Opticks* appeared in the early 1720s, but the notion of 'attraction', the definition and measurement of force (the so-called 'vis viva' controversy) and the question of the precision and universality of the inverse-square law, all remained serious points of dispute well into the 1750s. Up to the end of the century, when the work of Lagrange and Laplace helped resolve the last inequalities or theoretical irregularities in the celestial motions within the solar system, French practitioners were at the

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forefront of efforts both to find and to refine evidence in favour of Newton's theory.[1]

It is impossible to define a single approach or detailed body of doctrine that one might identify as 'Newtonian'. Newton's work in the natural sciences contained a wide range of clearly incompatible statements, visible most obviously in the difference between the atomist/vacuist cosmology of the *Principia* and the aetherial cosmology presented in the 'Queries' appended to the second English edition of his *Opticks* (1717/18). Nevertheless, in general terms, the 'Newtonian philosophy' referred to a particular method whereby mathematical approaches were used in tandem with reliable experimental and astronomical data to explain natural phenomena. More specifically, it referred to a commitment to an inverse-square force law governing the interaction between all mass elements in the universe. From the late 1730s, French scientists were increasingly prepared to accept the notion of 'attraction', agreeing with Newton that determining the physical cause of universal gravitation could be deferred to some later date. His strident injunctions against the illegitimate use of hypotheses and against systems of thought that were built on evidential sand all had resonances in disciplinary fields far beyond physics and astronomy.[2]

For commentators, the most astonishing feature of Newton's achievement was the fact that it seemed to be true and exhibited exceptional resilience in the face of apparent theoretical and evidential anomalies. As the extraordinary capacity of the inverse-square law to explain and occasionally predict complex celestial phenomena was repeatedly confirmed, Newtonianism was heralded as the pinnacle of human thought. Newton was held up as a remarkable genius who had single-handedly discovered the true laws governing the operations of the cosmos, at the same time showing others what was required to make a body of knowledge truly scientific. His doctrines became the subject of numerous popularizations, and ambitious individuals set out to become the Newton of their chosen field. Newtonianism became the totemic achievement of the Enlightenment, and in France, it became the intellectual and cultural weapon of choice for *philosophes* and others to batter what they took to be false scientific and religious systems.[3]

2. Before 1700

Newton first came to the attention of French scholars following the publication of his theory of light and colours in the *Philosophical Transactions* for February 1672. The substantial impact of this paper was enhanced by the announcement of his successful construction of a working reflecting telescope in the *Journal des Sçavans* later in the month, and a detailed account of the instrument appeared in the 25 March issue of the *Transactions*. The secretary of the Royal Society, Henry Oldenburg, had informed Christiaan Huygens about the existence of the device in early January, and it was this description plus Huygens's own account of the telescope that appeared in the French journal. The account of the reflector attracted the attention of several France-based astronomers and instrument-makers, including Huygens, Adrien Auzout and Jean-Baptiste Denys. Denys not only commented on Newton's telescope but also sent Oldenburg a recently printed account of a reflecting telescope designed by the priest Laurent Cassegrain. Newton spent some time responding to these queries, including pointing out to Oldenburg in early May why his own design was superior to that of Cassegrain.[4]

Newton's account of the heterogeneity of white light—and of the crucial experiment that purported to demonstrate its truth—received a variety of criticisms in the francophone world. Huygens—a leading figure in the Académie des Sciences—criticized Newton for offering only a plausible hypothesis that lacked an account of the physical basis of differential refrangibility. Without such a mechanism, he argued, Newton had not *explained* either the nature of, or the difference between colours, even if his discovery that white light was compounded of differently refrangible coloured rays was genuinely remarkable. The most extensive scrutiny of Newton's work came from a group of scholars based at the Jesuit College in Liège, who offered a variety of reasons for rejecting Newton's claims. Newton dealt variously with responses from Gaston Pardies, Francis Line and John Gascoines before receiving a more detailed critique from

Anthony Lucas in May 1676. Lucas claimed *contra* Newton that a series of experiments had shown that differently coloured rays had the same degree of refrangibility. When pushed by Newton to reproduce the crucial experiment, he reported that singly coloured ('uncompounded') rays emerging from the first prism became mixed with other colours when they emerged from the second. In 1678, Newton ended the increasingly fractious exchange, much of which had been published in the *Philosophical Transactions*.[5]

The most influential rebuttal of Newton's claims, as far as French audiences were concerned, came from the skilled experimental scientist Edmé Mariotte. Mariotte had attempted unsuccessfully to reproduce Newton's crucial experiment soon after it had appeared in the *Philosophical Transactions*, finding that violet rays emerging from the first prism did not remain the same colour on their emergence from the second. In the late 1670s, he performed a series of experiments on diffraction and on the refraction of light, which confirmed his earlier disconfirmation of the immutability of the colour of 'primary' rays emerging from prisms. He published the results of these experiments, and his conclusion that Newton's theory of the heterogeneity of white light was false, in his treatise *Traité la Nature des Couleurs* of 1681. The work played a key role in making Newton's optical doctrines unpalatable to French natural philosophers for almost three decades.[6]

Newton next came to the attention of the French scientific community in 1687 with the publication of his *Principia Mathematica*. The accounts of the work by John Locke in the *Bibliotheque Universelle et Historique* and by Christoph Pfautz in the *Acta Eruditorum* merely summarized its contents, but the anonymous review in *Journal des Sçavans* took issue with the notion that Newton's approach had any relevance for physics. The author of the review noted that the *Principia* had been composed by a 'geomètre' rather than by a 'physicien', and indeed he lauded Newton's great skill in the former. Nevertheless, Newton now had to provide an account of the real motions in the world that were as precise as those he had described *in abstracto*. In the wake of the publication of the *Principia*, and in response to its doctrines, Christiaan Huygens and Gottfried Leibniz both quickly produced works that offered physical explanations of celestial phenomena. They agreed that the concept of attraction was offensively unphilosophical but also thought that Cartesian *tourbillons* were incompatible with Kepler's laws.[7]

The immediate response to the *Principia* from within France was conditioned by several considerations. Like Huygens and Leibniz, French physicists and astronomers held that the doctrine of 'attraction' implied that bodies could act on each other across an empty space, and as such it was an obnoxious reversion to scholasticism. Interpreters raised in a Cartesian intellectual environment were bound to think that the refusal to offer a causal mechanism of universal gravitation amounted to a dereliction of scientific duty, and they were unsympathetic to the idea that Newton's approach did not rule out, but simply postponed the question of the physical basis for universal gravitation. To a certain extent, these sentiments were driven by nationalistic concerns, since the most obvious model for physical explanations of natural phenomena was Cartesian *tourbillons*. Some argued that the extent to which Newton had made mathematics central to natural philosophy was excessive, since mathematics and physics were distinct disciplines, and the operations of nature were not susceptible to the level of exactitude that mathematics demanded. Others responded positively to the new approach to scientific enquiry embodied by the *Principia,* confident that Newton's project could be improved if it could be transformed into Leibnizian analytical methods and notation.[8]

The most important early engagement with the text came from a group closely associated with the great Oratorian scholar Nicolas Malebranche, whose major work *Recherche de la Verité* (1675) went through six editions before his death in 1715. Several talented mathematicians and philosophers studied with Malebranche at the Oratory, attracted by his interest in applying mathematics to the natural world. These included Charles-René Reyneau, Pierre Rémond de Montmort, the Marquis de l'Hôpital (Guillaume François Antoine) and Pierre Varignon. Although they disdained the notion of attraction, this group believed that the way Newton had set out to conceptualize the natural world in terms of quantitative forces was a productive way of investigating nature. Having received extensive lessons in the Leibnizian calculus from the young Johann Bernoulli, de l'Hôpital published the first French account of Leibniz's new mathematics in 1696. However, the most significant French interpreter of Newton was Pierre Varignon, a Professor of Mathematics at the Collège Mazarin who first encountered the *Principia* in 1688. Varignon published *Projet d'une Nouvelle Mécanique* in 1687, and over the next two decades, he would incorporate insights from his reading of the *Principia* into his own efforts to render a new science of motion in Leibnizian terms.[9]

3. Optics

Despite the fact that the French and the English were once more engaged in military conflict (the War of Spanish Succession), Newton's election as President of the Royal Society in 1703, and the publication of his *Opticks* the following year, created new opportunities for making contacts with French scholars. In his role as a secretary of the Royal Society, Hans Sloane sent a copy of *Opticks* soon after its publication to the physician and chemist Étienne-François Geoffroy, an academician and member of the Royal Society. Geoffroy summarized the work in a French translation and in a series of meetings from the summer of 1706 he read his preçis to an audience of *académiciens* that included Malebranche, Varignon, Père Sébastien (the Carmelite name of Jean Truchet) and the 'perpetual secretary' of the Académie, Bernard le Bovier Fontenelle. Malebranche had outlined his own vibration theory of light in an Appendix to the fifth (1700) edition of the *Recherche*. Following his attendance at Geoffroy's sessions and his own immersion in *Optice*, he was drawn to Newton's theory, telling a friend in 1707 that although Newton was not a *physicien* he was an excellent mathematician, and his book was very useful to those who cultivated the 'right principles' of physics. In the final (1712) edition of the *Recherche,* Malebranche explicitly cited Newton's experiments, embraced Newton's doctrines and adopted Newtonian language. Although he retained a vibration theory of colour, he noted that each 'simple' ray had its own degree of refrangibility, while white light was an 'assemblage of different vibrations' of the aether, itself made up of fluid micro-tourbillons.[10]

The signing of the Peace Treaty of Utrecht in the spring of 1713 paved the way for closer connections between British and French scientists. Early in 1715, members of the Académie visited England, in part to attend demonstrations of Newton's optical experiments at the Royal Society and in part to watch a solar eclipse of 22 April (3 May, New Style). The delegation included Claude-Joseph Geoffroy (the younger brother of Étienne-François), de Montmort and the astronomer, the Chevalier de Louville (Jacques-Eugène d'Allonville), all of whom were soon recommended as fellows of the Royal Society by Newton himself. The English sky was predictably unhelpful for the eclipse observation, but at an earlier meeting, the delegation had seen a series of optical demonstrations that corroborated Newton's theory. The experiments were performed by the Huguenot Jean-Théophile Desaguliers, who had initially risen to prominence as a lecturer at Oxford in 1710. Following a stint in London as a public lecturer, from the spring of 1714, he became a regular demonstrator of experiments at the Royal Society under Newton's direction. Desaguliers became an expert in creating the exact conditions needed to reproduce Newton's optical experiments, particularly—to explicitly counter Lucas and Mariotte—in maintaining the same colour of a primary ray of light through successive prismatic refractions. The three members of the delegation were already well disposed to Newton's theories of light and colour, but Desaguliers's demonstrations convinced them that these doctrines were supported by experimental evidence.[11]

According to Pierre Coste, responsible for the first French translation of Newton's *Opticks* (published in Amsterdam in 1720), the malebranchiste Dortous de Mairan was the first person to successfully reproduce Newton's experiments in 1716 and 1717. On Malebranche's advice, in 1714 De Mairan had read the *Recherche de la Verité* and Newton's *Optice*, but it is unclear whether his reproduction of Newton's experiments owed anything to direct contact with any of the *académiciens* who had seen Desaguliers's demonstrations. Coste also reported that in 1719, Père Sébastien had successfully reproduced most of the experiments in *Opticks* before an audience including the Cardinal de Polignac, the royal typographer Jacques Jaugeon and the botanist Antoine de Jussieu. Sébastien told Newton in 1722 that he had benefitted from the linguistic expertise of Geoffroy Sr., adding that the audience had included 'a very numerous group of aristocrats and men deeply versed in physics, who are, as it were, blood-brothers of yours'. In the wake of the publication of Coste's translation, a new series of experiments were successfully performed by Nicolas Gauger, a mechanically-minded lawyer, in front of an audience that included the Chancellor of France, Henri François d'Aguesseau. Although a second edition of Coste's work appeared in 1722, Varignon had been approached in 1720 to assess whether the work (i.e. the translation by Coste) deserved to be published with a royal approval in France. Over the next two years, an official version was authorised and Varignon was the prime mover in seeing to press the lavish 1722 Parisian edition of the work.[12]

4. The *Principia*

In the first half of the eighteenth century, most French natural philosophers continued to be wary of the doctrine of attraction, instead being committed to some sort of vortex or fluidic explanation of celestial motions.[13] While serious scholars recognized that the *Principia* was a phenomenal intellectual achievement, it remained difficult to situate it in terms of conventional disciplinary divisions. One influential group charged that Newton applied mathematical techniques and approaches to physical domains where it was inappropriate. They lamented the fact that its forbidding mathematical form had created an illegitimate cadre of experts by rendering natural philosophy inaccessible to many readers. In several works, the Jesuit Louis-Bertrand Castel subjected Newton's philosophy—and the pretensions of mathematical philosophy in general—to a withering critique. Castel, a committed Cartesian, was a keen reader of the *Principia* and admired Newton's geometrical skill, but he was adamant that the work perversely mixed mathematics and physics and illegitimately substituted mathematical explanations for conventional physicalist accounts.[14]

While Newton and his followers were working to bring French scientists over to his views on light and colours, an opportunity arose to create new followers of his celestial physics. By the time the second edition of the *Principia* appeared in the summer of 1713, Newton had become embroiled in a battle with Leibniz and Johann Bernoulli over priority for the invention of calculus. The situation became increasingly complicated, as Leibniz mounted powerful critiques of Newton's cosmology, and Britain braced itself for a transition to a new Hanoverian monarchy. Now that Newton's opponents seemed to be clustered around the German philosopher, the publication of the new edition of the *Principia* paved the way for Newton, an *associé étranger* of the Académie since 1699, to attract French allies. Presentation copies were duly sent to Varignon, Fontenelle and the Abbé Bignon, President of the Académie. Newton told Bignon that the subject matter was difficult and might be particularly unwelcome to people because he had not offered hypothetical explanations. Nevertheless, he added that he had heard people say that science had thrived in France under Bignon's leadership, and he expressed his wish that mathematical physics in particular would flourish there. Fontenelle and Varignon were effusive in the praise they gave to Newton and his intellectual accomplishments, the latter telling him that reading the first edition had 'provoked many new ideas in my mind; by adding these to the margins of your extraordinary book, I have stained all of them with notes of this sort'. While French scholars adopted the analytical mechanics and the Leibnizian notation nurtured in the writings of Bernoulli, for the most part, they remained publicly neutral in the priority dispute.[15]

5. Popular Newtonianism

In the wake of Newton's death in March 1727, the outlines both of his own and the Cartesian system were increasingly discussed in Parisian salons. Although Fontenelle had published a delicately judged assessment of the relative merits of Newton and Descartes in his *éloge* to the former, the first systematic attempt by a French author to explain Newton's ideas to a wider public was made by the mathematician Pierre Louis Moreau de Maupertuis in his *Discours sur les différentes figures des astres* of 1732. A member of the Académie since 1723, Maupertuis spent a few months in England in 1728, where he met all the major Newtonians and was made a fellow of the Royal Society. In the following year, he wrote to Johann Bernoulli and visited Basel in the autumn to learn advanced analytical techniques. In the early 1730s, he published a series of papers on analytical mechanics, submitting his work to Bernoulli for his scrutiny before publication. His work led to his appointment as a senior *académicien* in 1731, and in the same year, he published a paper on the shape of rotating fluids in the *Philosophical Transactions*. By this time, he had already decided to publish a popular account of the Cartesian and Newtonian systems, explaining in a letter to a disgruntled Bernoulli that although he found Newton's explanation of the shape of the Earth overly obscure, his account would support the English philosophy. The *Discours* judiciously compared the Newtonian and Cartesian systems, finding in favour of the former.[16]

Although the *Discours* was the first French exposition of the Newtonian system, the most influential evangelist on its behalf was François-Marie Arouet, better known by his pen name Voltaire. Having forged a reputation in Parisian literary society, Voltaire had encountered Newton's philosophy around 1724, as a result of his connection to the Jacobite exile Lord Bolingbroke. Following a contretemps with an elite member of the Parisian nobility early in 1726, he escaped to England, where he believed that he had found a country that embodied freedom and tolerance, and which cultivated a true and not imaginary philosophy. In March 1727, he made a point of watching Newton's funeral cortège make its way to Westminster Abbey, and soon afterwards he spoke to Catherine Barton, Newton's half-niece, from whom he learned the famous story of the falling apple that had allegedly inspired Newton's initial thoughts about gravitation. He returned to France in 1729 and re-entered Parisian literary culture, embarking in the spring of 1733 on a deep personal and intellectual relationship with Émilie Le Tonnelier de Breteuil, Marquise du Châtelet. Du Châtelet received tuition in analytical algebra from both Maupertuis and the mathematical prodigy Alexis-Claude Clairaut in the early 1730s, and she gave advice to Voltaire while he reworked a text he had drafted while still in England. Famously, one of the 'letters' in his *Lettres … sur les Angloises et autres Sujets* (first published in France in 1734 and known as the *Lettres Philosophiques*) cleverly compared the Cartesian and Newtonian philosophies, but clearly to the detriment of the French system.[17]

The publication of the *Letters Philosophiques* made Voltaire once more unwelcome in the capital, and in 1734 Du Châtelet invited him to live at her Château de Cirey in Champagne, where he had a degree of protection from the authorities. The Italian writer and pro-Newtonian Francesco Algarotti visited Cirey in 1735 and was invited to stay there by Du Châtelet; the presence of Voltaire, Du Châtelet and Algarotti made Cirey a vibrant centre of intellectual life over the following years. In preparation for his own account of Newton's work, Algarotti also spent a great deal of time in Paris, where he met Maupertuis and Clairaut, and he published his immensely popular *Newtonianismo per le dame* in 1737 (translated into French the following year by Louis-Adrien Du Perron de Castera). The most influential Newtonian publication to emerge from Cirey was Voltaire's *Eléments de la Philosophie de Newton*, which appeared the year after Algarotti's work. This was intended to be both a serious exposition of Newtonianism for the general public and an attack on what he took to be a reactionary Cartesian ideology. In 1736, prompted in part by Algarotti's plans, Voltaire had committed himself to writing a much longer exposition of Newton's system, and he discussed his plans with several people, particularly

Maupertuis and the Dutch Newtonian Willem 's Gravesande, whom he met in Leiden in the same year.[18]

6. The shape of the Earth

The popular works of Algarotti and Voltaire appeared just as it was announced that a major scientific expedition to Lapland sponsored by the Académie and led by Maupertuis had determined that the Earth was an oblate spheroid. In terms of providing evidence in favour of the Newtonian system, by far the most effort was spent on investigating the shape of the Earth. In the first edition of the *Principia*, Newton had used a wide range of evidence drawn from various locations, much of which was produced by French astronomers. French work on cartography and geodesy had been given a boost by the founding of Académie des Sciences, which in the late 1660s had sponsored work by Jean Picard on determining the length of a degree of latitude through the Paris meridian. Both this and an expedition of Jean Richer to Cayenne (in the French West Indies) deployed astronomical pendulum clocks developed by Christiaan Huygens, and Richer found that a pendulum whose length beat seconds in Paris had to be shortened to do the same at the Equator. Newton made use of these findings to argue that the force of gravity at the Equator was less than it was at the poles, a fact that indicated that the Earth was an oblate spheroid—a position also held on different grounds by Christiaan Huygens. This directly conflicted with the implications of cartographic measurements that were undertaken by Gian Domenico (Jean Domenique) Cassini, whose work and that of his son, Jacques (Cassini II), had been sponsored by the Académie since the 1670s. For over half a century, the work of Cassinis provided apparently robust empirical evidence in favour of a prolate spheroidal earth, which was linked by commentators with the Cartesian position.[19]

In the early 1730s the Académie became the chief forum for discussions about whether an accurate determination of degrees of latitude or longitude on various parts of the Earth's surface would constitute the best means of ascertaining the true shape of the Earth. In 1733–1734, Maupertuis, the astronomer Louis Godin and the mathematician and physicist Charles Marie de la Condamine presented a series of papers to the Académie on the relative merits of measuring degrees of longitude or latitude, but the practical difficulty involved in doing the former led them to propose two expeditions that would measure degrees of latitude in northerly and equatorial settings. Maupertuis headed an expedition to Lapland, which departed in April 1736 and contained Clairaut, the astronomer Pierre Charles le Monnier and the Swedish natural philosopher Anders Celsius.[20]

Over the winter of 1736–1737, the Lapland group made a series of triangulation measurements and astronomical determinations of latitude, returning to Paris in the summer of 1737. In August, Maupertuis announced to the Académie that the length of 1° of meridian arc in Lapland was discernibly longer than the same length in Paris, thereby demonstrating that the Earth was an oblate spheroid. Although most scientists, along with the general public, took these results to be definitive evidence in favour of the Newtonian philosophy, Maupertuis was forced to defend himself and the work of his team against continuing attacks from a pro-Cassinist faction. In particular, Dortous de Mairan and Nicolas Fréret—the latter a major critic of Newton's work on chronology—sought to obtain information from Jesuits based in China that would undermine the standing of the Lapland results. Alongside Voltaire, Algarotti and others, Maupertuis vigorously attacked the enemies of Newtonianism in articles, books and salons. By 1744, when César-François Cassini de Thury (Cassini III) published a correction to the Paris meridian measurements made by his father and grandfather, there was little serious opposition in France to the reality of the inverse-square law.[21]

A year before Maupertuis' team had left France, an expedition had set out to measure the meridian at Quito (then in Peru but now Ecuador). This consisted of Godin, La Condamine, the royal professor of hydrography Pierre Bouguer, Joseph de Jussieu and the Spanish cartographers Jorge Juan y Santacilia and Antonio de Ulloa. Having crossed Central America across what is now Panama, they reached Quito in May 1736. The cartographic and astronomical work was beset by personal and logistical problems, and the team was disillusioned when they learned that the results of the Lapland expedition had already been announced and published. Despite these problems, news that the expedition's data were going to confirm the oblate spheroidal shape of the Earth was conveyed to European scientists early on in the proceedings. From August 1737, Bouguer performed pioneering measurements with a pendulum near the peak of Pichincha mountain to determine the variation of gravity at varying altitudes. At the end of 1738, based on a proposal made by Newton in the *Principia*, he and La Condamine made careful measurements of the horizontal deflection of a plumb-line near Chimborazo mountain. Designed to get a more accurate figure of the mean density of the Earth, Bouguer later claimed that both tests were consistent with the Newtonian theory of gravity, although he was unable to explain why the deflection of the plumb-line near Chimborazo was much less than he had expected. The final results were only calculated at the start of 1743, and were announced publicly in papers given to the Académie by the now estranged Bouguer and La Condamine over the next two years.[22]

7. Transforming the *Principia*

For elite Continental mathematicians such as Leonhard Euler and Johann Bernoulli, the geometrical reasoning of the *Principia* was badly outdated by the time its core doctrines were confirmed by the expeditions to Lapland and Peru. Nevertheless, there was substantial appetite for a new edition of the great work that would make its arguments and doctrines more comprehensible to an audience now used to the analytical methods and notation used to great effect by Bernoulli and Leonhard Euler. The 1739–1742 Genevan, or 'Jesuit', edition of the *Principia* emerged from a Swiss cultural, intellectual and publishing environment that promoted a culture of enlightenment while avoiding radical atheist or Spinozist views. The edition of the *Principia* edited by Jean Louis Calandrini and the two Minim friars Thomas Le Seur and François Jacquier would be the first and most important of four major works published as part of a coherent collection of Newton's 'Complete Works'. The second was an edition of *Optice* (1740) and the third a three-volume collection of Newton's mathematical, philosophical and 'philological' *Opuscula* (1744), both of which were published in Lausanne. The last, an edition of the *Arithmetica Universalis*, was completed by the mid-1740s but only appeared with an Amsterdam imprint in 1761.[23]

Although Le Seur and Jacquier were announced on the title page as the two men responsible for the edition of the *Principia*, Calandrini was the driving force behind the work. In the early 1720s, he had been jointly appointed to the Chair of Mathematics at the Genevan Academy with Gabriel Cramer, according to an arrangement where Calandrini taught algebra and astronomy and Cramer taught geometry and mechanics. Both men were sympathetic to Newton's philosophy and they emphasized the ways that it could bolster natural theology. Concerning the Genevan edition itself, Calandrini was responsible for the overall production of the volumes, including the correction of text composed by Le Seur and Jacquier, oversight of the typesetting and the rendering of the diagrams. His mathematical annotations were much more sophisticated than those of the Minim friars, and in many places, he attempted to offer novel interpretations of elements of Newton's reasoning. As Niccolò Guicciardini has shown, the production of the edition required extraordinary levels of political, religious and nationalist tact. While Calandrini supervised this monumental homage to Newton's greatest intellectual achievement, Cramer—who had learned higher calculus from Bernoulli and was a confidant of his son Johann II—was involved in the celebration of the eminent Swiss mathematician in the form of a 4-volume edition of his major writings. The latter was published in 1742, the same year that the third and final volume of the Genevan *Principia* appeared.[24]

Le Seur and Jacquier were based at the College of the Trinità dei Monti in Rome. Although it is not certain when Calandrini was first in contact with them, the two monks had been working on the edition since the mid-1730s, keen to make Newton's achievement accessible to a broader, and particularly local audience. Unlike Calandrini's situation in Geneva, the religious context in which they worked was hostile to heliocentric philosophies. At the start of the third volume, they wrote a 'Declaration' in which they confirmed that they recognized the decrees against the motion of the earth issued by Cardinals and claimed that they had been forced to assume the 'hypothesis' of a moving Earth to explicate Newton's theory. The Le Seur–Jacquier (and Calandrini) edition reproduced the Latin text of the 1726 work in full, adding extensive footnotes in numerous places and a long section in the final volume consisting of three prize-winning essays by Euler, Maclaurin and Daniel Bernoulli on tides. Their footnotes aimed at filling in gaps in the argument that Newton had either glossed over or assumed the appropriately skilled reader could supply. Like Calandrini and Cramer, the two Minims were engaged in a major effort of intellectual diplomacy. Emphasizing that they had no allegiance to any specific system, they referred to Newton's own profession of his dislike of disputes. Although the bulk of their references were to French sources, they cited a wide range of works. Moreover, while most of the footnotes appeared in the notational form of the Leibnizian calculus, the text occasionally referred to Newtonian terms.[25]

In 1744, Jacquier spent a substantial period travelling in France. He met Maupertuis, d'Alembert and Condillac, and Clairaut helped him become a corresponding member of the Académie. He stayed with Madame du Châtelet during two visits to Cirey between May and July 1744, and it was presumably while he was there that the Marquise committed herself both to translating the *Principia* into French and to offering a popular account of its contents. Du Châtelet was not an ardent Newtonian, and even as she supported Voltaire while he was writing his *Eléments,* she was composing a wide-ranging and eclectic work on the foundations of physics. In 1740, she published the anonymous *Institutions de Physique* in which she defended the use of *vis viva* (mv^2) as the most useful measure of force. She enhanced her reputation in the *Republic of Letters* by responding forcefully to an attack on her work by Dortous de Mairan, issuing a second edition of *Institutions* in 1742, now evidently under her authorship. She began her translation of the *Principia* in early 1745, finishing a draft by the end of the year, and Clairaut checked proofs of the work over the following months. In preparation for the translation, she was able to consult the Genevan edition as well as writings by Clairaut, d'Alembert, Daniel Bernoulli and others.[26]

Beginning in 1746, Du Châtelet worked on a commentary on the *Principia*, an extensive production that took up most of the second of the two volumes when her edition was published. Over the next three years, she remained in contact with Jacquier and received periodic but crucial assistance from Clairaut, who was at this point involved in the pioneering analysis of the motions of the Moon. She had finished all her revisions to the commentary by the summer of 1749 but tragically she died on 10 September, six days after giving birth. The first volume contained a historical preface by Voltaire, translations of prefaces by Newton and Cotes, and the two books of the *Principia*. The second volume contained a translation of Book Three, followed by an *Exposition abrégée du système du Monde*, and a *Solution analytique des principaux problèmes qui concernent le Système du Monde*. As its title suggests, the 'Exposition' focused on outlining Newton's treatment of tides, comets, the shape of the Earth and the motions of the Moon. Lacking diagrams or equations, it was aimed at a more general readership. On the other hand, the 'Analytic Solution' introduced budding analysts to what a reviewer called the 'sanctuary of the Newtonian philosophy' and offered algebraic transformations of key parts of the *Principia*. Delays over the preparation of the figures and other issues set back the publication of the *Principes Mathématiques* by many years. An extremely rare issue was printed in 1756, but a definitive version appeared in June 1759.[27]

8. Halley's Comet

For almost half a century, it was known that the return of the 1682 comet at some point in late 1758 or early 1759 would offer an extraordinary confirmation of the robustness of the inverse-square law. In prop. 40 of Bk. III of the 1687 *Principia,* Newton had shown that comets entering the solar system had to travel in conic sections, some of which would be elliptical and thus periodic. Following this, Edmond Halley, the 'editor' of the first edition, undertook an extensive research programme to find precursors to recently observed comets, in particular that of 1682. In 1695, he told Newton that the orbits of comets seen in 1531 and 1607 were sufficiently similar to that of 1682 to conclude that they were the same comet, returning at intervals of approximately 76 years, and he announced his findings to the Royal Society in June 1696. In 1705, he published his opinion that, in terms of their inclination to the Earth's orbit, and given the fact that they were all retrograde, the three events were manifestations of the same comet. Having compared the proximity of the comet to Jupiter and Saturn before and after perihelion in all three cases, Halley argued that the difference in periods was mainly due to the gravitational influence of Jupiter and, to a lesser degree, that of Saturn. In later publications, he argued that the path of the 1682 comet had taken it close to Jupiter, accelerating it and taking it to a higher orbit that would extend the length of the period before its return. By the 1740s, it was widely accepted that although the calculation of the date of its return would be exceptionally complex, using the inverse-square law to predict the return of the comet within a specified period would count as a spectacular confirmation of the power of Newtonian theory.[28]

The triumphant confirmation of Newton's views by the two expeditions to Lapland and Peru had not put an end to disputes over the exactness and truth of Newton's theory of universal gravitation. In the 1740s, there was extensive debate over whether the influence of Jupiter and Saturn was sufficient to give rise to the major discrepancies between the periods of the 1682 comet, but the decade witnessed extraordinary progress in the development of techniques for explaining the motions of the Moon according to the inverse-square law. Immediately following the publication of Clairaut's monumental *Théorie de la Figure de la Terre* of 1743, he began to work on the motion of the Moon, publishing an influential paper on the subject in 1744. In November 1747, he delivered a famous memoir to the Académie in which he variously proposed adding an inverse third or fourth power to the inverse-square law. This was rebutted in the following year by George-Louis LeClerc (after 1773 the Comte de Buffon), and Clairaut retracted his proposal in 1749, offering a theory of the Moon 'deduced from the sole principle of attraction reciprocally proportional to the square of the distances'. This work was the first to demonstrate — as Newton had not — that the inverse-square law *by itself* could account for the apsidal precession of the Moon. Between 1749 and 1753, Clairaut, Euler and d'Alembert all made major refinements of Newton's principle of universal gravitation. These theories now had to take into account James Bradley's recent (1748) discovery of the existence of lunar nutation, which was itself further confirmation of Newton's theory.[29]

Clairaut began the tedious work needed to compute the return of the 1682 comet in the summer of 1757 with the help of the astronomer Joseph-Jérôme Lalande and the *savante calculatrice* Nicole-Reine Lepaute. It was a pioneering exercise in large-scale numerical integration that required hundreds of calculations of the perturbatory effects of Jupiter and Saturn. Aware that the predictive force of his work would be rendered useless by an early sighting of the comet, Clairaut gave his initial estimate for the date of its return at a meeting of the Académie des Sciences on 14 November 1758. Before doing this, he compared the observed orbit of the comet in the two previous periods (1531–1607 and the much shorter orbit of 1607–1682) with the calculated path, considering the effect of Jupiter on both the inward and outward parts of the orbit. He found that the calculated difference between the two periods was 436 days, 33 days fewer than the actual observed figure; this degree of agreement by itself was a major confirmation of the Newtonian philosophy.[30]

As for the date of the imminent return of the comet, Clairaut argued that the combined effect of the two major planets would extend the period following its 1682 manifestation to 618 days longer than the span from 1607 to 1682, giving a predicted perihelion of within a month either side of mid-April 1759. The comet was first seen by the German astronomer Johann Georg Palitzsch on 25 December 1758, and on 21 January 1759, it was detected at the observatory in the Hôtel de Cluny by Charles Messier, assistant to Joseph-Nicolas Delisle, geographical astronomer of the Navy. In early April, Parisian astronomers confirmed that this was the same comet as the one that had appeared in 1531, 1607 and 1682, and they calculated that perihelion had occurred on 13 March. This (just about) fell within the range offered by Clairaut and represented a further and remarkable confirmation both of the power of Newtonian theory and of the quality of the work of Clairaut, Lalande and Lepaute. In a lecture to a public assembly of the Académie on 25 April 1759, Lalande proclaimed: ‘The Universe sees this year the most satisfying phenomenon that Astronomy has ever offered us: unique event up to this day, it changes our doubts into certainty, and our hypotheses into demonstrations’. Within two months, Madame du Châtelet’s *Principes Mathematiques* had appeared, explicating for a French audience the doctrines that had made possible the return of what was now known as Halley’s Comet.[31]

9. Conclusion

The successful prediction of the return of Halley’s Comet represented yet another corroboration of the power of Newtonian science. Nevertheless, the theory could not be considered completely confirmed until it had been shown that the inverse-square law could account for all the apparent anomalies (‘inequalities’) in the complex ways that the sun and the planets interacted with each other. Following pioneering work by Euler, Clairaut and d’Alembert, the friendly rivalry between Joseph-Louis Lagrange and Pierre Simon Laplace in the 1770s and 1780s made the largest contribution to resolving this issue. The last great inequality was announced as having been solved in a famous address to the Académie given by Laplace in 1787, in which he showed analytically that the observed acceleration of the Moon was caused by the eccentricity of the Earth’s orbit. This, the culmination of the programme of work carried out by himself and Lagrange over many years, showed how and why the Solar System was stable over a long period of time, despite the numerous and powerful mutual perturbations that constituted it. Laplace presented all his findings in his monumental *Traité de Mécanique Célèste* (5 vols, 1798–1825); the most important text in celestial mechanics since Newton’s *Principia*, it set out the foundational basis for physical astronomy—celestial mechanics—in the first half of the nineteenth century.[32]

Despite its great explanatory success, the limits of the Newtonian philosophy were beginning to emerge. Under Napoleon, Laplace created a new research programme that was explicitly modelled on what he and others understood as Newtonian science. This approach sought to account for phenomena at all scales in terms of attractive and repulsive forces; it posited the existence of both ponderable and imponderable fluids, the last of which constituted the physical basis of heat (caloric), light, electricity and magnetism. Nevertheless, it was clear that this programme could only superficially accommodate revolutionary scientific developments such as Lavoisierian chemistry, the invention and deployment of the Voltaic pile, and pioneering research in electrochemistry and electromagnetism. Moreover, there was growing evidence, notably based on the work of Thomas Young and Augustin Fresnel, that the behaviour of light could only partially be understood in terms of attractions between particles. Although the Newtonian paradigm had been inordinately successful, the methodology that functioned so well for physical astronomy could not serve as a template for work in these new sciences, any more than it could be a serious exemplar for research in natural history, or in emerging fields in the life and earth sciences.[33]

More broadly, the astonishing success of Newtonian science in physical astronomy became the central plank at the heart of the general movement that *philosophes* described as the 'siècle des lumières'. In Diderot and d'Alembert's *Encyclopédie*, and in countless other works, the Newtonian achievement was lauded as proof that humans could free themselves from the seductions of imagined systems, theories and hypotheses, and thus conquer the tyrannies of false traditions in religion and science. Nevertheless, outside of the natural sciences, simplistic efforts to apply Newtonian methods to medicine, philosophy, political economy or the social sciences all failed, and individuals who had tried to become the Newtons of their various intellectual domains gave up their quests. In the aftermath of the French Revolution, Newtonianism suddenly appeared not so much as a demonstration of the power of unaided human reason but as a candidate for a rational religion that might check the destructive tendencies that had caused so much social and political mayhem. In his *Lettres d'un Habitant de Genève à ses Contemporains* of 1802, Henri Saint-Simon argued that societies around the world—and indeed on every planet—should be reorganized and their spiritual authority led by a scientific priesthood devoted to the worship of Newton and his doctrines. Although Saint-Simon himself quickly abandoned this scheme, Newton's francophone followers continued to admire and even revere his achievements throughout the nineteenth century and beyond.

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Endnotes

[1] Newton's key publications are [1,2] (with subsequent editions in 1713 and 1726) and [3] (with a Latin translation in 1706 and a second English edition in 1717/18). Although the mathematical community had been aware of Newton's expertise in integration techniques from volume 2 of John Wallis's *Opera Mathematica* (1693), the first published text that gave clear evidence of his mastery of this branch of the calculus ('De Quadratura curvarum') was appended to the first and subsequent editions of *Opticks*. The controversy over Newton's chronological views in eighteenth-century France is discussed in [4].

[2] The Newtonian 'style' is discussed in [5], while for the analytical utility of the category of Newtonianism, see [6].

[3] For popular Newtonianism in the French Enlightenment, see [7].

[4] Newton to Oldenburg, 4 and 21 May 1672; in [8, 1: 153–4]. See also [9] for the identity and work of Cassegrain.

[5] See [10, pp. 84–7].

[6] See [10, pp. 98–9], [11, pp. 89–94].

[7] See [12,13]. For Leibniz's composition of the *Tentamen de Motuum Coelestium Causis* as a response to the *Principia*, see [14] and especially [15].

[8] For the invocation of tourbillons, see the classic account in [16].

[9] See [17] and for a recent analysis [10, pp. 56–61], [18–20].

[10] More generally, see [10, pp. 101–3, 107–10] and [21].

[11] See [10, pp.120–36] and [22, pp. 239–41]. For Castel's critique of Newton's theory of light and colours, see [23].

[12] See [24] and [8, 7: 111–13]. See also [10, pp. 112–16, 139–59] and [22, pp. 245–6].

[13] For contemporary accounts, see [25–28]. In general, see [29].

[14] For the commitment to tourbillons see [26,27,30] and the very late contribution by Fontenelle [28]. See [29]. Castel's major publications critical of Newton's methodology and cosmology were [31–33]; more broadly see [7, pp. 194–209] and [34].

[15] See [8], 6: 41–3, 59–60, 145–6 and 187–8.

[16] See [35], [25, pp. 44–7] and [7, pp. 245–53].

[17] See [36] and [7].

[18] See [37–39]. See more generally [40–43].

[19] See [44–47]. Newton's use of data from Richer and others to support and refine his theory is discussed in [48].

[20] For recent assessments, see [49,50] and [25].

[21] See [51,52]. I am grateful to Xiaona Wang for showing me her excellent paper on the mobilization of Chinese data by de Mairan and Fréret.

[22] See [53,54]; see also [55,56].

[23] See [57]; for analysis of the content and contexts of the edition, see [58–60].

[24] See [59, pp. 348–51].

[25] See [59, 341–2]. See also [61].

[26] See [62, 2: 153–4] and [59, pp. 365–6].

[27] See [63]; a modern critical edition reproducing the printed version and the surviving manuscript of the text was overseen by Michel Toulmonde and appeared in 2015. See further [64, 65], especially pp. 229–36 and 243 fn.31. In 1746, the Dutch mathematics teacher and translator Élie de Joncourt brought out a French translation of the third (1742) edition of his mentor Willem's Gravesande's *Physices Elementa Mathematica* (orig. 1720–1721), while Colin Maclaurin's 1748 *Account of Sir Isaac Newton's Philosophical Discoveries* was translated by the physician Louis-Anne Lavirotte [66].

[28] Halley [67] was speedily republished and appeared in several subsequent editions. More generally, see [68], especially pp. 125–8 [69, 70].

[29] See [45].

[30] See [70, pp. 72–8].

[31] See [68–70]. Clairaut's work was published in [71, 72].

[32] See [73–80] and for continuing hostility to Newton's doctrines in the later eighteenth century, see [61].

[33] For the Laplacian programme, see [77].

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