Hist. Sci., xlvii (2009)

NEWTON ON THE BEACH: THE INFORMATION ORDER OF *PRINCIPIA MATHEMATICA*

Simon Schaffer
Cambridge University

WHAT I MAY SEEM TO THE WORLD

> I know not what I may seem to the world, but as to myself, I seem to have been only like a boy playing on the sea-shore and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me.[1]

It is one of the most celebrated of Isaac Newton's *obiter dicta*. Like many such, its provenance is hazy. The literary reference may well be to a passage from John Milton's great redemptive poem *Paradise regained* (1671) where, in dialogue with Satan, Christ praises divine illumination above pagan learning: "who reads / Incessantly, and to his reading brings not / A spirit and judgment equal or superior, / … Uncertain and unsettled still remains, / Deep verst in books, and shallow in himself, / Crude or intoxicate, collecting toys / And trifles for choice matters, worth a spunge, / As children gath'ring pebbles on the shore".[2] But the remark's immediate relation with Newton is more ambiguous. The earliest version is found in a conversation of April 1730, three years after Newton's death, between the gossipy man of letters Joseph Spence and the Jacobite, freemason and court tutor Andrew Ramsay. While chatting about Newton's debt to ancient theology and his strange attitudes towards the doctrine of the Trinity, Ramsay quoted Newton's phrase, adding it was "as great as all" of *Principia mathematica*.[3] Never one to let a nice epigram slip, Ramsay then incorporated the expression in his 1732 *Plan of education for a young prince*, composed to help tutor the heirs of a noble French clan. But in commending his own version of Newtonian philosophy Ramsay modified the sense: "as Sir Isaac Newton said, all the Discoveries Mortals can make are like those of a Child upon the Borders of the Sea, that has only crack'd some pebbles and open'd some shells, to see what is in them, while there lies beyond him a boundless ocean of which he has no idea." The reference was to Pauline doctrine in 1 *Corinthians* 13: "now we see through a glass darkly, but then face to face." Newton's loyal nephew John Conduitt, concerned with materials for the great man's biography, dutifully pasted into his own scrapbook a cutting from a Jacobite newspaper that carried this extract from Ramsay's *Plan*.[4] The remark passed into wide currency, republished or evoked by such writers as Lord Byron in *Don Juan* (1820–21) and by David Brewster in *The life of Isaac Newton* (1831). Much has been made of the imagery of the "ocean of truth". Even more attention has been paid to the alleged modesty of the opening phrase: "I know not what I may seem to the world." In his psychobiography of Newton, Frank Manuel

0073-2753/09/4703-0243/$10.00

hazarded that "this guileless and disarming simile may also be his confession".[5]

But the concern here is different. Newton was never on the seashore nor discovered the ocean. He saw no tides save along the Thames and did not use the Moon's place to navigate at sea. No great traveller, he spent his life in Lincolnshire, Cambridge and some London houses, pubs and offices. He is known to have boated only with Christiaan Huygens upriver to Hampton Court in summer 1689 to lobby the monarch for a college job and presumably on a series of journeys in the early 1700s in the barge of the Royal Mint between the Tower of London and Whitehall stairs to attend ceremonial coin trials in Westminster. Then as now he seemed to the world a remarkably stationary man, the embodiment of spiritual and scholarly solitude. One of his admirers, the Lincolnshire antiquary William Stukeley, recalled that at Cambridge "we gaz'd on him, never enough satisfy'd … as on somewhat divine". Stukeley claimed that even when a public figure Newton had been "drawn forth into light before, as to his person, from his beloved privacy in the walls of a college where … he published his *Principia*, that prodigious and immortal work". As early as spring 1688, when its patient editor Edmond Halley gave *Principia* its first review, readers were told that "the incomparable Author having at length been prevailed upon to appear in Publick, has in this Treatise given a most notable instance of the extent of the powers of the Mind".[6]

There was a rather direct connexion, as Rob Iliffe has shown, between an ingeniously worked image of seclusion and authority and the religious and cosmological programme Newton espoused. In strategic comments on the proper status of the virtuous natural philosopher, Newton urged that the wars of the learned were due to making public what should be secreted and the affairs of a corrupt state and church poisonous for the pursuit of truth. Jan Golinski has traced the ways in which the "noble and secret" works of philosophical alchemy were important for Newton's knowledge map. In his analysis of the relation between experimental location and the "ambivalent or hostile" reaction of Newton to its public milieu, Steven Shapin has cited Milton on the mind as "its own place", convincingly reasoning that "the solitary philosopher" is taken to "elaborate a world wholly free of his corporeal situation". Nowhere and everywhere, indeed nowhere *therefore* everywhere, this Newtonian solitude allowed an *imitatio Dei*.[7]

Newton's playful and sublime seashore and its importance in his self-image provide an apt stimulus for these reflections on information, insulation and geography. In an astute chiasmus, the figure of the beachcomber locates divine verities in the realm of sublime travel ("the ocean of truth") and sets curious natural history in trivial solitude ("a prettier shell"). Historical geographers have recently paid fresh attention both to the territories of enlightened knowledge and to what has been called the "social and material space" of the littoral. Here, the aim is to explore that space in an account of Newtonian global knowledge.[8] The case of his comparative seclusion and immobility seems striking because his programme, first launched in the mid-1680s and under revision for the next three decades, evidently mastered vast cosmologies and chronologies, involving heights of tides, lengths of pendulums, positions of comets and satellites, the tales of well-travelled mariners and missionaries, merchants and mercenaries. The divine Newton could describe how bodies acted on each other instantly and at a distance because, so it seems, he could also act instantly and at a distance without mediation.

But immediate action at a distance is plausible neither as a historical nor sociological principle. The aim here is to use the figure of Newtonian solitude to examine the emergence and working of information systems in early modern natural philosophy. *Principia mathematica* remains a glorious achievement of a putatively secluded analyst of the mathematics of motion. The remark about the beachcomber and the ocean of truth has helped underwrite a weird notion that nothing like reportage or trust could play a consequential role in the Newtonian triumph nor in any successfully completed analytical science. Yet the networks through which reports reached Newton and on the integrity of which so much of his work relied were crucial for his enterprise. The cloister and the ocean fit together as components of a system that helped solitude and testimony function together.[9]

The knowledges in question in this case seem unusually interesting examples of such socially institutionalized practices. While part of this essay's provocation is a desire to put Newton back on the beach where he belongs, part also wishes to invoke some of the claims of Boris Hessen some seventy-five years ago, which at least started the project to analyse the final book of *Principia mathematica* in terms of its relation with navigation and trade: "in a work treating of natural philosophy", Hessen remarked, "we cannot expect to find references to the low sources of its inspiration".[10] A relocation of Newton's programme would be highly informative about sources of inspiration and in particular about the information order and the knowledge flows through which his masterpiece was produced.

INFORMATION ORDERS AND CREDIT ECONOMIES

Long-range systems of accumulation of facts and commodities were decisive aspects of the early modern information order. Adapting prestigious accounts of colonial voyage and conquest under the aegis of the Catholic Monarchy, enterprises such as the Baconian instauration linked distant travel and advances in knowledge. Joint-stock trading corporations and the vast missionary enterprises of the Society of Jesus, for example, set up networks of trade, storage and communication through which new kinds of knowledge and performance were developed. Jesuits' networks involved innovative genres of reportage and display relying on well-institutionalized patterns of trust and vigilance.[11] Though Newton's relations with Jesuit natural philosophers and historians were notoriously and traumatically fraught, these priests would provide recalcitrant but indispensable resources for his own endeavours. Importantly for the argument presented here, protagonists were peculiarly aware of the modes of travel and knowledge their work developed. The ecstatic heavenly journeys composed by Jesuits such as Athanasius Kircher in his museum in Rome or Valentin Stansel in his college in Brazil were modes of imagining travel and its spiritual sense, as though delegates could move without obstacles around a world revealed by the new information order.[12] Similarly, in her brilliant study of what she calls the "information ceremonies" of the old regime, Michèle Fogel shows how at a period seen as marking the dawn of modern civil society, control over information production was surrounded with complex rituals where state power was dramatized and reinforced. John Brewer's comparable analysis of the fiscal-military excise system shows the liaison between flows of information and of goods in the regime of the period. Larry Stewart has demonstrated the entanglement of Newtonian natural philosophy with the commercial revolution of Georgian Britain, and has pursued these connections in the globalized trade networks Britain's empire established. These historians bring out the spatial, political and commercial dimensions of early modern information orders.[13]

'Information' here is a term designed to describe matters more broadly shared and less explicitly challenged than formalized knowledges. Information is the commonly taken-for-granted, rather less disputed and less disputable; knowledge looks more mutable, its status certainly more debatable. "In early modern societies", C. A. Bayly points out, "the information order was decentralised, consisting of many overlapping knowledge-rich communities". Within these orders there were information brokers, men such as Henry Oldenburg and Hans Sloane. As Peter Burke suggests, they functioned in an information order that sometimes called itself the Republic of Letters, in which there was print commerce, stock investment, news books, subscription systems and encyclopaedias.[14] This was the epoch of foundation both of the natural philosophical journal and of the newspaper. There were hosts of reports of marvels and prodigies linked with commercial and political events, whose credibility was a concern for magistrates and priests, natural philosophers and merchants. All this was "paper fuel" for news books and coffee houses.[15] In managing accounts of exotic and wondrous phenomena, rival criteria of assessment of the possible capacities of the world were disputed. There was a culture of what Brendan Dooley has called the "information underground" of early modern European news. To know what might happen in the world it was important to know whom to trust.[16]

Reports of striking phenomena, increasingly vouchsafed in numerical terms, were understood as the output of observers equipped with artful devices and instruments. It was puzzling to persuade distant audiences of the plausibility of these stories and measures, especially when managing discrepancy or contradiction. This persuasion could be achieved by urging the skill involved in wielding instruments. Such skills were assayed as part of a credit system that relied on travel, trade and empire. The system's exemplary institutions were libraries, cabinets and museums, as well as mints and assay rooms. The key assay practices, including pharmacy and alchemy, were dependent upon and often debated the provenance of globally distributed goods and measures whose virtues were connected with the precise characteristics of the sites whence these valuable commodities were shipped.[17]

As example of how this order was put to work, consider Newton's first extant letter, apparently written in Cambridge in spring 1669 to his college friend Francis Aston. Newton copied out another virtuoso's instructions concerning the inquiries travellers should make about navigation, mining, pendulum clocks and metallurgy.

He then added notes from a favoured alchemical text edited by Michael Maier and asked about transmutations and for news of a medical chemist ("I think he usually goes clothed in green") whose repute in Amsterdam he wished to judge: "pray enquire whether his ingenuity be any profit to the Dutch." In fact this ingenious adept had left the Netherlands for Denmark and ultimately Papal imprisonment in Rome. This did not prevent news sheets carrying tell-tale reports of his deeds that reached eminent London natural philosophers such as Robert Boyle, so giving credit to other alchemical pretenders. Alchemy provides a good case of the links between professed solitude and ingenious commerce, since without global supply chains alchemical labour would lack its materials. Historians' readings of the letter from Newton to Aston are telling. Westfall reckons it a sign of Newton's "isolation" (because it is his only personal letter of the period). Manuel asserts that "Newton remained insular all his life" and "was surely not curious enough to travel". Hessen, by contrast, uses the document as evidence of Newton's real interest in gathering reliable information about distant techniques.[18]

In tracing such networks of trade and knowledge, we might rather follow the suggestions of recent historians of the process, such as Hal Cook and Steven Harris. In his analysis of Dutch merchant enterprise and natural history, Cook rightly points out how collective creditworthy accumulation of goods and information characterized the Dutch economic system and its knowledge regime. Inventory investment, the invention of maintenance technologies of storage, classification and warehousing were systems of knowledge accumulation in libraries, gardens, pharmacies or museums. Harris uses the career of the Dutch VOC, alongside those of Habsburg and Jesuit knowledge networks, to chart how travel, expropriation and accumulation provided both the social modes of the early modern capitalist system and the information networks and genuinely big sciences of these institutions.[19] The economic systems of global European commercial networks vouchsafed the scope of the information order while that order also underwrote the power of those systems. It could therefore help make a world, judging persons under regimes of credit and trust alongside the judgment of creation's contents. It saw the acquisition of knowledge as the stocking of a cabinet to correct the effects of the Fall. The divinely sanctioned reasons of creation were supposed to guarantee the possibility of knowing it and relying on its products.

There was thus a link between the colonial information order and the empiricist knowledge regime of the late seventeenth century, between forms of epistemology, providentialism and domination. The preface to Awnsham and John Churchill's collection of *Voyage and travels* (1704), perhaps by John Locke or by Edmond Halley, made the link. "Natural and moral history is embellished with the most beneficial increase of so many thousands of plants it had never before received, so many drugs and spices, such unaccountable diversity. Trade is raised to highest pitch, and this not in a niggard and scanty manner as when the Venetians served all Europe … the empire of Europe is now extended to the utmost bounds of the Earth."[20] The Restoration world reinforced the colonial economy and the plantation system. The slave-trading

Royal Africa Company, founded in 1660 and reformed in 1672, was described by the eloquent historian Thomas Sprat as the "twin" of the Royal Society.[21] Leaders of the Royal Society such as its treasurer Abraham Hill, its president the Earl of Carbery and its chief Augustan patron the Duke of Chandos were also leaders of the slave economy. Newton's successor as the Royal Society's president, the naturalist, traveller and fashionable physician Hans Sloane, gained his finance and social capital from the West Indian plantations and was commissioned by Chandos in the 1720s to act as a node of the information order that underwrote the plantation system by assaying plant samples such as quinine, balsam and dyestuffs.[22]

Remarkable information systems like those run by the Society of Jesus, the VOC and the Royal Africa Company, and in London by Oldenburg or by Sloane, involved the assay of persons as well as goods. This accumulation explicitly depended on credit and credibility, which could always go wrong. Newton, Sloane and Locke knew that well.[23] What counted were the criteria with which plausibility could be assessed. How to discriminate, for example, between reports from eastern Asia that reached London through Jesuit and commercial sources in the early eighteenth century, whether those of Engelbert Kaempfer on Japan, managed into print by Sloane, or those in the same waters of Lemuel Gulliver, printed at the same time and with the same publisher as Sloane's *Voyage* and Newton's *Mathematical principles*?[24] There was also the contemporary case of the young Frenchman who went by the name of George Psalmanazar, passed himself off in England in 1704 as a Formosan in flight from Jesuit masters, published a natural and civil history of his island, then professed its (invented) language at Christ Church Oxford, before becoming too suspect and eventually confessing his deception. The Royal Society's president, Isaac Newton, summoned the supposed Formosan for interview. The author used the conventions of this information order — of probability, conjecture and assay — to make his story credible. Sloane led an inquiry. He sent a veteran of the Jesuits' China mission, Jean Fontaney, to Avignon to check on Psalmanazar's credentials, which proved all too faulty. The Astronomer Royal John Flamsteed sent Psalmanazar's book (along with a fine quadrant and a copy of Newton's new *Opticks*) to his colleague James Pound, then employed by the East India Company at a trading base in the South China Sea. Pound confirmed that Psalmanazar was not to be credited.[25] Others, however, faced with a choice between Jesuit and anti-Catholic witnesses, trusted Psalmanazar. Tales of papist cannibalism in Formosa chimed nicely with Protestant horrors of the eucharist and Swift's ferociously plausible jokes about Anglo-Irish anthropophagy.[26]

This perverse exercise in the manipulation of credit evokes the historiographic puzzle of the relation between regimes of curiosity and natural philosophy. The historian Krzysztof Pomian read such curiosity as an intermediate state between (medieval) theology and (enlightened) sciences. Historians of the Royal Society have often seen Sloane's succession to Newton's presidential chair in 1727 as a moment when the energies of mathematical physics started to dissipate in trivial *naturalia*. Contemporary philomaths and Augustan satirists, documented in Margaret 'Espinasse's account of the "decline and fall of Restoration science", judged the change similarly harshly: the sonorous eternities of portentous planets were displaced by the silly skewering of ephemeral butterflies. The epoch's ferocious public conflicts helped establish an important distinction between versions of curious natural history and of mathematical natural philosophy with *Principia mathematica* its cynosure. The polemical dedication placed at the head of the *Philosophical transactions of the Royal Society* in 1727 by its then editor, the Cambridge-trained medic James Jurin, lauded the "Glory of Sir Isaac Newton" and claimed "that Great Man was sensible, that something more than knowing the Name, Shape and obvious Qualities of an Insect, a Pebble a Plant or a Shell was requisite to form a Philosopher, even of the lowest rank". Compare and contrast the Newtonian self-image of the 1730s in which infantile diversion "in finding a smoother pebble or a prettier shell" leaves the "ocean of truth" undiscovered.[27]

To see the force and consequence of the claimed separation of mathematical-

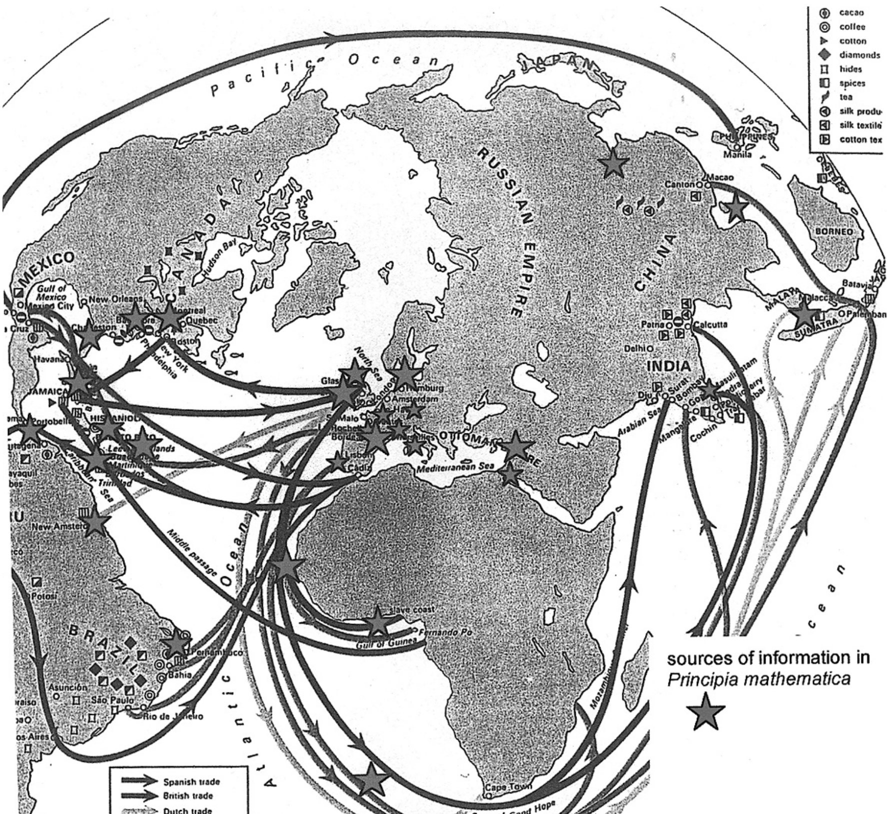

FIG. 1. Sources of information for *Principia mathematica* and the trade networks of early modern European empires.

experimental and natural historical enterprises, it helps to understand how *Principia* drew calculation and curiosity together. There is a need for a re-assessment of the relation between learned natural history and the natural philosophy whose mathematical principles the work presented. For example, the apparent contrast between *Principia mathematica* and contemporary works of learned curiosity also published under the Royal Society's aegis, such as Nehemiah Grew's *Musaeum Societatis Regalis* (1681), a copy of which Newton gave his own college, may become less stark.[28] We need a better map of the information order of the early modern period's knowledge regimes.

TIDES AND CURRENTS: A TONKIN RESOLUTION

Newton's first signed publication, in 1672, was a new edition of the definitive geography textbook of the age, the *Geographia generalis* of the Leiden scholar Bernhard Varenius. Varenius identified geography within mixed mathematics. Newton followed suit, setting the work in a general account of the cosmos.[29] He owned more than twice as many works on geography, voyages and travel as on astronomy. From 1696 he administered the Royal Mint and from 1703 the Royal Society, soon to give him troublesome responsibility for the affairs of the Royal Observatory down river at Greenwich and its manager Flamsteed, whose data were vital resources for Newton's work, and for the Board of Longitude, established in 1714. Newton also stood at the centre of the financial revolution that saw the establishment of the Bank of England in 1695, the recoinage of 1696 as a response to the circulation of bad metal, and the emergence of paper credit and the growth of the stock market in London. He was one of the few East India Company proprietors who owned more than ten thousand pounds in stock and invested heavily in the notorious South Sea Company, set up in 1711 to trade with Spanish colonies in south America. These fiscal systems were but one aspect of the settlement of the new Anglo-Dutch regime after the Glorious Revolution of 1688. That regime relied on stable values in its capital and its imperial network in the Atlantic. There were advantages, in ways which other studies of information flow in early modern Europe have taught us, both in intimate and speedy communication and in the engineering of distance, isolation and withdrawal.[30] Such principles also governed the information order of *Principia mathematica*.

Expert in monarchical law and a member in the Convention Parliament that legitimated William's regime in 1689, Newton often linked right government with knowledge of divine creation as interpreted by natural philosophers. Newton did not achieve several major insights and techniques of his chronology, cosmology and celestial mechanics until the early 1680s. *Principia* was first written during the twelve months to autumn 1685. It is striking that the closing sections were initially supposed to "demonstrate the frame of the System of the World" and "compos'd ... in a popular method, that it might be read by many". This account of the "system of the world" was initially and significantly designed to make *Principia* more popular. Unlike preceding material on the laws of motion that Newton feared "may have appeared ... dry and barren", the final volume demanded detailed assays of information from a wide range of protagonists.[31] Such appeals and assays concerned Newton's first editor Halley, an Atlantic astronomer and voyager who carried the costs of *Philosophical transactions* just as he did for *Principia*. Halley published much in those years mapping global phenomena such as tides, compass variation, trade winds and monsoons, correcting Varenius's mistakes after "having had the opportunity of conversing with navigators acquainted with all parts of India, and having spent a considerable time between the Tropicks". He exploited information networks of the trading corporations and dockyard experts, such as those used in his friend John Seller's *Oriental pilot.* He sometimes had to delay publication "by reason of the absence of a person extraordinarily knowing in this matter, whose information was thought necessary". Expert on getting such reports into print, he told Newton in June 1686 that the "application of this Mathematical Part to the System of the World is what will render it acceptable to all naturalists, as well as Mathematicians, and much advance the sale of the book".[32]

After briefly contemplating omitting all this material, partly because of his fury with the rival claims of Robert Hooke, Newton soon used it for the last book of *Principia*. From the first drafts of this work on planetary paths in 1684, Newton began to consider how "a large number of observations, no matter how many", could best be reduced to "a single conclusion" by taking "a mean point" for an elliptical orbit's focus. A reliable mean might imply weighting observations by accuracy, assaying relative trustworthiness of estimated positions. In the *Principia* project Newton and his collaborators often constructed mean values from varying estimates of celestial and earthly phenomena.[33] They faced the problems of handling widely distributed data accumulated by astronomers and priests, academicians and mariners. In an argument about the best balance between "a large number of observations" and a few trustworthy ones, Hooke's London lectures on cometography had already described the problem of ordering information that Newton must also manage: "saving the exact Observations of some few … truly diligent and accurate men, the greater the Collections of Observations are, the more trouble and difficulty is created to the Examiner; they not only confounding one another, but perplexing those also which are real and perfect."[34] The problem was thus to judge select reporters' diligent accuracy in comparison with large data collections, especially where the programme demanded exquisite exactitude from resources globally distributed in time and space.

A good case of Newton's management of these data is his striking providentialist argument, published in a corollary early in this last book, that "God placed the planets at different distances from the Sun so that each one might, according to the degree of its density, enjoy a greater or smaller amount of heat from the Sun". The claim relied on a prior "analogy that is observed between the forces and bodies of the planets", so depended on good estimates of planets' sizes. In his initial version of the corollary, completed by autumn 1685, Newton gave figures for Saturn's radius from measures of its body and ring by Hooke, Halley, Huygens and the Avignon priest Jean-Charles Gallet. "I am still at a loss for Saturn", Newton confessed to Flamsteed in early 1685, "I have not at all minded Astronomy of some years till on this occasion which makes me more to seek". The Astronomer Royal gave Newton these details and his own measures. Newton proposed publishing all these different values, then took the values' "mean ratio [*ratio mediocris*]" for Saturn's diameter as 21 seconds. He hadn't finished. By analysing observations from Huygens, Gallet, Halley and the Danzig astronomer Johannes Hevelius, he was able cunningly to urge that unequal refrangibility increased planets' apparent size, so reckoned it reasonable to reduce Saturn's true radius from 11 to 9 seconds. Newton's modern editor, I. Bernard Cohen, calls the manoeuvre "pure nonsense". Even Newton's disciple the Scottish mathematician David Gregory questioned his master's tactics. But this lower number helped claims about the relation between planets' forces and sizes, thus about divine wisdom in the solar system. All this was transferred to the published *Principia* in 1687 then abbreviated in later editions. The rationale for this disposition was no longer set out, nor the careful averaging of observers' numbers for Saturn. In many sections of the great work, Newton and his collaborators worked this hard to assay and adjust such astute interpretations of many other observers' work.[35]

Compare some later, more fraught, exchanges with the precise and pious Flamsteed in 1694–95. Newton and his allies wanted at last an adequate lunar theory based on gravitational analysis. They understood that such a theory would have important implications in navigational astronomy. Newton and Gregory visited Greenwich to obtain good lunar data from the Astronomer. In the next eight months Flamsteed supplied at least fifty such observations. "All the world knows I make no observations my self", Newton told him, "and therefore I must of necessity acknowledge their Author: And if I do not make a handsome acknowledgement, they will reckon me an ungrateful clown". Newton claimed the virtues of *Principia*'s gravitational lunar theory would make Flamsteed seem "the exactest observer that has hitherto appeared in the world". But the boundary between theory and data was socially troublesome. Flamsteed provided not his raw observations but those rectified for refraction, parallax and the Sun's apparent motion. As Buchwald has pointed out, astronomers such as Flamsteed adopted "an ethos of artisanal perfection", producing allegedly refined reports without much debate on data selection. Within a few months, relations with Greenwich collapsed: "I want not your calculations but your observations only", Newton thundered, before exchanges were broken off.[36] So, too, was the lunar enterprise. Newton's predictions for the progression of the line of apsides barely reached an accuracy of ten minutes of arc. He never designed more than a kinematic account of the movement of the centre of the Moon's orbit, one that certainly did not show the role of gravitation in lunar movement. "Without adequate data", writes the historian Curtis Wilson, "the difficulties proved too great". By 1713 Newton excised two references to Flamsteed that had appeared in the first 1687 edition.[37] It was hard to establish the right relation between calculation and observation, authorship and gratitude. Similar travails affected most data with which Newton's group worked as they sought to make the third book "exact".

In *Principia* analysis of lunar motion was set alongside Newton's model of the tides. It is now known that his estimate of the ratio of lunar and solar tidal components is two times too large. Though he recognized that the effects of Sun and Moon depended on the inverse cube of their distances from Earth, he erred in claiming tides are determined entirely by the vertical component of the disturbing forces and in assuming that solar tidal forces on the Earth's surface all act in parallel. Yet this was the first attempt to offer a numerical calculation of tidal forces.[38] In the 1680s he described celebrated marvels of tidal ebb and flow in the East Indies, the Straits of Magellan and the Pacific. Keen to show the global grip of his gravitational model of lunar pull, Newton faced characteristic troubles of trust in travellers' tales. "The tide is propagated through the ocean with a slower motion than it should be according to the course of the Moon", he explained in 1685, "and it is probable that the Pacific Sea is agitated by the same laws". He had reliable reports from the coasts of Peru and Chile, "but with what velocity it is thence propagated to the eastern coasts of Japan … I have not yet learned".[39] To estimate numbers meant using the global information order to amass testimony. It was the management of such numbers that drew most attention when the brilliant Cambridge mathematician Roger Cotes, who became an expert on methods for managing observational errors and an observatory manager, began to help rework the entire *Principia* between 1709 and 1713. Faced with threatening rivals to their cosmology, notably the Leibnizian programme, Newton and Cotes now sought massively to reinforce the apparent precision and the global grasp of their numbers. They discussed, for example, whether to omit or include specific tide data from variably reliable Plymouth or Bristol mariners alongside their assumptions about such parameters as the Earth's density.[40]

Tide observations had long been crucial in the Atlantic information order. Robert Moray, Scottish traveller and eminent FRS, already encouraged new data programmes by the Jesuit Athanasius Kircher in the 1650s and reported on the remarkable tides around his own estates in the Hebrides in 1665. The young Newton made careful notes on Moray's reports, juxtaposing them with what he knew of the work of tidal devices on the Danube.[41] In *Directions for sea men* (1666) the Royal Society demanded tidal measures from as far as New England, St Helena and Bermuda.[42] The same year, in response to a complex philosophical model of Channel tide patterns by the mathematician John Wallis, Moray proposed a routinized tidal observatory using instruments made by the Society's operator Richard Shortgrave and distributed along the Thames and the Channel coasts. In the 1660s Newton read these reports and offered criticisms of Wallis's tide theory, noting that "astronomers are much puzzled with the irregularities of the Moon".[43] Appraisal of local expertise, in ways made familiar in Steven Shapin's account of the trust economy of Restoration Britain, worked to powerful effect. Wallis reported his chats with "some inhabitants of Romney Marsh", whose testimony he eventually accepted because their business so depended on tidal flooding.[44] The Baconian astrologer Joseph Childrey similarly appealed to Thames-side inhabitants and his experience of riverbank flooding. Moray's observatory programme would have relied on "any waterman or other understanding person".[45] When the Plymouth observer Samuel Colepresse began his own tide survey, he initially found "the sullen humour and irreconcileable opinions of the Seamen" frustrated his survey plans. The Bristol mariner and navigational writer Samuel Sturmy reported in late 1668 with data about the time and height differences between highest and lowest tides, reporting numbers as "45 feet *circiter*". Sturmy judged that "to make them always so near as to half inches, is neither easy, nor material, nor useful". [46]

It was the data of Colepresse and Sturmy that played a vital role in *Principia*'s third book. To calculate the precession of the equinoxes, Newton needed to know the proportion of the forces of Moon and Sun. This ratio could in principle be derived from the heights of spring tides, which he reckoned was due to the sum of the forces at syzygies, and of neap tides, due to their difference at quadratures. Here the reliability or credulity of local informants mattered. Flamsteed accompanied his tide tables sent from Greenwich to the Royal Society with the remark that "considering how much the River of Thames is frequented by shipping and how long it has been the chief place of commerce in this part of the world, one would think our seamen's accounts of its tides should be very exact and their opinions concerning them very rational, whereas … nothing will be found more erroneous and idle". In the 1680s Flamsteed and Newton discussed whether a soli-lunar model of tidal causation was plausible, while Halley was certainly dubious of Flamsteed's own tide data. Against Halley's notion that Flamsteed's tables failed in the North Sea, the Greenwich astronomer appealed to "the authority of our Yacht captains", while claiming that Halley's own account was "nothing but what almost every Waterman says". Informants' status counted in these rival stories about the motions of the sea.[47] When Halley presented a copy of *Principia* to the monarch and former naval commander James II in 1687, tidal theory's global extent took pride of place: "the whole appearance of these strange Tides is without any forcing naturally deduced from these principles, and is a great argument of the certainty for the whole Theory." In 1701, Halley was sent by the Admiralty on a Channel cruise to survey tidal streams: "where there are irregular and half Tides to be more than ordinarily curious in observing them." Halley's impressive tidal chart was printed in London by the end of the year then distributed with Seller's *English pilot*. Such maps might allow the Royal Navy's Channel fleet to tide over, to stay at sea and at anchor while the tidal stream was adverse.[48]

Manipulation of the numbers reported by coastal mariners such as Sturmy and Colepresse dominated these sections of Newton's programme for decades. In his first attempt at a tidal model in 1685, while crediting "the tide tables which Flamsteed has composed from a great many observations", and mentioning observations from the Channel, the East Indies and the Straits of Magellan, Newton relied almost exclusively on Sturmy's numbers for the range of tide heights at Bristol, "till we can more certainly determine the proportion from observation". But a year later, seeking a better match between these tide ratios and those of the solar and lunar forces from which he could then derive precession, he decided also to incorporate Colepresse's somewhat larger height ratio from Plymouth and announced in print that "until something more certain is established by undertaking more accurate observations we shall use the mean proportion [*proportio mediocris*]".[49]

When he later started working with Cotes on these tidal propositions in early 1712, the relative weight to be given to Sturmy's and Colepresse's numbers demanded fresh attention: the young editor told Newton that analysis of the lunar force at syzygies and quadratures gave a proportion that "falls without the Limits at Bristol & Plymouth. I shall therefore leave it to Your self to settle the whole Proposition as You shall judge it may best be done". A month later, Newton had decided that his account of the ratio of lunar and solar forces demanded a return to the 1685 strategy, with Colepresse's observations suppressed. "In the calculation of the Moon's force", Newton told Cotes, "your scruple may be eased (I think) by relying more upon the observation of the tide at Chepstow than on that at Plymouth". The rationale for this manoeuvre was explained to *Principia*'s readers: "because of the magnitude of the tide in Bristol harbour, Sturmy's observations seem to be more trustworthy". Newton also decided to "rely" on carefully managed numbers for the varying density of the Earth, since lower density nearer its surface would increase the globe's equatorial bulge. Assays of mariners' reports and the Earth's structure eventually gave him a number for the precession that matched better than one part in three thousand. "Some might consider it a rather ambitious conclusion to draw from measurements of a retired sea captain", remarks Newton's biographer R. S. Westfall. Newton could not tolerate difference between his divinely warranted order and such numbers.[50]

The same method was directed at celebrated tidal puzzles, notably those of the Gulf of Tonkin, where it was reported that there was but one tide per day and a gradual periodic variation in its height over a fortnight. When the Moon was near the equator, twice a month, there was a period of two days with no tides at all.[51] The writer who first presented these numbers was an American, Francis Davenport, a Boston mariner who went to India in 1670 before working, initially as boatswain, at the East India Company base at Tonkin set up there in 1672. The Tonkin factor, Thomas James, ordered Davenport to survey the tides at the bar of the Red River between May and July 1678 armed with a reliable compass, but "not so good as I could have wished whereby to take the bearings … better instruments are requisite for observations in such unstable stations". Davenport found it dangerous to cross the bar in stationary periods and advised captains to wait a few days for a strong tide to venture over. He was also concerned that the "subtle Tonqueen pilots" exaggerated the shifts of currents and sandbanks "only to prevent their being kicked out of imployment, wherein yet with safety the best of them all cannot wholly be relied on".[52]

Good East India Company numbers would, perhaps, supplant dubious local informants. The strange tidal patterns were confirmed in 1683 by an East India captain Robert Knox, veteran of twenty years' imprisonment in Sri Lanka, ally of Hooke and supplier of the Royal Society with its first samples of oriental *ganja*. The numbers were supported when an East India ship was wrecked on the Tonkin bar in early 1683. News of these episodes reached the Royal Society via London merchants in spring 1684.[53] Close ally of the Company after his successful St Helena voyage in 1678, Halley then reprocessed Davenport's data for Royal Society consumption. He used the mariner's estimates of the maximum tidal range, which he treated as though they were precise astronomical numbers rather than local estimates of tidal flow. During

1684 he produced a quantitative model of exaggerated exactitude that linked the daily tide and its monthly cycle to the distance of the Moon from the equinoctial points. His model assumed a maximum tidal variation of at least 18 feet. Currently accepted numbers are closer to 10 feet and the best modern model of this strange tidal pattern proposes a resonance of the lunar twelve-hour tide in the gulf, setting up a standing wave with a stationary node at just the point where Davenport was working.[54]

Thus the London and Cambridge analysts were presented at a decisive moment in their computations with testimony about one of the world's most perverse tidal systems. In 1688 the global navigator William Dampier reported that "the most irregular tides I did ever meet with are at Tonqueen described at large by Mr Davenport".[55] By the time Newton turned his attention to this strange marvel, Davenport had moved his employment from Tonkin to the west coast of Siam, where he worked as agent for an entrepreneurial and militant East Indies trader, Samuel "Siamese" White. Associated with this notorious interloper, Davenport's repute was much in question in London pamphlet wars of 1687–88 that raged after White's piracy led to the destruction of the English trading base in Siam. White and his allies publicly attacked the credit of his erstwhile aide Davenport: "this vile wretch Davenport, on whose evidence the company have so much dependence is one of the most notorious rogues in nature and so esteemed by all honest men that ever had the unhappiness to have been concerned or acquainted with him." [56]

A dubious report from the Gulf of Tonkin by a disreputable American had to be checked for its creditworthiness. Halley, veteran of the East India Company's ships, and thus Newton, had indeed to depend on the accounts of the nature of tides which "this vile wretch" provided. Newton gave an ingenious explanation of the perverse tidal phenomena at Tonkin, omitting the name of his source. There must be a periodic addition and subtraction of two tidal streams from two separate entries from ocean into the gulf, one of the very first published accounts of wave interference. Even Newton had no account of why the daily motion was so strong, referring the puzzle to later navigators in the East.[57] What Newton, Cotes and Halley needed was ever more testimony from reliable mariners in Formosa and Tonkin, from the Horn and the south Atlantic. Without that information order, the astonishing balance Newton hoped to strike between his finicky sums and the rough data of the observers ("45 feet *circiter*") would fail.

COMETS AND PENDULUMS: INFORMATION OBSCURED BY CLOUDS

Demonstrations that comets move like planets in conic sections with the Sun in one focus occupied *Principia*'s final propositions and provided one of its most important achievements. Cometography's appearance at the end of the work obscured the fact that it came at the start of Newton's project. Cometary phenomena first drew his attention to astronomy in the 1660s. In the decisive years between 1681 and 1685 his compilation of puzzling catalogues of informants' accounts of comets' positions, motions and nature drove much of his radical new work on the theological significance and mathematical principles of natural philosophy. In 1681 Newton lacked the notion of universal gravitation. Then as he started compiling natural histories of cometary marvels, he began gradually to develop such a notion.[58] His colleagues and informants were sensitive to the problems of the cometary information order. When Flamsteed reported on a comet seen in spring 1677 he conjectured it might return every twelve years; such regularity would undermine the astrological "superstition of the vulgar". But the vulgar were not always wrong. In the very next line of this letter Flamsteed confessed he'd first heard a report of this comet around Easter, "but being it came but from ordinary labourers I gave little credit to it". The labourers proved right, at least in this case.[59]

Observations made throughout Europe, in Maryland, Brazil and China, as well as information from carefully sifted chronicles, were all used by Newton and his collaborators such as Cotes and Halley to back *Principia*'s authority. Consider as example the reports of Kircher's Jesuit colleague Valentin Stansel, a missionary trained at Prague in the 1650s, then based at his order's college in Bahia on the Brazilian coast from 1663. Like Kircher, Stansel held to a cosmology that valued the monstrous, the singular and the newsworthy. Cometography admirably matched his aims in charting the natural history of wonders and marvels. Ill-equipped with an antiquated set of survey instruments, devoted to the astral cosmology of his colleague Kircher, Stansel used Tychonic methods to estimate cometary positions in 1664–65 and 1668. He composed a widely read set of dialogues on astronomy, colonial commerce and natural history, debating how "physicians in Brazil or America" could reason on the astrological effects of comet transits when these bodies were of necessity unknown to the ancients. His data were transmitted to Roman journals, thence via Huygens to the Royal Society.[60] Newton used Stansel's observations of the dramatic cometary tail of 1668 to argue against the Jesuit's view that such appearances must be due to refracted sunlight from these nearby bodies.[61]

Such critical judgement of past observers was decisive. The historic method Newton concocted relied on comparisons between past observations of cometary transits to forge a cosmology in which activity travelled throughout the heavens, restoring vitality to Earth and confirming the truths of ancient philosophy. In late 1682, when Newton and Halley launched this project, Hooke lectured in London on exactly this puzzle. "I found the accounts of several historians concerning them so very different one from another in most things that I knew not which to rely upon. Which I suppose might be caused, either from their differing way of observing, or from the difference of the goodness of their sight, or for the most part from the differing hypotheses they had made to themselves, or been prepossessed withal from the writings or doctrines of other men."[62] Appraisal of cometographic testimony became indispensable. This mattered especially for Newton, because he was the first to urge that all comets moved round the Sun in elliptical orbits for which parabolas might be good approximations.

In his elaborate studies of chronology and prophecy Newton had to analyse ancient chronicles for signs of periodic regularity; so in the last propositions of *Principia* he did this for signs of regular cometary returns. He consulted such chronicles as the cometography of the Polish religious reformer and astronomer Stanislas Lubieniecki, then based in exile in Hamburg. Important cometary data also came from Hevelius and from Halley, either directly or via Flamsteed. In summer 1679 Halley visited Hevelius's observatory in Danzig. The aim was to allow the Royal Society and the Astronomer Royal to judge the quality of Hevelius's controversial open-sighted instruments *in situ*. As Jed Buchwald has asked of this project: "How was Hevelius, given his distance and background, to convince others far away that his observations should be accorded trust?" So this was an assay trip. "Had I not seen", Halley told Flamsteed in June 1679, "I could scarce have credited the Relation of any; Verily I have seen the same distance repeated several times ... so that I dare no more doubt of his Veracity".[63] Yet doubts remained about Hevelius's work. Steven Shapin has shown how these doubts were used to judge the Danzig cometary and lunar data. Halley still grumbled about Hevelius's claims: "it is our common concern to vindicate the truth from the aspersions of an old peevish gentleman who would not have it believed that it is possible to do better than he has done."[64]

Halley planned a visit to Tycho's ruined observatory at Uraniborg and also went on a tour of France and Italy in 1680–82. In Paris in early 1681 he worked closely with the royal astronomer Jean Dominique Cassini, then much concerned with the great comet of 1680–81 that Halley had first seen on the road to the French capital and whose report Newton copied into his comet catalogue. Halley obtained from Cassini his crucial book on the comet, later of importance in Newton's calculations. The great comet was "remarkable for its size and dreadful in the eyes of the vulgar". Halley tried and failed to make a path that would satisfy all the phenomena he got from his Parisian informants. Here discussions of theories of cometary motion, such as the dubious claim of Cassini that it orbited the Earth with a period of $2\frac{1}{2}$ years, were fully integrated into the culture of virtuosity and the lettered.[65]

Halley also gathered from his French colleagues important information about Jean Richer's 1672 astronomical expedition to the French base at Cayenne. Further travels helped. At Avignon Halley met Gallet whose observations of the 1680 comet were also to be used in *Principia*. While in Rome in 1681 Halley joined the group around the observatory and cabinet of Queen Christina at the Palazzo Riario. She offered a prize, for which both Cassini and Hevelius competed, to compute the path of the 1680 comet. The Queen's astronomers at Ciampini's academy, including Marco Antonio Cellio and Giuseppe Pontio, provided Halley with further cometary positions. He sent Cassini all his latitude data on the road from Paris to Rome, and all the Roman comet observations too. Many reached Flamsteed and Newton; Flamsteed began lecturing on the reports at Gresham College in London in May 1681.[66] All this material was used in *Principia*. Back in London by early 1682, Halley then threw himself into astronomical observations and the debates with Hooke that eventuated in the travelling astronomer's portentous visit to Cambridge in summer 1684.[67] Halley's exchanges with Newton from the mid-1680s relied on a natural history of comets and an information order that exploited conventions of testimonies within the Republic of Letters to evaluate both positions and observers.

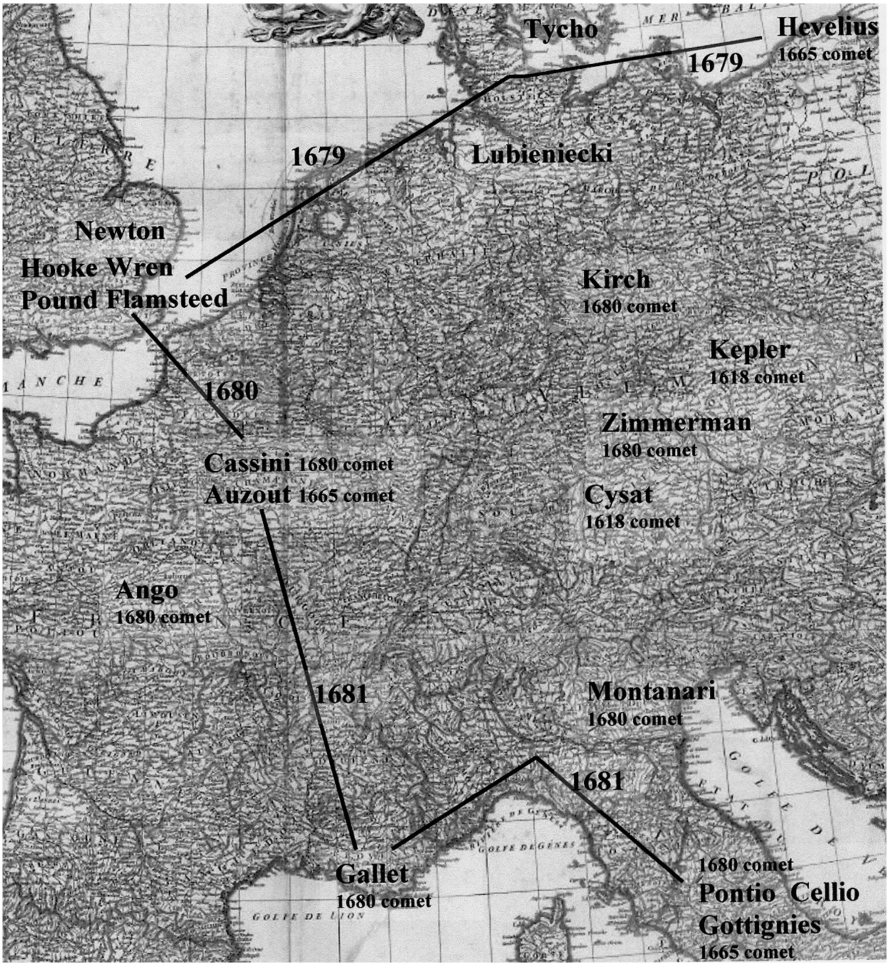

FIG. 2. Edmond Halley's European journeys of 1679–81 and the sources of cometary observations in *Principia mathematica*.

In his notebooks of 1681–82 Newton used the cometography of Hevelius and other sources to go back over records from Aristotle, from medieval chronicles and those from informants whom Halley and Flamsteed had appraised. Thus, so he told Newton, Flamsteed interviewed one English cometary observer, a "Canterbury Artificer" Thomas Hill, and "found him a very ignorant well willer yet I believe his observation as good as those of Cellio made at Rome". The Astronomer Royal lectured his London audiences on the difficulties of reconciling reports from Cambridge and Avignon, Rome and Canterbury.[68] In many cases Newton sought to exclude data that failed to fit his models, then find rationales from judgements of informants that would help this hostility. Sometimes he adapted his models to incorporate testimony whose authority looked unshakeable. The technique of assessing past observers' data was used by Halley in numerous cases — on the secular acceleration of the Moon and the proper motion of stars, for example.[69] In the final propositions of *Principia*, these techniques told. Small differences between ellipses and parabolas would only emerge if the database were reliable. In the case of Gallet's data from Avignon in 1680, puzzles included a mistake by Flamsteed in dating French reports (he used old style calendars); doubts about which star catalogue French astronomers used to determine cometary positions, and the relative size of Paris and Greenwich instruments; and an obvious contradiction between what Gallet saw in November 1680 and what was seen of the comet's tail by a Cambridge student. Newton "was the more scrupulous in examining this scholar because I knew not what to make of these things they not agreeing to the Comet of December. And when he saw me at a puzzle he was concerned and added there were divers other scholars who saw it with him". He decided to quiz his colleague Humphrey Babington about observations of the comet over the roof of King's College Chapel, showing the tail much more southerly than Gallet said. But in a further redrafting, Newton decided the comet moved very close to the ecliptic and Babington's story was suppressed. To add to the complexity, Flamsteed simply continued to defend Gallet's virtues because his earlier (1677) observations of the transit of Mercury were so reliable.[70]

These were the circumstances in which Newton also helped himself to cometary observations by Flamsteed's correspondent Thomas Brattle in Massachusetts, collated in London by Halley before the American came in person to London in 1682–89 and established close links with the Astronomer Royal.[71] Similar information came from Newton's former Grantham schoolmate Arthur Storer, Babington's nephew. Storer maintained correspondence with Newton from Maryland, where he was a planter slave-owner at Prince Frederick in Calvert County. Storer sent the Cambridge mathematics professor measures of the azimuth of the Pole Star and data on the spectacular comet of winter 1680–81. "The instrument by which I observed was but a pocket piece and therefore cannot be so exact as those of far larger sizes", the Maryland observer conceded. His observations of what is now known as Comet Halley, that of 1682, are superior to those of Halley himself or indeed of Hevelius, though he asked Newton for a "good large forestaff about 6 foot long so that it bow or bend not by the weight of the vanes", plus astronomical tables better than those of the seamen's almanacs on which he had relied till then. Since Storer's stories fitted well with Newton's cometary model, he approved them in print.[72]

Similar strategies were used in the case of the Paduan astronomer Geminiano Montanari, a notable disciple of Galilean natural philosophy. Montanari was nevertheless criticized because his observations of the 1680 comet were seen to be defective by the standard set by the path Newton and his editors were constructing. In his London lectures, Hooke had amply discussed Montanari's Venetian reports, asserting that such information was not enough to ascertain whether the two comets were indeed one, because of "the differing observations of several men, who possibly may not be sufficiently skilful to make the observations, of others who though they may have skill enough, may yet want fitting instruments for that purpose". So in 1713 Cotes and Newton decided to include the remark that "Montanari had the suspicion that his observations were in the end obscured by clouds".[73]

In general, the only way of getting out the elements of a specifically elliptical orbit was first to spot two similar comets in the historical record, then to calculate what ellipse would give an orbit with that period, finally to check retrodictions from this ellipse against the observations. This was the historic method commended by Newton and practised by Halley throughout the 1690s. It let Halley famously to "dare venture to foretell" that the comet of 1682 would return in 1758, to bewail the "very uncommon way" French astronomers made their observations, and in the same publication to regret the absence of reliable informants on more recent comets: "If any one shall bring from India, or the Southern parts, an accurate series of requisite observations, I will willingly fall to work again." This work depended on the conventions of an information order in which knowing positions involved decisions about knowing persons.[74]

The links between assay of locally reliable instruments, persons and God's creation were even clearer in Newtonian work on the length of pendulums in Europe, the Americas and Africa. While painstakingly revising the new *Principia* between 1709 and 1713, Cotes was also working with his colleague Jurin to rework Newton's Varenius. The young Cambridge scholars, concerned with geographical knowledge, were also assessing observers' credit in astronomy and geodesy, especially their reports of the lengths of pendulums beating seconds. Jurin called this puzzle "the French dilemma", because of the variation between different measures of pendulums' lengths reported by French observers.[75] The dilemma was treated in Proposition 20 of *Principia*'s third book on the weights of bodies in different parts of the Earth and the apparent shortening of such pendulums near the equator where it seemed effective gravity was weaker. In the 1680s Newton had hoped that "the excess of gravity in these northern places over gravity at the equator" would be "finally determined exactly by experiments conducted with greater diligence".[76] Cotes "considered how to make that Scholium appear to the best advantage as to the numbers", drawn from selected French estimates of pendulum lengths. The English mathematicians would make a table of the variations in the length of a seconds pendulum at different points on Earth. This table had to be visibly accurate over very small length differences of fractions of a line (12 lines = 1 Paris inch). Cotes held that such "exactness, as well here as in other places, are inconsiderable to those who can judge rightly of Your book; but the generality of Your Readers must be gratified with such trifles, upon which they commonly lay the greatest stress".[77] To reach such exactness *Principia*'s author and editor had to judge the standard of matter of which the Earth was made and the standards met by (mainly French) instrumentalists.

The astronomer Jean Richer's celebrated ten month's work at Cayenne in 1672 was taken as a standard. Newton eventually reported that during observations of meridian transits Richer had first found his pendulum clock slower than mean solar time, then deliberately conducted an experiment to measure the length of a pendulum that "would

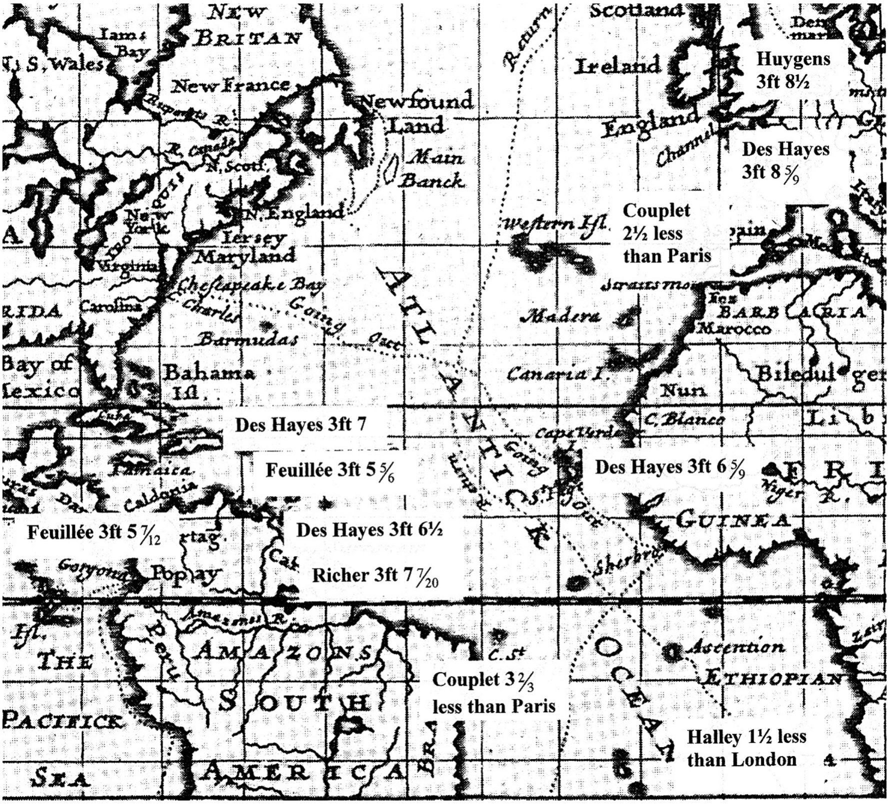

FIG. 3. Sources of information for the length of a pendulum beating seconds used in *Principia mathematica*. Numbers refer to estimates of length in feet, inches and lines: Newton claimed that suitably judged these numbers showed a systematic shortening of the seconds pendulum nearer the equator.

oscillate in seconds as measured by the best clock". If Richer's data were privileged and allowance made for the expansive effects of tropical heat on pendulum cords, then Newton's estimate of weaker effective gravity nearer the equator and of the Earth's shape would be well confirmed. If a range of French data from the Antilles and west Africa were taken into account, then the numbers would suggest a planet denser near its centre and even more flattened at its poles.[78] In the notebook Newton kept in 1681 to collate observations of the great comet of that year, he already recorded Richer's observations, presumably passed on from Halley, who, so Newton then remarked, concluded that the pendulum had to be shortened at Cayenne. Newton also noted that in Gorée (the newly established west African base of the Compagnie du Sénégal) "observation was less exact". The delegates sent there had bickered. Their claim from the tropical slaving fort that pendulums also needed shortening, and by more than had earlier been reported by Richer, was questionable. It was important that travellers could show themselves reliable delegates. For example, Richer recorded that he had made sure to secure the local meridian by having a fine polished stone on which to fix his instruments constructed at La Rochelle before his departure, then installed at Cayenne on fortuitously placed millstones lying near his observatory.[79]

Though it seemed that Richer's observations had been obscured by clouds, as in the case of Montanari's cometary work, Newton later wrote that this Frenchman's "diligence and caution seems to have been lacking in other observers".[80] The aim was to establish a trustworthy value for the systematic difference in lengths between what Newton began calling "isochronic" pendulums in France and the tropics. Cotes first proposed taking "3 feet $8\frac{10}{19}$ lines for the length of the Pendulum; for the French sometimes make it $8\frac{1}{2}$, sometimes $8\frac{3}{5}$, & $8\frac{10}{19}$ is a mean betwixt these numbers". A week later, after meditation on "inconsiderable" variations in these measures, Cotes agreed to swap $8\frac{10}{19}$ for $8\frac{3}{5}$ because "the fraction is more simple & already in use amongst the French". But there were difficulties in simple reliance on French usage. Cotes told Newton that some French delegates found seconds pendulums needed shortening by somewhat more than his desired limit of $2\frac{1}{4}$ lines; somehow these reports needed explaining, or explaining away.[81] Furthermore, in 1684 the chief Parisian astronomer Jean-Dominique Cassini had set out doubts about Richer's work and thus gave the instructions to the French travellers sent out to measure pendulum lengths: "by very exact experiments made by the gentlemen of the Academy at Paris, at the Hague, at Copenhagen and at London, the length of a pendulum which makes one oscillation in one second has by everyone been found the same. Only at Cayenne has it been found shorter, but it is doubted whether that might not have happened because of some fault in the observation."[82]

Eventually Newton dismissed the astronomer Claude-Antoine Couplet's measures made during a voyage from France via Portugal to Guiana in 1697–98: "he is less trustworthy because of the crudity of his observations." Values from Gorée in West Africa in 1682 and observations at Cayenne in 1700 were once again deemed "less accurate".[83] Tropical heat and wind might affect pendulum length, as Newton and Cotes knew. According to Newton all the French travellers agreed that pendulums with the same period were shorter at the equator; what Newton and Cotes called a "mean quantity [*quantitas mediocris*]" of data from across the West Indies and from Gorée gave $2\frac{9}{40}$ lines for this shortening. "Because of the heat of places in the torrid zone, let us ignore $\frac{9}{40}$ of a line, and a difference of 2 lines will remain". But "all the difference in the length of pendulums with the same period cannot be ascribed to differences in heat, nor can this difference be attributed to errors made by the astronomers sent from France. For although their observations do not agree perfectly with one another, the errors are so small that they can be ignored". They claimed that "the differences between the measurements" of different French voyagers "are nearly imperceptible" — fractions of a line — "and could arise from imperceptible errors in the observations". A decade later, for the final edition of the book, Newton decided not to publish a "mean quantity", but instead expanded this useful appeal to imperceptible but certain variability. "This disagreement might arise partly from the errors of the observations, partly from the dissimilitude of the internal parts of the earth, and the height of mountains; partly from the different temperatures of the air". As the mathematics historian John Greenberg points out, Newton was "tinkering with certain details of the theory in a qualitative way in order to justify observations that did not accord with the theory".[84]

In the early modern information order, such tinkering and justification came at a price. As example, in February 1712 Cotes told Newton to consult a recent report by the well-travelled French priest Louis Feuillée on pendulum lengths measured over three months at Porto Bello on the Panama isthmus in autumn 1704 and later during more than eight months' work at Martinique. Newton at once read Feuillée's reports and wrote them into a draft for *Principia*. But Feuillée's measure for Porto Bello was as much as 3 lines less than that at Paris, a larger difference than Newton could tolerate: "he made an error in his observation", Newton publicly stated in *Principia* in 1713.[85] The next year Feuillée explained in print that the pendulum measures he made at Porto Bello "though of little consequence did not give me peace. I long searched for the cause without finding it. Sometimes I attributed it to the great humidity caused by the rains, sometimes to the changes of the winds, and at last I took a mean length [*une moïenne longueur*] which I believed came close to the true one". He boasted, too, that his pendulum experiments used threads of silk-grass and of iron and a reliable copper rod for length measures: "I had no doubt at all about their difference."[86]

These remarks won attention when the celebrated natural historian Feuillée's probity was violently questioned by a French mariner and spy also just returned from the Spanish colonies in the Americas, the military engineer Amédée-François Frézier. Frézier charged that the priest was too aged, his life too soft, to conduct properly strenuous surveys and too devoted to "physics, botany and astronomy" to be of aid to navigators. These attacks reached London readers in 1717, partly because Andean and Pacific stories were of fascination to new investors in the ambitious South Sea Company, partly because Frézier had dared criticize Halley's celebrated charts of compass variation.[87] Feuillée reacted with fury, charging Frézier with geographical, instrumental and theological errors in his surveys of the Americas and the South Seas. He also took the chance to answer Newton's criticisms of his work at Porto Bello. The English mathematician ought to be aware of the notoriously humid climate: it was impossible "to reduce to geometric rules a seasonal variation of length in variable pendulums". Newton allegedly had no proof of his claim that Feuillée's observations of "isochronic pendulums" were at fault, but had bluntly asserted their error to save his "imagined hypotheses", which had been produced "in a cabinet, sheltered from the storms and bad weather that one must suffer in journeys made only to perfect the Sciences and the Arts". Frézier picked up on the elderly priest's remarkable attack on Newton's seclusion and prejudice, since it confirmed that Feuillée's "observation, even if made with care, could not provide a certain determination". Issues of instrument use, survey work and the attribution by cloistered analysts of errors to remote travellers were all at stake in such public and telling conflicts.[88]

In all these cases, relations between travel and seclusion were vital for the production of trust and certainty in global knowledge. Incorrigible variations of humans and of creation were somehow used to explain away variations in measures. Then these measures were used to attempt the projection of Newtonian uniformity, to be assayed in its turn by French, Spanish and Swedish surveyors of the Earth's figure in northern Europe and south America during the 1730s. With the somewhat forced co-operation of an anonymous native engraver, travelling astronomers had the equatorial length of a seconds pendulum set in the wall of Quito's Jesuit college in marble, bronze, silver and gold. The permanently inscribed length was the "mean [*moyenne*]" of "results that scarcely differed among themselves by more than $\frac{1}{100}$ of a line". As their historian Neil Safier points out, troubles of long-range trust and control continued to mark these travellers' endeavours to achieve "scientific commemoration at a distance". As several historians have shown, it was only after immense labour around instrumentation, observation, credibility and status that it became possible, as Voltaire notoriously put it, to joke that remote delegates had found what the divine Newton "knew without leaving home".[89]

IN HEAVEN AS IT IS ON EARTH

Distant action depended on the resources of the early modern information order. Recognizing these resources, judgement of instrumental data in *Principia* can be compared with the treatment meted out to errant individuals during Newton's Royal Mint administration and to the way he read Scriptural and secular histories. In the same years as he worked with Cotes to establish that measures of tidal heights or pendulum lengths fell securely within the tolerable "limits" of his global models, Newton also struggled with the so-called "remedy" that governed the acceptable range of assays of coin weight and fineness regularly performed at ceremonial trials of his Mint's output. As the statistician Stephen Stigler has noted, exactly contemporary work by the Master of the Mint on estimates of the lengths of ancient reigns, designed to undermine exaggerated gentile claims to antiquity, also involved Newton in similar puzzles of numerical estimation and credit.[90] Newton found it useful reflexively to read Scriptural history as full of tales of the travels of reliable knowledge and of the deeds and sufferings of reliable testimony. It is significant that the apparently immobile scholar was impressed by chronicles linking expert travel and sources of true cosmology: "when the Egyptians applied themselves to Navigation, that they might leave the sea coasts by which men had hitherto sailed & guide themselves in the middle of the Seas by the Sun Moon & starrs, their kings and Princes & chiefly their Admirals applied themselves to the observation of the heavens & the study of Astronomy."[91]

Projects he pursued from at least the 1680s, when he began composing *Principia*, helped him make sense of how travel and truth had divine warrant. He showed the true cosmology had in ancient times been distributed worldwide by adept voyagers and that in the millenarian world angelic travellers would freely navigate cosmic space. Neither claim was entirely novel. The celebrated prophetic tag from *Daniel* 12:4 exploited by Francis Bacon and his admirers, "at the time of the end, many shall run to and fro and knowledge shall be increased", was taken to indicate visionary links between travel, truth and the last days. Newton could draw on somewhat familiar tropes of the celestially ecstatic journey and the diffusion of ancient wisdom. But both claims acquired peculiar importance as Newton constructed his own global system.

Newton helped devise a complex story of how pious philosophical travels had aided the construction of the true world system. There had been true and ancient cosmology, "the religion which Noah propagated to his posterity" as he put it in the 1680s during the period just before the completion of *Principia*. This original cosmology described a central Sun, an attractive force acting at a distance on planets, moons and comets, sustained by a public cult of social virtue. These views, according to Newton, were once distributed globally. They were commemorated and embodied in "prytanea", circular temples centred on altars for fire.[92] For *Principia* and for his study of its ancient theology, Newton read writings by Jesuits and Calvinists, antiquarians and missionaries. Devoting to these scholars' and travellers' accounts of ancient monuments from China to Ireland exactly the same techniques of collation and judgement he directed at measures of comets, tides and pendulums, in exactly the same years from 1683 into the 1690s and beyond, Newton argued that such cosmic models were visible in Stonehenge, in Denmark and in Palestine, in the East Indies and China.[93] Ancient travellers, such as Orpheus and Pythagoras, had early traded with the Egyptians, thence taken their cosmology. Voyagers spread the true doctrine as they travelled land and sea. Corruption set in, with the doctrine of solid spheres, geocentrism and the resultant false worship of dead monarchs and the evil tyranny of monkish superstition, when these migrations ceased and the gentiles lapsed into paganism. Some of this was already interpolated in 1684–85 in the opening sections of Newton's initial drafts of *Principia*'s final book, "The system of the world", as a lengthy preface to his public treatment of tide and comet data from mariners and mathematicians.[94]

We see this process of divine validation of global data management in the most celebrated additions to *Principia*'s second edition. In 1713 some "hypotheses" adapted from his rules for interpreting the Book of Revelation, then prefaced to the third book in 1687, were reworked as *regulae philosophandi.* The second rule stated that "to the same natural effects we must, as far as possible, assign the same causes. As to ... the descent of stones in Europe and in America". So Newton here made this principle a prudent instruction to natural philosophers rather than one derived from Nature. *Principia*, in this sense, was a *handbook for travellers*.[95] Then he also wrote a final General Scholium to answer his rationalist critics with a clear account of God's agency in natural philosophy. Using his massive research on the scriptural and prophetic texts concerning God's rule, Newton now publicly argued that God's supreme authority, rather than His wise plan, was the guarantee of the constancy and uniformity of Nature.[96]

Newton's pragmatic rule of philosophising at the start of the book suggested that natural philosophers should assume that stones fell for the same reason in Europe and America. But it was the supreme authority of Newton's God, underlined at the book's end, which made this assumption true. That deity underwrote the meaning and power of the knowledge regime imagined by natural historians and natural philosophers alike, in Europe and in America, and thus throughout creation. In the 1680s, as he began work on the *Principia* project, Newton made long notes on the geography of the heavenly city. For Newton, as for his contemporaries, divine uniformity underwrote created variety, so helped the knowledge regime of which *Principia* is the towering achievement: "As all regions below are replenished with living creatures … so may the heavens above be replenished with beings whose nature we do not understand." The heavenly regime outlined by Newton was an intrinsic component of his information order. This eloquent passage, *ipsissima verba*, gives a juster image than that of seashells on the shore. It indicates how Newton himself saw the intimately related virtues of converse, travel and dominion, in Heaven as it is on Earth:

> As the Planets remain in their orbs, so may any other bodies subsist at any distance from the Earth, and much more may beings, who have a sufficient power of self motion, move whether they will, place themselves where they will, and continue in any regions of the heavens whatever, there to enjoy the society of one another, and by their messengers or Angels to rule the Earth and converse with the remotest region.… And to have thus the liberty or dominion of the whole heavens and the choice of the happiest places for abode seems a greater happiness than to be confined to any one place whatever. [97]

Stories about the information order of the *Principia* might help show how such localized distribution ever happens. It might also make sense of the celestial transcendence then attributed to such reasoning and what kind of "dominion" it involved. It would give a better genealogy for the fascinating relation between social mechanisms of testimony and the moral status of "confinement". Within months of Newton's death, the Scottish poet James Thomson imagined the great man's "arrival on the coast of bliss", his "dread discourse" with angels, and his travels, "mounted on cherubic wing, comparing things with things, in rapture lost". Thomson's verses were somewhat commonplace Augustan themes, but neatly and influentially transferred the Newtonian information order to the heavens.[98]

Enlightened and imperial British culture made much of Newtonian natural philosophy, the information order of the world economy and the celestial plan. However, it seemed equally important to keep global travel and spiritual voyaging quite separate. The very status of genius seemed to depend on adepts' isolation and the virtues of genius evident in planetary triumph. The balance between Newtonian apotheosis and such voyages stayed current. One of Thomson's later readers, the Cambridge graduate William Wordsworth, then adapted his lines on "the noiseless tide of time" and "vast eternity's unbounded sea" for much greater purpose. Wordsworth famously added a couplet to the final version (1850) of his 1805 *Prelude*, evoking Newton's immobile statue in Trinity College Chapel, "the marble index of a mind for ever / voyaging through strange seas of Thought, alone".[99] The aim here has been to show that the successes of this strangely cognitive voyage depended on the fact that Newton was not and could not be, in any significant sense, alone.

ACKNOWLEDGEMENTS

An earlier version of this paper, delivered as the Hans Rausing Lecture at Uppsala University, was published as *The information order of Isaac Newton's Principia Mathematica* (Uppsala, 2008). I am very grateful to all those who have commented so helpfully on this work and to my many generous hosts at Aberystwyth, Harvard, Paris, Stanford, Warwick and Uppsala.

REFERENCES

1. Edmund Turnor, *Collections for the history of the town and soke of Grantham* (London, 1806), 173 n. 2, where it is claimed this was said by Newton "a little before his death".
2. John Milton, *Paradise regained*, Book 4, line 330 (from *The poetical works of Mr Milton* (2 vols, London, 1720), ii, 86, the version Isaac Newton owned); see Patricia Fara, *Newton: The making of genius* (London, 2002), 206.
3. Joseph Spence, *Observations, anecdotes and characters of books and men*, ed. by James M. Osborn (2 vols, first published 1820; Oxford, 1966), i, 462.
4. Andrew Ramsay, *A plan of education for a young prince* (London, 1732), p. iii; extract from *Fog's weekly journal*, no. 195 (29 July 1732) in King's College Cambridge, Keynes MS 129 (N). In June 1729 Conduitt already suggested that a proposed artistic memorial for Newton must be set "by the seaside". See Francis Haskell, "The apotheosis of Newton in art", in Robert Palter (ed.), *The annus mirabilis of Sir Isaac Newton* (Cambridge, MA, 1970), 302–21, p. 315.
5. Fara, *Newton* (ref. 2), 206–7; W. K. Thomas and Warren U. Ober, *A mind forever voyaging: Wordsworth at work portraying Newton and science* (Edmonton, 1989), 41; Frank E. Manuel, *A portrait of Isaac Newton* (1968; London, 1980), 389.
6. William Stukeley, "Memoirs of Sir Isaac Newton's life", in Rob Iliffe (ed.), *Early biographies of Isaac Newton* (London, 2006), 250–1; Edmond Halley, "*Philosophiae naturalis principia mathematica.* Autore Is. Newton", *Philosophical transactions*, xvi (1688), 291–7, p. 291.
7. Rob Iliffe, "'Is he like other men?' The meaning of the *Principia* and the author as idol", in G. Maclean (ed.), *Literature, culture and society in the Stuart Restoration* (Cambridge, 1995), 159–78; Jan Golinski, " The secret life of an alchemist", in John Fauvel, Raymond Flood, Michael Shortland and Robin Wilson (eds), *Let Newton be!* (Oxford, 1988), 147–68; Steven Shapin, "'The mind is its own place': Science and solitude in seventeenth-century England", *Science in context*, iv (1990), 191–218, pp. 204–6.
8. Charles W. J. Withers, *Placing the Enlightenment: Thinking geographically about the Age of Reason* (Chicago, 2007), 45–61; David Lambert, Luciana Martins and Miles Ogborn, "Currents, visions and voyages: Historical geographies of the sea", *Journal of historical geography*, xxxii (2006), 479–93, p. 485. Compare the histories and methods of ships, beachcombing and cargo discussed in Greg Dening, *Islands and beaches* (Honolulu, 1980), 129–30, 157–61, and Dening, *Beach crossings* (Melbourne, 2004), 16–18, 270.
9. Steven Shapin, *A social history of truth: Civility and science in seventeenth-century England* (Chicago, 1994), 243–7. For 'team-work' in making *Principia*, see D. Bertoloni Meli, *Thinking with objects: The transformation of mechanics in the seventeenth century* (Baltimore, 2006), 256 and 285.
10. Boris Hessen, "The social and economic roots of Newton's *Principia*", in P. G. Werskey (ed.), *Science at the crossroads: Papers presented to the International Congress of the History of Science and Technology* (1931; London, 1971), 147–212, pp. 171.
11. For Bacon's Iberian sources see Juan Pimentel, *Testigos del mundo: Ciencia, literatura y viajes en la ilustración* (Madrid, 2003), 55–57, 91–93; Jorge Cañizares-Esguerra, *Nature, empire and*

nation: Explorations of history of science in the Iberian world (Stanford, 2006), 14–23. For Jesuit networks see Steven J. Harris, "Confession building, long-distance networks, and the organization of Jesuit science", *Early science and medicine*, i (1996), 287–318.

12. Rob Iliffe, "'Those whose business it is to cavill': Newton's anti-Catholicism", in James E. Force and Richard H. Popkin (eds), *Newton and religion: Context, nature and influence* (Dordrecht, 1999), 97–120, pp. 112–17; Carlos Ziller Camenietzki, "Baroque science between the Old and the New World: Father Kircher and his colleague Valentin Stansel", in Paula Findlen (ed.), *Athanasius Kircher* (London, 2004), 311–28.
13. Michèle Fogel, *Les cérémonies de l'information dans la France du XVIe au XVIIIe siècle* (Paris, 1989); John Brewer, *The sinews of power: War, money and the English state 1688–1783* (London, 1989), chap. 8: "Public knowledge and private interest: The state, lobbies and the politics of information"; Larry Stewart, *The rise of public science: Rhetoric, technology and natural philosophy in Newtonian Britain, 1660–1750* (Cambridge, 1992); and Stewart, "Global pillage: Science, commerce and empire", in Roy Porter (ed.), *The Cambridge history of science: Eighteenth-century science* (Cambridge, 2003), 825–44.
14. C. A. Bayly, *Empire and information: Intelligence gathering and social communication in India, 1780–1870* (Cambridge, 1996), 5; Peter Burke, *A social history of knowledge from Gutenberg to Diderot* (Cambridge, 2000), 25; Withers, *Placing the Enlightenment* (ref. 8), 50–57.
15. Jerome Friedman, *Miracles and the pulp press during the English Revolution* (London, 1993), 239–53; Joad Raymond, *Pamphlets and pamphleteering in early modern Britain* (Cambridge, 2003), 324–41; William Burns, *An age of wonders: Prodigies, politics and Providence in England, 1657–1727* (Manchester, 2002), 57–96. For coffee houses see Markman Ellis, *The coffee house: A cultural history* (London, 2004), 68–74.
16. Shapin, *Social history of truth* (ref. 9), 194–211; Brendan Dooley, *The social history of skepticism: Experience and doubt in early modern culture* (Baltimore, 1999), 12–18.
17. Pamela H. Smith and Paula Findlen (eds), *Merchants and marvels: Commerce, science and art in early modern Europe* (London, 2002); Londa Schiebinger and Claudia Swan (eds), *Colonial botany: Science, commerce and politics in the early modern world* (Philadelphia, 2005); James Delbourgo and Nicholas Dew (eds), *Science and empire in the Atlantic world* (London, 2008). For the importance of skill in creditworthy instrument use at remote sites see Shapin, *Social history of truth* (ref. 9), 245–7; Jed Buchwald, "Discrepant measurements and experimental knowledge in the early modern era", *Archive for history of exact sciences*, lx (2006), 565–649, pp. 583, 590.
18. Newton to Aston, 18 May 1669, *Correspondence of Isaac Newton*, ed. by H. W. Turnbull, J. F. Scott and A. R. Hall (7 vols, Cambridge, 1959–77), i, 9–11; R. S. Westfall, *Never at rest: A biography of Isaac Newton* (Cambridge, 1980), 193; Manuel, *Portrait of Newton* (ref. 5), 162–4; Hessen, "Social and economic roots" (ref. 10), 171–3. For news-sheets and Newton's interest in this adept Francesco Giuseppe Borri, see Noel Malcolm, "Robert Boyle, Georges Pierre des Clozets, and the Asterism: A new source", *Early science and medicine*, ix (2004), 293–306, pp. 304–6. For other advice to travellers on tides and geography see A. R. Hall and M. B. Hall (eds), *Unpublished scientific papers of Isaac Newton* (Cambridge, 1962), 392–3.
19. Harold J. Cook, "Time's bodies: Crafting the preparation and preservation of naturalia", in Smith and Findlen (eds), *Merchants and marvels* (ref. 17), 223–47, and Cook, *Matters of exchange: Commerce, medicine and science in the Dutch Golden Age* (New Haven, 2007), 267–76, 325–9; Steven J. Harris, "Long-distance corporations, big science and the geography of knowledge", *Configurations*, vi (1988), 269–304.
20. "An introductory discourse containing the whole history of navigation", in *A collection of voyages and travels* (3 vols, London, 1704), ii, p. lxxiii; Sarah Irving, *Natural science and the origins of the British empire* (London, 2008), 92–93.

21. Thomas Sprat, *History of the Royal Society* (London, 1667), 406–7.
22. Mark Govier, "The Royal Society, slavery and the island of Jamaica 1660–1700", *Notes and records of the Royal Society*, liii (1999), 203–17; Larry Stewart, "The edge of utility: Slaves and smallpox in the early eighteenth century", *Medical history*, xxix (1985), 54–70; James Delbourgo, "Slavery in the cabinet of curiosities: Hans Sloane's Atlantic World", http://www.britishmuseum.org/PDF/Delbourgo%20essay.pdf, accessed June 2008.
23. Stewart, "Global pillage" (ref. 13), 828–38; Daniel Carey, "Compiling nature's history: Travellers and travel narratives in the early Royal Society", *Annals of science*, liv (1997), 269–92, pp. 275–6.
24. Robert Markley, *The Far East and the English imagination 1600–1730* (Cambridge, 2006), 241–68.
25. Chamberlayne to Newton, 2 February 1704, *Correspondence of Newton* (ref. 18), iv, 412; Fontaney to Sloane, 1 August 1704, British Library MS Sloane 4039, fol. 334; Flamsteed to Pound, 15 November 1704, and Pound to Flamsteed, 7 July 1705, in Eric Forbes, Lesley Murdin and Frances Willmoth (eds), *Correspondence of John Flamsteed* (3 vols, Bristol, 1995–2002), iii, 100–1, 182. See Rodney Needham, *Exemplars* (Berkeley, 1985), 75–116.
26. Frank Lestringant, *Une sainte horreur, ou le voyage en Eucharistie XVIe–XVIIIe siècle* (Paris, 1996), 311–30. The Psalmanazar literature is vast: Needham gives a bibliography in *Exemplars* (ref. 25), 229–40. Recent studies include Susan Stewart, "Antipodal expectations: Notes on the Formosan 'ethnography' of George Psalmanazar", in George W. Stocking (ed.), *Romantic motives: Essays on anthropological sensibility* (Madison, 1989), 44–73; Richard Swiderski, *The false Formosan: George Psalmanazar and the eighteenth-century experiment of identity* (San Francisco, 1991); Peter Mason, *The lives of images* (London, 2001), 56–79; Michael Keevak, *The pretended Asian: George Psalmanazar's eighteenth-century Formosan hoax* (Detroit, 2004).
27. Krzysztof Pomian, *Collectors and curiosities: Paris and Venice 1500–1800* (1987; Cambridge, 1990), 53–64, 125–35; Barbara M. Benedict, *Curiosity: A cultural history of early modern inquiry* (Chicago, 2002), 52–70; Margaret 'Espinasse, "The decline and fall of Restoration science", *Past and present*, xiv (1958), 71–89. Jurin's dedication is in *Philosophical transactions*, xxxiv (1727), sig. A2. For censure of the Royal Society's output in this period see J. L. Heilbron, *Physics at the Royal Society during Newton's presidency* (Los Angeles, 1983), 35–40; Mordechai Feingold, "Mathematicians and naturalists: Sir Isaac Newton and the Royal Society", in Jed Z. Buchwald and I. Bernard Cohen (eds), *Isaac Newton's natural philosophy* (Cambridge, MA, 2001), 77–102.
28. Peter Dear, *Discipline and experience: The mathematical way in the Scientific Revolution* (Chicago, 1995), 246–8 on mathematical philosophy's weaker role for patterns of trust; Harris, "Long-distance corporations" (ref. 19), 274 on Grew and Newton. For Newton's gift of Grew's *Musaeum Societatis Regalis* to his college in 1680 see John Edleston, *Correspondence of Sir Isaac Newton and Professor Cotes* (Cambridge, 1850), p. xxix.
29. Isaac Newton (ed.), *Bernhard Vareni Geographia generalis* (Cambridge, 1672); William Warntz, "Newton, the Newtonians and the *Geographia generalis Varenii*", *Annals of the Association of American Geographers*, lxxix (1989), 165–91, p. 177. Compare Newton's planned role in John Adams's 1681 English meridian survey: Thomas Birch, *History of the Royal Society* (4 vols, London, 1756), iv, 65–66 (19 January 1681).
30. J. S. Peters, "The Bank, the press and the return to nature", in John Brewer and Susan Staves (eds), *Early modern conceptions of property* (London, 1996), 365–88; Westfall, *Never at rest* (ref. 18), 623, 862. For communication networks see Burke, *Social history of knowledge* (ref. 14), 149–76; Ian K. Steele, *The English Atlantic 1675–1740: An exploration of communication and community* (Oxford, 1986).
31. Isaac Newton, *The mathematical principles of natural philosophy* (2 vols, London, 1729), ii, 200–1, and Newton, *The Principia,* ed. by I. Bernard Cohen and Anne Whitman (Berkeley, 1999), 793.

See D. T. Whiteside, “Before the *Principia*: The maturing of Newton’s thoughts on dynamical astronomy, 1664–1684”, *Journal of the history of astronomy*, i (1970), 5–19; I. Bernard Cohen, *Introduction to Newton’s Principia* (Cambridge, 1971), 132–5; Westfall, *Never at rest* (ref. 18), 443–4, 458–62, 861–2.

32. Edmond Halley, “An historical account of the trade winds and monsoons”, *Philosophical transactions*, xvi (1686), 153–68, p. 153 (compare *ibid.,* 149, for Halley’s editorial comment on delay in publication); Halley to Newton, 7 June 1686, *Correspondence of Newton* (ref. 18), ii, 434. See D. W. Waters, “Captain Edmond Halley FRS, Royal Navy, and the practice of navigation”, in Norman J. W. Thrower (ed.), *Standing on the shoulders of giants: A longer view of Newton and Halley* (Berkeley, 1990), 171–202, pp. 180–2; Alan Cook, *Edmond Halley: Charting the heavens and the seas* (Oxford, 1998), 190–6.
33. D. T. Whiteside (ed.), *The mathematical papers of Isaac Newton* (8 vols, Cambridge, 1967–81), vi, 51 n. 62; compare Hall and Hall (eds), *Unpublished scientific papers* (ref. 18), 279. Newton’s editor Roger Cotes summarized the method in the 1710s: see Roger Cotes, “Aestimatio errorum in mixta mathesi”, in *Harmonia mensurarum, … accedunt alia opuscula mathematica*, ed. by Robert Smith (Cambridge, 1722), 1–22 (second pagination), p. 22.
34. Robert Hooke, *Lectures and collections* (London, 1678), 22 (on Hevelius and others on comets).
35. Newton to Flamsteed, 12 January 1685, and Flamsteed to Newton, 27 January 1685, in *Correspondence of Newton* (ref. 18), ii, 413, 414; Isaac Newton, *A treatise of the system of the world* (composed 1685; London, 1728), 29; Newton, *Principia* (ref. 31), 228–9, 812–14. The sources include Christiaan Huygens, *Systema Saturnium* (The Hague, 1659), 47; Edmond Halley, “A correction of the theory of the motion of the satellite of Saturn”, *Philosophical transactions*, xiii (1683), 82–88, p. 86; Jean-Charles Gallet, “Système des apparences de Saturne”, *Journal des sçavans*, 12 June 1684, 197–201, p. 199. Compare Albert van Helden, *Measuring the universe: Cosmic dimensions from Aristarchus to Halley* (Chicago, 1985), 146–8.
36. Newton to Flamsteed, 16 February and 29 June 1695, in *Correspondence of Newton* (ref. 18), iv, 87–88, 134. See Nick Kollerstrom and Bernard Yallop, “Flamsteed’s lunar data, 1692–5, sent to Newton”, *Journal for the history of astronomy*, xxvi (1985), 237–46; Buchwald, “Discrepant measurements” (ref. 17), 603; Westfall, *Never at rest* (ref. 18), 540–8; Iliffe (ed.), *Early biographies* (ref. 6), pp. xxii–xxiv, 15–17, 186.
37. D. T. Whiteside, “Newton’s lunar theory: From high hope to disenchantment”, *Vistas in astronomy*, xix (1975–76), 317–28. For the removal of Flamsteed’s name, compare *Correspondence of Newton* (ref. 18), iv, 3–4 and 277; Alexandre Koyré and I. Bernard Cohen (eds), *Isaac Newton’s Philosophiae naturalis principia mathematica: The third edition with variant readings* (Cambridge, 1972), 658; and Newton, *Principia* (ref. 31), 869–71. For the failings of Newton’s lunar theory see Curtis Wilson, “The Newtonian achievement in astronomy”, in René Taton and Curtis Wilson (eds), *Planetary astronomy from the Renaissance to the rise of astrophysics*, Part A: *Tycho Brahe to Newton* (Cambridge, 1989), 233–74, pp. 262–7.
38. E. J. Aiton, “The contributions of Newton, Bernoulli and Euler to the theory of the tides”, *Annals of science*, xi (1955), 206–23, pp. 210–13; Nick Kollerstrom, “Newton’s lunar mass error”, *Journal of the British Astronomical Association*, xcv (1985), 151–3; Newton, *Principia* (ref. 31), 238–46.
39. Newton, *System of the world* (ref. 35), 71–72; compare Newton, *Principia* (ref. 31), 835.
40. Cotes to Newton, 28 February 1712; Newton to Cotes, 9 April and 22 April 1712; and Cotes to Newton, 26 April 1712, in *Correspondence of Newton* (ref. 18), v, 243–4, 263–9, 273–5, 278–80. For Cotes’s work as editor, see Westfall, *Never at rest* (ref. 18), 703–12, 729–51; Cohen, *Introduction* (ref. 31), 227–35; Ronald Gowing, *Roger Cotes, natural philosopher* (Cambridge, 1983), 14–19, 80–108.
41. Moray to Bruce, 8 January 1658, in David Stevenson (ed.), *Letters of Sir Robert Moray to the Earl of Kincardine* (London, 2007), 113; Robert Moray, “A relation of some extraordinary tydes

in the West-Isles of Scotland", and Moray, "Considerations and enquiries concerning tides", *Philosophical transactions*, i (1665–6), 53–55 and 298–301; Margaret Deacon, *Scientists and the sea 1650–1900* (London, 1971), 72. Newton's notes on tides in the Hebrides and the Danube are reprinted in J. E. McGuire and Martin Tamny (eds), *Certain philosophical questions: Newton's Trinity notebook* (Cambridge, 1983), 404; Newton's notes on these tidal reports in *Philosophical transactions* are at Cambridge University Library MS Add 3958.1, fol. 9.

42. Margaret Deacon, "Founders of marine science in Britain: The work of the early Fellows of the Royal Society", *Notes and records of the Royal Society*, xx (1965), 28–50, p. 32.
43. Moray, "Considerations and enquiries" (ref. 41), 299–301, and Moray, "Patternes of the tables proposed to be made for observing of tides", *Philosophical transactions*, i (1665–6), 311–13; Deacon, *Scientists* (ref. 41), 99–100. Newton's comments against Wallis are at Cambridge University Library MS Add 3958, fol. 12v and his notes on Moray's observatory at fol. 13r.
44. John Wallis, "An essay exhibiting his hypothesis about the flux and reflux of the sea", *Philosophical transactions*, i (1665–6), 263–81, pp. 275–6; Shapin, *Social history of truth* (ref. 9), 258–66; Dear, *Discipline and experience* (ref. 28), 230–1.
45. Joseph Childrey, "A letter containing some animadversions upon the Reverend Dr John Wallis's hypothesis about the flux and reflux of the sea", *Philosophical transactions*, v (1670), 2061–8, pp. 2062–3; Moray, "Considerations and enquiries" (ref. 41), 297–8; Deacon, *Scientists* (ref. 41), 102–8.
46. Deacon, *Scientists* (ref. 41), 101–2; Samuel Sturmy, "An account of some observations made this present year in Hong-Road within four miles of Bristol", *Philosophical transactions*, iii (1668), 813–17, p. 815.
47. John Flamsteed, "A correct tide table", *Philosophical transactions*, xiii (1683), 10–15, p. 12; William Molyneux, "An account of the course of tides in the port of Dublin", *Philosophical transactions*, xvi (1686), 192–3; Flamsteed to Newton, 26 September 1685, in *Correspondence of Newton* (ref. 18), ii, 427–8; Flamsteed to Molyneux, 17 January 1687 and to Towneley, 12 February 1687, in *Correspondence of Flamsteed* (ref. 25), ii, 328 and 338.
48. Edmond Halley, "The true theory of the tides", *Philosophical transactions*, xix (1697), 445–57 (composed 1686); Halley to James II, 1687, British Library 537.g.30, p. 12; Cook, *Halley* (ref. 32), 284–90; Waters, "Captain Edmond Halley" (ref. 32), 196.
49. Newton, *System* (ref. 35), 76, 78, 87–88; Cohen and Koyré (eds), *Principia* (ref. 37), 667 n.
50. Newton to Cotes, 26 February 1712; Cotes to Newton, 28 February 1712; Newton to Cotes, 8 April 1712, in *Correspondence of Newton* (ref. 18), v, 241, 243, 264; Newton, *Principia* (ref. 31), 875. For the manipulation of tide data, see Richard S. Westfall, "Newton and the fudge factor", *Science*, clxxix (1973), 751–8, pp. 756–8.
51. David E. Cartwright, "The Tonkin tides revisited", *Notes and records of the Royal Society*, lvii (2003), 135–42.
52. Davenport to James, 12 July 1678, in "Tonqueen Journal Register" (1678–79), British Library, India Office Records MS G/12/17, part 5, fol. 233v; compare "Tonqueen Journal transcrib'd by Francis Davenport", British Library MS Sloane 998, fols. 49–50, "Mr Henry Baker's Account of the Flowing of the Waters" (1673): "I found the Waters to have no course with the Moon."
53. Birch, *History of the Royal Society* (ref. 29), iv, 289–90 (23 April 1684); Anna Winterbottom, "Producing and using the *Historical relation of Ceylon*: Robert Knox, the East India Company and the Royal Society", *The British journal for the history of science*, xlii (2009), forthcoming.
54. Francis Davenport, "An account of the course of the tides at Tonqueen", with Edmond Halley, "The theory of them at the barr of Tonqueen", *Philosophical transactions*, xiv (1684), 677–88; the original of Davenport's account, which differs in some significant passages, is at British Library, India Office Records MS G/12/17, fols. 237–40.

55. William Dampier, *A new voyage round the world* (London, 1698), "Discourse of the trade-winds, breezes, storms, seasons of the year, tides and currents of the Torrid Zone throughout the world" (separate pagination), 97.
56. Francis Davenport, *An historical abstract of Mr Samuel White* (London, 1688); George White, *Reflections on a scandalous paper entituled the Answer of the East-India Company to two printed papers of Mr Samuel White together with the True character of Mr Francis Davenport* (London, 1689), citation from p. 3. See Maurice Collis, *Siamese White* (London, 1936), 95–99 and 293–6: Davenport "became one of the best-known names in London".
57. Newton, *Principia* (ref. 31), 839; I. Bernard Cohen, "The first explanation of interference", *American journal of physics*, viii (1940), 99–106, pp. 105–6; Cartwright, "Tonkin tides" (ref. 51), 137–8.
58. Henry Guerlac, *Newton on the Continent* (Ithaca, 1981), 34–40; Sara Schechner Genuth, *Comets, popular culture, and the birth of modern cosmology* (Princeton, 1997), 133–42; J. A. Ruffner, "Newton's *Propositions on comets*: Steps in transition, 1681–84", *Archive for history of exact sciences*, liv (2000), 259–77.
59. Flamsteed to Towneley, 11 May 1677, in *Correspondence of Flamsteed* (ref. 25), i, 552.
60. Juan Casanovas and Philip C. Keenan, "The observations of comets by Valentin Stansel, a seventeenth century missionary in Brazil", *Archivum Historicum Societatis Iesu*, lxii (1993), 319–30, pp. 327–8; Carlos Ziller Camenietzki, "The celestial pilgrimages of Valentin Stansel, Jesuit astronomer and missionary in Brazil", in Moti Feingold (ed.), *The new sciences and Jesuit science: Seventeenth century perspectives* (Dordrecht, 2003), 249–70, pp. 260–2; and Camenietzki, "Baroque science" (ref. 12), 316.
61. Newton, *Principia* (ref. 31), 927.
62. Robert Hooke, "A discourse of the nature of comets" (1682), in Richard Waller (ed.), *Posthumous works of Robert Hooke* (London, 1705), 149–90, p. 151.
63. Buchwald, "Discrepant measurements" (ref. 17), 592; Halley to Flamsteed, 7 June 1679, in Eugene Fairfield MacPike, *Hevelius, Flamsteed and Halley: Three contemporary astronomers and their mutual relations* (London, 1937), 86–87.
64. Shapin, *Social history of truth* (ref. 9), 272–87; Halley to Molyneux, 27 March 1686, in Eugene Fairfield MacPike, *Correspondence and papers of Edmond Halley* (Oxford, 1932), 60.
65. MacPike, *Correspondence and papers of Halley* (ref. 64), 48–52; Cook, *Halley* (ref. 32), 105–15.
66. Cook, *Halley* (ref. 32), 119–24, 127; *Correspondence of Flamsteed* (ref. 25), i, 751–5; Eric G. Forbes, "The comet of 1680–1681", in Thrower (ed.), *Standing on the shoulders of giants* (ref. 32), 312–23, pp. 313–17; Eric G. Forbes (ed.), *The Gresham lectures of John Flamsteed* (London, 1975), 107. See Susanna Åkerman, *Queen Christina of Sweden and her circle: The transformation of a seventeenth century philosophical libertine* (Leiden, 1991), 176–7, 254–5.
67. Cook, *Halley* (ref. 32), 147–51; Westfall, *Never at rest* (ref. 18), 402–7.
68. Newton's cometary notes in Cambridge University Library MS Add 4004, fols. 101–5 and MS Add 3965.14, fols. 581–2, 613–14, described in Ruffner, "Newton's *Propositions on comets*" (ref. 58); Flamsteed to Newton, 25 September 1685 (first draft), in *Correspondence of Flamsteed* (ref. 25), ii, 247–8; a later version is at *Correspondence of Newton* (ref. 18), ii, 421–8. Compare Forbes (ed.), *Gresham lectures of Flamsteed* (ref. 66), 113.
69. Allan Chapman, "Edmond Halley's use of historical evidence in the advancement of science", *Notes and records of the Royal Society of London*, xlviii (1994), 167–91.
70. Newton to Crompton for Flamsteed, 28 February 1681, in *Correspondence of Newton* (ref. 18), ii, 340–7; compare Flamsteed to Halley, 17 February 1681, in *Correspondence of Flamsteed* (ref. 25), i, 760–3; Flamsteed to Crompton for Newton, 7 March 1681, in *Correspondence of Newton* (ref. 18), ii, 348–55. For redrafts involving French and Roman observers, as well as Hill and

Babington, see Koyré and Cohen (eds.), *Principia with variant readings* (ref. 37), 717–32.

71. Brattle to Flamsteed, 4 June 1681, in *Correspondence of Flamsteed* (ref. 25), i, 789–90. For Brattle and Flamsteed, and his lack of direct knowledge of Newton, see Rick Kennedy, "Thomas Brattle and the scientific provincialism of New England 1680–1713", *The New England quarterly*, lxiii (1990), 584–600.
72. Peter Broughton, "Arthur Storer of Maryland: His astronomical work and his family ties with Newton", *Journal of the history of astronomy*, xix (1988), 77–96, p. 92; Newton, *Principia* (ref. 31), 913, 927.
73. Hooke, *Posthumous works* (ref. 62), 154; Koyré and Cohen (eds), *Principia with variant readings* (ref. 37), 730.
74. Shapin, *Social history of truth* (ref. 9), 287; Edmond Halley, *A synopsis of the astronomy of comets* (London, 1705), 19 and 21–22.
75. For the French dilemma see James Jurin (ed.), *Bernhardi Varenii Geographia generalis* (Cambridge, 1712), appendix (separate pagination), 3–4 and 40; Warntz, "Newton" (ref. 29), 188.
76. Newton, *Principia* (ref. 31), 827.
77. Cotes to Newton, 16 and 23 February 1712, in *Correspondence of Newton* (ref. 18), v, 226, 233.
78. Newton, *Principia* (ref. 31), 829; John Olmsted, "The scientific expedition of Jean Richer to Cayenne", *Isis*, xxxiv (1942), 117–28; John Greenberg, *The problem of the Earth's shape from Newton to Clairaut* (Cambridge, 1995), 7.
79. Nicholas Dew, "*Vers la ligne*: Circulating measurements around the French Atlantic", in Delbourgo and Dew (eds), *Science and empire in the Atlantic world* (ref. 17), 53–72, pp. 60–64, and Dew, "Scientific travel in the Atlantic world: The French expedition to Gorée and the Antilles, 1681–1683", *The British journal for the history of science*, xliii (2010), forthcoming. See Jean Richer, "Observations astronomiques et physiques faites en l'isle de Caïenne", in *Recueil d'observations faites en plusieurs voyages par ordre de sa Majesté* (Paris, 1693), separate pagination, 36–37. Newton's notes on Cayenne, Richer and Halley are in "Waste Book", Cambridge University Library MS Add 4004, fol. 101v; compare Cook, *Halley* (ref. 32), 116. He also owned a copy of the *Recueil d'observations*.
80. Newton, *Principia* (ref. 31), 832. Compare Justel to Oldenburg, 16 August 1673, in A. R. Hall and M. B. Hall (eds), *Correspondence of Henry Oldenburg* (13 vols, Madison, 1965–86), x, 152–3, cited in Dew, "*Vers la ligne*" (ref. 79), 70 n. 29.
81. Newton to Cotes, 3 April 1712; Cotes to Newton, 16 February 1712; Cotes to Newton 23 February 1712; in *Correspondence of Newton* (ref. 18), v, 257, 226, 233–5.
82. Dew, "*Vers la ligne*" (ref. 79), 61–62; Cassini, "Les elemens de l'astronomie verifiez par M. Cassini par le rapport de ses tables aux observations de M. Richer", in *Recueil d'observations* (ref. 79), 55.
83. Newton, *Principia* (ref. 31), 830–2.
84. Newton, *Principia* (ref. 31), 831; compare Cotes to Newton, 23 and 28 February 1712 and Newton to Cotes, 26 February and 3 April 1712, in *Correspondence of Newton* (ref. 18), v, 234–7, 240–3, 261. For "tinkering" see Greenberg, *Problem* (ref. 78), 14.
85. Cotes to Newton, 23 February 1712 and Newton to Cotes, 26 February 1712, in *Correspondence of Newton* (ref. 18), 235, 240–1; Jacques Cassini, "Des observations faites aux Indes Occidentales en 1704, 1705 et 1706 par P. Feuillée Minime, Mathématicien du Roy, comparées à celles qui ont été faites en même tems à l'Observatoire Royale", *Mémoires de l'Académie Royale des Sciences,* 1709, 5–16, on 7–8; Newton, *Principia* (ref. 31), 830.
86. Louis Feuillée, *Journal des observations physiques, mathématiques et botaniques faites par ordre du Roi sur les côtes orientales de l'Amérique Méridionale et aux Indes Occidentales* (2 vols, Paris, 1714–25), ii, 326–7, 407–8. Newton's copy of this work is in Trinity College Cambridge,

NQ.10, 23–24.

87. Amédée-François Frézier, *Relation du voyage de la Mer du Sud* (Paris, 1714), p. viii, and Frézier, *A voyage to the South-sea* (London, 1717), sig. A2r, which also prints Halley to Bowyer, 6 April 1717. Compare Jorge Cañizares-Esguerra, *How to write the history of the New World* (Stanford, 2001), 15–17; Neil Safier, *Measuring the New World: Enlightenment science and South America* (Ithaca, 2008), 215–17.

88. Feuillée, *Journal* (ref. 86), ii, 86–87 (published 1725); Amédée-François Frézier, *Relation du voyage de la Mer du Sud*, 2nd edn (Paris, 1732), "Réponse à la preface critique du Livre intitulé *Journal des Observations*", separate pagination, 8.

89. Charles-Marie de la Condamine, *Journal du voyage fait par ordre du roi à l'Equateur* (2 vols, Paris, 1751), i, 162; Neil Safier, *Measuring the New World* (ref. 87), 39–43. Compare Antonio Lafuente and Antonio Mazuecos, *Los caballeros del punto fijo* (Madrid, 1987), 19–22, 172–86; Mary Terrall, "Representing the Earth's shape: The polemics surrounding Maupertuis' expedition to Lapland", *Isis*, lxxxiii (1992), 218–37; Rob Iliffe, "'Aplatisseur du monde et de Cassini': Maupertuis, precision measurement and the shape of the Earth in the 1730s", *History of science*, xxxi (1993), 335–75 and Iliffe, "Ce que Newton connut sans sortir de chez lui: Maupertuis et la forme de la terre dans les années 1730", *Histoire et mésure*, viii (1993), 355–86.

90. Stephen M. Stigler, "Eight centuries of sampling inspection: The Trial of the Pyx", *Journal of the American Statistical Association*, lxxii (1977), 493–500, pp. 497–8; Newton to the Treasury, December 1710, in *Correspondence of Newton* (ref. 18), 82–90; Newton, draft of "Chronology of Ancient Kingdoms amended", New College Oxford, MS 361.1 B, fols. 104–6 and *Chronology of ancient kingdoms amended* (London, 1728), 52–54; Frank Manuel, *Isaac Newton historian* (Cambridge, 1963), 55.

91. Isaac Newton, New College Oxford MS 361.3, fol. 25; see Manuel, *Newton* (ref. 90), 87; Kenneth J. Knoespel, "Newton in the school of time: The *Chronology of ancient kingdoms amended* and the crisis of seventeenth-century historiography", *The eighteenth century*, xxx (1989), 19–41, pp. 24–28.

92. Rob Iliffe, "Apocalyptic hermeneutics and anti-idolatry in the work of Isaac Newton and Henry More", in Richard Popkin and James Force (eds), *The books of nature and scripture* (Dordrecht, 1994), 55–88; Robert S. Westfall, "Isaac Newton's *Theologia gentiles origines philosophicae*", in W.Warren Wagar (ed.), *The secular mind: Transformations of faith in modern Europe* (New York, 1982), 15–34; citation from Isaac Newton, "The original of religions", Jewish National Library MS Yahuda 41, fol.4r.

93. Newton, "Original of religions" (ref. 92), fol. 2v.

94. Newton, *System of the world* (ref. 35), 1–4.

95. Newton, *Mathematical principles* (ref. 31), ii, 202, and Newton, *Principia* (ref. 31), 198–200, 795. Compare Cohen, *Introduction* (ref. 31), 240–5; Alexandre Koyré, *Newtonian studies* (1965; Chicago, 1968), 265–6. For the rules in eschatology, see Maurizio Mamiani, "To twist the meaning: Newton's *Regulae philosophandi* revisited", in Buchwald and Cohen, *Isaac Newton's natural philosophy* (ref. 27), 3–14. For application to Atlantic measures see Dew, "*Vers la ligne*" (ref. 79), 54–56. Einstein is read as offering "a handbook for travellers" in Bruno Latour, "A relativistic account of Einstein's relativity", *Social studies of science*, xviii (1988), 3–44.

96. Newton, *Mathematical principles* (ref. 31), ii, 390–1, and Newton, *Principia* (ref. 31), 941–2; see Larry Stewart, "Seeing through the Scholium: Religion and reading Newton in the eighteenth century", *History of science*, xxxiv (1996), 123–65; Stephen Snobelen, "'God of Gods, and Lord of Lords': The theology of Isaac Newton's General Scholium to the *Principia*", *Osiris*, xvi (2001), 169–208.

97. Newton, "The end of the world day of Judgment and world to come", Jewish National Library MS Yahuda 9.2, fols. 139–40, partly transcribed in Frank E. Manuel, *The religion of Isaac Newton*

(Oxford, 1974), 101–2. A source for Newton's remarks is Joseph Glanvill, *A philosophical endeavour towards the defence of the being of witches and apparitions* (London, 1666), 9. This text was republished in 1681 after Glanvill's death as *Saducismus triumphatus* by Henry More. Newton later reaffirmed his claim that there are "intelligent beings superior to us who superintend these revolutions of the heavenly bodies": see Iliffe (ed.), *Early biographies* (ref. 6), 165.

98. James Thomson, *To the memory of Sir Isaac Newton* (1727), lines 7 and 190–5; see Fara, *Newton* (ref. 2), 59–97.

99. William Wordsworth, *The prelude* (1850), Book 3, lines 60–63. See Thomas and Ober, *A mind forever voyaging* (ref. 5), 47–48.