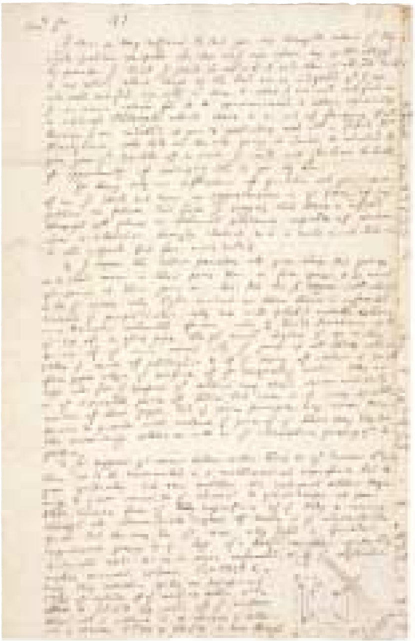
making sense of motion

Gravity was one of a number of forces whose operation Newton investigated in his working papers and eventually in the *Principia*. Unfortunately, Newton's description of force generated problems for the explanations of matter in motion that he had once accepted and that continued to be used by many of his contemporaries. One consequence of this was that the search for a material cause for the effects of gravity and other forces was a prominent theme in his writing both before and after the publication of the *Principia*. This was particularly noticeable in the queries that he composed for later editions of the *Opticks*, which eventually seemed to propound some sort of spiritual origin for gravity. Despite such difficulties, his account of gravity was triumphantly successful in its solution to some of the outstanding problems of seventeenth-century science. One of the most notable examples of this success was the proof of the parabolic or elliptical orbits of comets. Based on exhaustive investigation of the historical record, the collection of contemporary observations, and careful calculation, this was a critical example of the accuracy of Newton's interpretation of celestial mechanics.

45 cambridge university library, macclesfield collection, box 3/4/62
(figure 26)
29.3 × 18.3

Newton had first become acquainted with the writings of Robert Boyle (1627–91) in the mid-1660s (see catalogue number 11). The two men met at the Royal Society in 1675. As Newton's work on light progressed in the mid-1670s, he began to depend more and more on notions derived from chemical experiments and from consideration of the form and structure of matter. These were techniques and topics that Boyle had


26


27

figure 26
Newton writes to Boyle about the nature of the aether and the possible mechanical causes of the behaviour of light, University Library, Macclesfield Collection, Box 3/4/62.

figure 27
The effects of gravity in a uniformly contained fluid, from Newton's essay 'De gravitatione et aequipondio fluidorum', University Library, Ms. Add. 4003, f. 22r.

discussed extensively and Newton's notebooks from this period frequently mention both Boyle's own writings and the works that had influenced them. Newton's only surviving letter to Boyle (figure 26) was written on 28 February 1679 and developed ideas that Newton had advanced in earlier correspondence with Oldenburg (see catalogue numbers 26 and 28). In particular, it discussed the nature of the aether, which Newton supposed 'pervades all gross bodies, but yet so as to stand rarer in their pores then in free spaces, & so much [the] rarer as their pores are less.' The intermingling of rarer with denser aether at the edges of opaque bodies allowed Newton to offer an explanation for the refraction of light into several colours as it passed them by. Newton went on to discuss other consequences of this aether, which he suggested might explain attraction and repulsion between bodies, and chemical reactions, especially between metals and acids. He also put forward a conjecture 'about [the] cause of gravity'. He argued that the descent of bodies under gravity might be caused by the pressure of the aether, which became denser as one moved further away from the centre of the earth.

H. W. Turnbull, J.F. Scott, A.R. Hall and Laura Tilling (eds), *The Correspondence of Isaac Newton*, 7 vols (Cambridge, 1959–77), vol. 2, 288–96 (which prints this letter).

Purchased from the Earl of Macclesfield by Cambridge University Library, August 2000.

46 cambridge university library, ms. add. 4003, f. 22r
(figure 27)
19.4 × 15 cm
Bound notebook of 191 leaves

The first three folios of this notebook are blank. The next forty pages have been numbered by Newton, who also ruled the margins of folios four to thirty-one. The forty numbered pages (or twenty folios) were used at some point by Newton for the composition of an essay entitled 'De Gravitatione et aequipondio fluidorum et solidorum in fluidis' ('On the Gravity and Equal Weight of Fluid and Solid Bodies in Fluids'). The rest of the notebook was left blank.

'De gravitatione' is one of Newton's most important essays. It probably dates from winter 1684 or early spring 1685, since its contents suggest some familiarity with the tract 'De motu' but do not hint at the revisions that Newton soon made to it (see catalogue numbers 42 and 16). It provides the clearest evidence of Newton's break with Cartesian physics at the time of the composition of the *Principia*. Unusually careful and exact citations from Descartes' works accompany Newton's criticisms. Moreover, the argument of 'De gravitatione' depends in part on the results of pendulum experiments that Newton probably conducted during 1684. These experiments suggested that resistance due to penetration by the aether was very small, whereas, when he had written to Boyle in November 1679, Newton had believed that it was sufficient to explain the repulsion of one body by another (see catalogue number 45). In denying that motion might simply be the result of the pressure of small particles on larger bodies, Newton rejected Descartes' relative interpretation of matter and space. In its place, he suggested that space must be understood in absolute terms. Only infinite space and finite matter were compatible with divine creation. The pages from 'De gravitatione' that are on display (figure 27) illustrate this argument. In a discussion of non-elastic fluids, Newton proposed that 'compression does not cause a motion of the parts among themselves'. He went on to demonstrate this with the aid of a diagram that showed that 'moreover… all the parts exert pressure on each other equally and they do so with the same intensity of pressure as is exerted upon the external surface.'

The composition of 'De gravitatione' therefore represented a break with Newton's earlier writing about the aether. Although Newton decided that the straightforward effects of matter in motion could not explain the action of gravity, he did not abandon theories based on the aether entirely. Instead he modified them to take into account of his notion of force and continued to suspect that something like a rarefied aether might explain the behaviour of light, electricity, and other phenomena, perhaps including gravity itself.

A. Rupert Hall and Marie Boas Hall (eds), *Unpublished Scientific Papers of Isaac Newton* (Cambridge, 1962), pp. 89–156; John Herivel, *The Background to Newton's Principia* (Oxford, 1965), pp. 91–3, 219–235 [The Halls print and translate the entire text of 'De gravitatione'; Herivel prints and translates part of it. They all date the manuscript by appearance to the mid-1660s.]; Betty Jo Teeter Dobbs, *The Janus Faces of Genius* (Cambridge, 1991), pp. 139–46 [which convincingly redates the manuscript by content]; I. Bernard Cohen, *The Newtonian Revolution* (Cambridge, 1980), pp. 113–118; Robert Palter, 'Saving Newton's Text: Documents, Readers, and the Ways of the World', *Studies in History and Philosophy of Science*, 18 (1987), 385–439; Alan E. Shapiro, 'Light, Pressure, and Rectilinear Propagation: Descartes' Celestial Optics and Newton's Hydrostatics', *Studies in History and*

figure 28
Newton's record of observations of the comet of 1682, written on a scrap of paper perhaps torn from a letter, University Library, Macclesfield Collection Box 43.

Philosophy of Science, 5 (1974), 239–96. [It is unlikely that the dating of this manuscript can be confirmed by the watermark (Arms of Amsterdam). Newton used paper with a similar watermark and no countermark in the late 1660s (see catalogue number 54). Paper with this watermark and the countermark 'AI' also appears in the mid-1670s (see catalogue number 28), and some sheets with another countermark can be found in catalogue numbers 52 (1680s or 1690s), and 16 (1685). Unfortunately, the binding of the notebook containing 'De gravitatione' is too tight to enable proper examination of the watermark, in particular for exact measurement or to identify any countermark. For discussion of dating by watermarks, see Alan E. Shapiro, 'Beyond the Dating Game: Watermark Clusters and the Composition of Newton's *Opticks*', in P.M. Harman and Alan E. Shapiro (eds), *The Investigation of Difficult Things* (Cambridge, 1992), pp. 181–227.]

Assessed 'Not fit to be printed' on behalf of Newton's executors by Thomas Pellet (25 September 1727); presented to Cambridge University Library by the fifth Earl of Portsmouth. See *A Catalogue of the Portsmouth Collection of Books and Papers written by or belonging to Sir Isaac Newton* (Cambridge, 1888), p. 48.

47 cambridge university library, macclesfield collection box 43

(figure 28)

17.6 × 22.4 cm

This scrap of paper was presumably torn from the foot of a letter, since Newton's signature appears in the top right-hand corner. Beneath this, Newton has recorded observations of the comet of 1682 (see catalogue number 44) that he made on four successive nights, starting on 19 August. A very similar, but more complete, record appears in Newton's 'Waste Book' (see catalogue number 33). It seems reasonable to suppose that Newton originally wrote out his observations in the 'Waste Book' and subsequently communicated them to one of his correspondents, several of whom provided him with information about comets in the early 1680s. Robert Boyle (see catalogue number 45) wrote to Newton about '[the] Apparition of a Comet' on 19 August 1682, the day that Newton's observations began. In this letter, Boyle also commented that [the] darke weather joynd to my want of health, have for the two last nights kept me from lookeing after it.' It is tempting to suggest that Newton's account of his observations formed part of a reply to Boyle. However, the letter's recipient was presumably responsible for its subsequent annotations, of which those giving the dates are certainly in neither Newton's nor Boyle's hand.

H. W. Turnbull, J.F. Scott, A.R. Hall and Laura Tilling (eds), *The Correspondence of Isaac Newton*, 7 vols (Cambridge, 1959–77), vol. 2, 379–81 (which prints this manuscript); Richard S. Westfall, *Never at Rest. A Biography of Isaac Newton* (Cambridge, 1980), p. 396.

Purchased from the Earl of Macclesfield by Cambridge University Library, August 2000.

48 cambridge university library, ms. add. 3965, f. 564v-5r

(figure 29)

29.5 × 19.1 cm

During the years between 1681 and 1686, Newton built up an extensive network of informants who provided him with observations of comets. The most prominent of these were John Flamsteed (see catalogue number 18), who sent Newton sightings from Greenwich, and Arthur Storer, who had been at school with Newton in Grantham and who had begun to send him astronomical information in 1678. Storer's observations were especially interesting since they were made in Maryland, New England. As the importance of calculations relating to the comet of 1680 grew with the composition of Book III of the *Principia*, Newton tried to obtain further corroboration of the observations available to him.

On 7 March 1681, Flamsteed had written a letter to be passed onto Newton in which he described a number of observations of the recent comet. He discussed the sightings made by Continental astronomers in both Paris and Rome, news of which had been sent to him by Halley (see catalogue number 42), and also mentioned 'an observation… made at Canterbury by one Hill an artificer with an instrument of 4 foot Radius on Friday morneing [November] 11'. At this stage, what interested Newton was to defend his belief that he had seen two comets in the winter skies of 1680 and 1681. By 19 September 1685, however, Newton was passionately anxious for information about the single comet of 1680–1, for which Flamsteed had earlier argued. He was trying to unravel the discrepancies between various accounts of the comet, which were complicated by the fact that different calendars were employed in England and on the Continent. He therefore applied to Flamsteed again for further information about the lowly Hill, whom he had ignored completely four and a half years earlier. Flamsteed drafted a reply on 25 September, attempting to help Newton sort matters out. He suggested

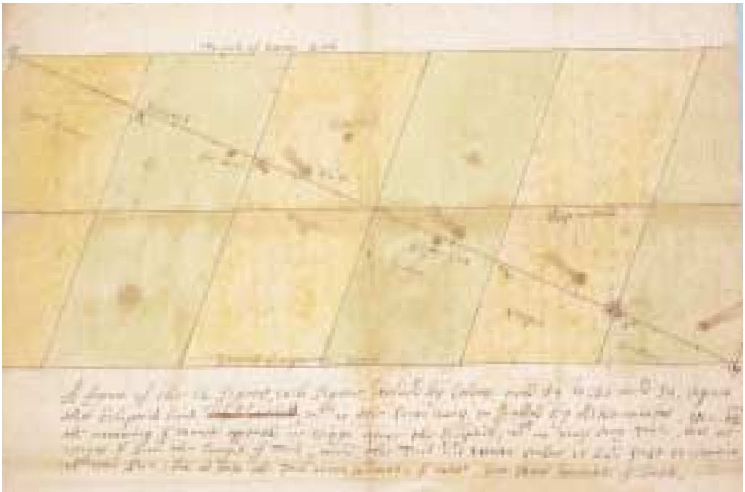


figure 29
Observations on the comet of 1680 by Thomas Hill of Canterbury, perhaps sent to Newton by John Flamsteed in 1685, University Library, Ms. Add. 3965, f. 564v.

that 'As for the Canterbury observation it is a very course one. I discourst with the person that made it but found him a very ignorant well willer, yet I beleive his observations as good as those… made at Rome…' A version of this response was sent to Newton on 26 September, together with a letter that Hill had written to Flamsteed on 29 December 1681. This indicated that Hill had in fact first seen the comet on the morning of 12 November 1680 and revealed that he had continued to observe it until 3 January 1681, making a final sighting on 3 February.

The subject of this exchange between Flamsteed and Newton was Thomas Hill, a Canterbury artificer about whom no more is known. Hill's sightings of the comet of 1680–1 were communicated to Flamsteed at the Royal Observatory. Flamsteed later sent Newton more than a single letter from Hill. A drawing by Hill of the path of the comet through the heavens, accompanied by a detailed account of his 'Observations of the Comet 1680' (figure 29) can be found among the reports that Newton collected from that year.

H. W. Turnbull, J.F. Scott, A.R. Hall and Laura Tilling (eds), *The Correspondence of Isaac Newton*, 7 vols (Cambridge, 1959–77), vol. 2, 348–56, 372–3, 419–28; Eric G. Forbes, Lesley Murdin, and Frances Willmoth (eds), *The Correspondence of John Flamsteed*, 3 vols (Bristol, 1995–2001), vol. 1, 749, 772, 843–4, 925; vol. 2, 245–56.

Presented to Cambridge University Library by the fifth Earl of Portsmouth. See *A Catalogue of the Portsmouth Collection of Books and Papers written by or belonging to Sir Isaac Newton* (Cambridge, 1888), p. 4–5.

49 cambridge university library, ms. add. 3982, number 6
30.2 × 18.8 cm

Newton's calculations in Book III of the first edition of the *Principia* had demonstrated that comets travelled in parabolic paths. During the mid-1690s, Edmond Halley (see catalogue number 42) began to recalculate some of Newton's data and to demonstrate that some cometary orbits at least were elliptical. One consequence of this was the realisation that particular comets might have appeared previously in the historical record. The easiest of these comets to identify turned out to be that of 1682, subsequently known as 'Halley's Comet', which Halley was quickly able to compare with the comet of 1607. Although it took Halley many more years to develop in full his prediction of the return of this comet, the popularity of this idea among Newton's disciples suggested that it chimed well with their master's attempts to give a single account of nature, history, and theology.

Halley's calculations in the mid-1690s depended on information provided by others, just as Newton's had done in the mid-1680s. Flamsteed in particular shared his observations with the two men who were subsequently to become the bane of his life.

In August 1695, Halley began by working out the orbit of the comet of 1683. He soon considered that of 1664 (see catalogue number 2), where he was hampered by the lack of sufficiently accurate observations, and suggested that he might also tackle the observations of 1680–1. By the end of September, Halley had made corrections to the information that Newton had used in the *Principia* and had improved on Newton's description of the line of the comet through arithmetical calculation. He wrote that 'I find certain indication of an Elliptick Orb in that Comet and am satisfied that it will be very difficult to hit it exactly by a Parabolick.' In a letter of 17 October, Newton indicated that Halley's reasoning had now convinced him, although he supplied numerous corrections to the calculations. Halley welcomed these in his letter of 21 October (on display), in which he also mentioned his ideas about the comet of 1682.

The calculations that Halley provided for Newton eventually made their way into the second edition of the *Principia* (see catalogue number 44). Halley's work also encouraged Newton to reconsider the effects of the gravitation of the planets on cometary orbits. It was thus related to the ideas that Newton put forward in his treatment of the motion of the moon (see catalogue number 19). Newton's reliance on Halley is revealing in other ways. Firstly, it illustrates the extent to which Newton by the 1690s depended on younger men to enforce the mathematical rigour for which he had once been famous. It also highlights the collaborative nature of the final Newtonian synthesis, despite the very solitary methods of Newton's own original work. Furthermore, Newton's acceptance of Halley's assistance draws attention to some of the problems that confronted him in the 1690s. In that decade of theological paranoia, when accusations of atheism or deism were rife, Halley's friendship was to some extent a liability because of the reputation for immoral behaviour that he had acquired. This may account for Newton's reluctance to support Halley in the contest for the Savilian chair of astronomy at Oxford in 1691, when David Gregory was elected. Yet the readiness to court controversy displayed by Newton's younger friends in general helps to explain why he retreated from publishing many of the bolder statements that he had advanced in private during the 1690s, despite the success of the *Principia*.

H. W. Turnbull, J.F. Scott, A.R. Hall and Laura Tilling (eds), *The Correspondence of Isaac Newton*, 7 vols (Cambridge, 1959–77), vol. 4, 165–83 (part of which prints this letter); Alan Cook, *Edmond Halley* (Oxford, 1998), pp. 205–17; I. Bernard Cohen, *The Newtonian Revolution* (Cambridge, 1980), pp. 269–71.

Presented to Cambridge University Library by the fifth Earl of Portsmouth. See *A Catalogue of the Portsmouth Collection of Books and Papers written by or belonging to Sir Isaac Newton* (Cambridge, 1888), p. 36.

50 cambridge university library, ms. add. 3974, f. 2bv

(figure 30)

20.4 × 16 cm

There were other forces at work in the world besides gravity. One of these was magnetism, which together with electricity exhibited the patterns of attraction and repulsion that occupied Newton for much of his life. Electricity only began to excite Newton's serious interest as a result of experiments performed at the Royal Society during his presidency of that body. Ideas derived from electrical investigations were included in the queries to the *Opticks*, especially in those added to the second edition (see catalogue numbers 29 and 30). Newton himself never made any serious observations of electrical phenomena. This was also true of magnetism, although mentions of magnets and lodestones

figure 30
Newton's experiments with magnets and iron filings, University Library, Ms. Add. 3974, f. 2bv.

occur sporadically in Newton's writings. A magnet was among his purchases in 1667 (see catalogue number 3), but he owned few books related to magnetism. In the mid-1660s, Newton had entered several queries about 'Atraction Magneticall' into his philosophical notebook (see catalogue number 2). His main concern seems to have been to consider whether a stream of magnetic particles might be employed to turn a perpetual motion machine. Some years later, however, perhaps towards the end of the 1660s or even in the early 1670s, Newton attempted a slightly more complete investigation of magnetic attraction. After making notes on the history of compasses and the manufacture of magnets, he explored the simple properties of attraction and repulsion in hammered iron magnets. He also conducted rather more extensive experiments with lodestones, attempting to map the pattern of their interactions using iron filings (figure 30).

These were basic observations that repeated work that was already standard in the philosophical literature about magnetism. Despite this, Newton's work on magnets had obvious relevance for his investigation of the causes of other natural phenomena. Experiments with magnets and iron filings seem at first to have confirmed the idea that a stream of active particles moving in a particular direction might be responsible for the effects that Newton described: '[the] ~~rays~~ streames of [the] same nature meeting in [the] aire doe comply [with] one anothers motions & those of divers natures doe resist one another in [the] aire.' This was very similar to the language with which Newton sought to explain the behaviour of light in the early 1670s and which he used when investigating the swing of pendulums at that time. Newton continued to deploy magnetic analogies in his later work on the aether and in his attempts to explain the gravity. But as he moved away from Cartesian or material explanations the relevance of these simple magnetic experiments decreased.

J.E. McGuire and Martin Tamny (eds), *Certain Philosophical Questions: Newton's Trinity Notebook* (Cambridge, 1983), pp. 377–9.

Presented to Cambridge University Library by the fifth Earl of Portsmouth. See *A Catalogue of the Portsmouth Collection of Books and Papers written by or belonging to Sir Isaac Newton* (Cambridge, 1888), pp. 19–20.

51 cambridge university library, ms. add. 3970, f. 619r
30.1 × 18.5 cm

This draft for the final query (23) of the *Opticks* was probably composed in autumn or winter 1705. It differed substantially from the published query as it appeared in the Latin *Optice* of the following year. In particular, it began with a direct allusion to the atomist philosophy of the ancients, that by the mid-1680s Newton supposed to be a precursor of his own. It also suggested that an omnipresent God was himself the cause of gravity, since 'matter depends upon a Deity for its laws of motion as well as for its existence'. The draft attempted to explain how Newton's revival of ancient theories of divine harmony differed from Cartesian attempts to make 'God the author of all motion'. Newton's distinctions did not impress contemporary Continental philosophers. In particular, the suggestion that 'all space be the sensorium of a thinking being', when it appeared along with some of the other material from this draft in the published Query 20, excited Leibniz to argue that Newton had made God dependent on space as an organ through which he might perceive creation.

Few people understood the explanations that Newton now gave for the activity of light and gravity. David Gregory, who saw the new queries for the *Opticks* in draft in December 1705, commented that Newton had 'shewed that Light is neither a communication of motion nor of a Pressure. He inclines to believe it to be projected minute bodys.' The folio on display gives some indication of the difficulty that Newton found in demonstrating the affinity between his natural philosophy and ancient ideas of 'actuating matter harmonicaly by the God Pan's playing upon a Pipe& attributing musick to the spheres'. It bears extensive signs of correction and rewriting and was never published in anything like this form. Nevertheless, it provides a clear indication of Newton's persistence with explanations for the function of gravity that he had begun to develop in the mid-1680s (see catalogue number 43 and 44).

J.E. McGuire and P.M. Rattansi, 'Newton and the "Pipes of Pan"', *Notes and Records of the Royal Society of London*, 21 (1966), 108–143; J.E. McGuire, *Tradition and Innovation. Newton's Metaphysics of Nature* (Dordrecht, 1995), pp. 190–238; W.G. Hiscock (ed.), *David Gregory, Isaac Newton and their Circle* (Oxford, 1937), pp. 29–30.

Presented to Cambridge University Library by the fifth Earl of Portsmouth. See *A Catalogue of the Portsmouth Collection of Books and Papers written by or belonging to Sir Isaac Newton* (Cambridge, 1888), pp. 9–10.

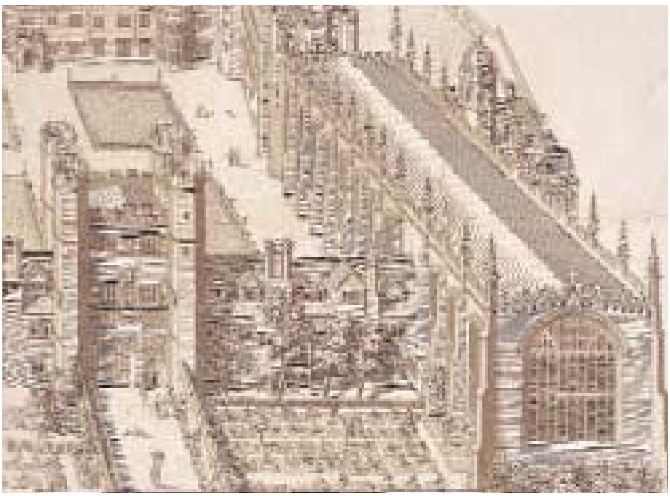


figure 31
Newton's rooms in Trinity College, on the first floor to the right of the gatehouse, from David Loggan's *Cantabrigia illustrata* (1690), University Library, Ii 9.3.