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The Information Order of Isaac Newton's Principia Mathematica

THE HANS RAUSING LECTURE 2008
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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 a bit hazy. The literary reference is surely 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.[2] But the statement's immediate relation with Newton is more ambiguous. The earliest version is to be found in an Oxford 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 speaking of the strange attitudes of Newton and his allies towards the religious doctrine of the Trinity,

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1 Edmund Turnor, *Collections for the History of the Town and Soke of Grantham* (London: William Miller, 1806), p. 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; see Patricia Fara, *Newton: the Making of Genius* (London: Macmillan, 2002), 206.

Ramsay quoted Newton's remark, adding it was "as great as all his book."[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 the Newtonian philosophy Ramsay significantly 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 aim was to link the phrase with the celebrated Pauline doctrine expressed 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* (1820-1) 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 mock-modesty of the opening phrase: "I know not what I may seem to the world." In his psychobiography of Newton, Frank Manuel hazarded that "this guileless and disarming simile may also be his confession."[5]

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3 Joseph Spence, *Observations, Anecdotes and Characters of Books and Men*, ed. James M. Osborn, 2 vols. (first published 1820; Oxford: Clarendon Press, 1966), vol. 1, 462.

4 Andrew Ramsay, *A Plan of Education for a Young Prince* (London: Wilford, 1732), 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 had already proposed that a proposed artistic monument to Newton must be set "by the sea-side." See Francis Haskell, "The Apotheosis of Newton in Art," in Robert Palter (ed.), *The Annus Mirabilis of Sir Isaac Newton* (Cambridge, MA.: MIT Press, 1970), 302-21, on 315.

5 Fara, *Newton*, 206-7; W.K.Thomas and Warren U. Ober, *A Mind Forever Voyaging: Wordsworth at Work Portraying Newton and Science* (Edmonton: University of Alberta Press, 1989), 41; Frank E. Manuel, *A Portrait of Isaac Newton* (1968; London: Muller, 1980), 389.

The concern here, however, is very different. Newton was never on the seashore nor discovered the ocean. He saw no tides save along the Thames and never used the Moon's place to navigate at sea. No great traveller, he spent his entire life in Lincolnshire, Cambridge and a number of 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 at 40 years of age he published his *Principia*, that prodigious and immortal work." [6] There was a rather direct connexion between an ingeniously worked image of seclusion and authority and the religious and cosmological programme Newton espoused. The wars of the learned were due to making public what should be secreted and the affairs of a corrupt state and church were poisonous for the pursuit of truth. Historians have also traced the ways in which the "noble and secret" works of philosophical alchemy were important for the knowledge map that Newton helped draw. In his analysis of the relation between experimental location and the "ambivalent or hostile" reaction of Newton to its public milieux, Steven Shapin has tellingly cited Milton on the mind as "its own

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[6] William Stukeley, "Memoirs of Sir Isaac Newton's Life," in Rob Iliffe, ed., *Early Biographies of Isaac Newton* (London: Pickering and Chatto, 2006), 250-1.

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 to these reflexions on information, solitude and geography. 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 solitude and immobility seems striking precisely because his programme, first launched in the mid-1680s and under revision for the next three decades, so evidently mastered a global creation, 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 any mediation (**figure 1**). But immediate action at a distance is neither a plausible 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

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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: Cambridge University Press, 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: Oxford University Press, 1988), 147-68; Steven Shapin, " 'The Mind is its Own Place': Science and Solitude in Seventeenth-century England," *Science in Context* 4 (1990), 191-218, on 204-6.

8 Charles W. J. Withers, *Placing the Enlightenment: Thinking Geographically about the Age of Reason* (Chicago: university of Chicago Press, 2007); David Lambert, Luciana Martins and Miles Ogborn, "Currents, Visions and Voyages: Historical Geographies of the Sea," *Journal of Historical Geography* 32 (2006), 479-93, on 485.

Figure 1. *Frontispiece to Andrew Motte's English edition of Isaac Newton, Mathematical Principles of Natural Philosophy, London, 1729. Newton posthumously converses directly in heaven with a divine spirit; above, lines adapted from Edmond Halley's Ode prefacing the Principia.*

natural philosophy. His *Principia Mathematica* remains a glorious testimony to the achievements of a putatively cloistered analyst of the mathematics of motion. The tell tale remark about the beachcomber and the ocean of truth helps 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. Though its author travelled little, the work depended absolutely on travellers' tales and assays of their reliability as knowers.[9]

The knowledges in question in this case seem unusually interesting examples of such socially institutionalised practices. This intricate order of social appraisal and knowledgeable assays looks like an apt topic for constructive historical enquiry. So 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

[9] Martin Kusch, *Knowledge by Agreement: the Programme of Communitarian Epistemology* (Oxford: Oxford University Press, 2002), 71.

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] My conjecture is that 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 that allowed accumulations of facts and commodities were decisive aspects of the information order of early modern Europe. 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-institutionalised patterns of trust and vigilance. Though Newton's relations with Jesuit natural philosophers were notoriously and traumatically fraught, these priests would provide recalcitrant but indispensable resources for his own cosmological endeavours. Importantly for the argument presented here, protagonists were peculiarly aware of the modes of travel and knowledge their work developed. The remarkable "ecstatic heavenly journeys" around the cosmos composed by Jesuits such as Athanasius Kircher in his museum in Rome or Valentin Stansel in his college in Brazil were rather deliberate modes of imagining

[10] Boris Hessen, "The Social and Economic Roots of Newton's Principia," in P.G.Werskey, ed., *Science at the Crossroads: Papers from the Second International Congress of the International History of Science and Technology 1931* (1931; London: Frank Cass, 1971), 147-212, on 171. For Hessen's reading of Newton see Simon Schaffer, "Newton at the Crossroads," *Radical Philosophy* 37 (1984), 23-28.

travel and its spiritual sense, as though delegates could move without obstacles around a world revealed by the new information order.[11] Similarly, in her brilliant analysis of what she calls the "information ceremonies" of the old regime, Michèle Fogel shows how at a period that has been seen as marking the dawn of modern civil society, the control over production of information was surrounded with complex rituals where the state's power was both dramatised and reinforced. John Brewer's comparable analysis of the fiscal-military system of excise shows the liaison between the flow 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 insights in the newly globalised trade networks Britain's empire then established. These historians bring out the spatial, political and commercial dimensions of the early modern information orders.[12]

"Information" here is a term designed to describe matters somewhat more broadly shared and less explicitly challenged than formalised knowledges. It's helpful because it inverts a received hierarchy: information is the commonly taken-for-granted, rather less disputed and less disputable; knowledge looks more mutable,

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11 Steven J. Harris, "Confession Building, Long-distance Networks, and the Organization of Jesuit Science," *Early Science and Medicine* 1 (1996), 287-318; 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: Kluwer, 1999), 97-120, on 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: Routledge, 2004), 311-28.

12 Michèle Fogel, *Les Cérémonies de l'Information dans la France du XVIe au XVIIIe Siècle* (Paris: Fayard, 1989); John Brewer, *The Sinews of Power: War, Money and the English State 1688-1783* (London: Routledge, 1989), chapter 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: Cambridge University Press, 1992) and Stewart, "Global Pillage: Science, Commerce and Empire," in Roy Porter, ed., *The Cambridge History of Science: Eighteenth-century Science* (Cambridge: Cambridge University Press, 2003), 825-44.

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." And as Fogel and Brewer both demonstrate, these orders were polemical fields, preconditions of knowledge formation and regulation. Within these orders there were information brokers – as Peter Burke suggests, their names are familiar as protagonists of the knowledge systems that concern us: Bacon, Mersenne, Hartlib, Renaudot, Vossius, Oldenburg, Bayle, Leibniz, Sloane. And 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 encyclopedias.[13]

This was the epoch of foundation both of the natural philosophical journal and of the newspaper. There were hosts of new reports of marvels, wonders and prodigies artfully linked with commercial and political events, whose credibility was a matter of urgent concern for magistrates and priests, natural philosophers and merchants. All this was "paper fuel," as it was called, for news books and coffee houses. The social history of such stories has typically been described in terms of the "decline of magic" and the "disenchantment of the world."[14] Somehow or other, it is claimed, early modern culture managed to tease apart the rational, scientific, veridical wheat from the superstitious, traditional, eccentric chaff.

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13 C.A.Bayly, *Empire and Information: Intelligence, Gathering and Social Communication in India, 1780-1870* (Cambridge: Cambridge University Press, 1996), 5; Peter Burke, *A Social History of Knowledge from Gutenberg to Diderot* (Cambridge: Polity, 2000), 25.

14 Jerome Friedman, *Miracles and the Pulp Press during the English Revolution* (London: Routledge, 1993), 239-53; Joad Raymond, *Pamphlets and Pamphleteering in Early Modern Britain* (Cambridge: Cambridge University Press, 2003), 324-41; William Burns, *An Age of Wonders: Prodigies, Politics and Providence in England, 1657-1727* (Manchester: Manchester University Press, 2002), 57-96. For coffee houses see Markman Ellis, *The Coffee House: a Cultural History* (London: Weidenfeld and Nicolson, 2004), 68-74.

Rival criteria of assessment of the possible contents and capacities of the world were hotly disputed. There was a potent 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.[15] The credit system that allowed judgments of trust put natural history, travel, trade and empire at its centre. Its exemplary institutions were libraries, cabinets and museums, but also mints and assay rooms. Pharmacy and alchemy were then vitally dependent upon and often debated the provenance of globally distributed goods whose virtues were intimately connected with the precise characteristics of the sites whence these valuable commodities were shipped. This information order judged persons under regimes of credit and trust alongside the judgment of creation's contents. It modeled the acquisition of knowledge as the stocking of a cabinet to correct the effects of the Fall. It was much concerned with global reach, with the providential order of creation and its particularities as facts, commodities and exotica.[16]

As example of how this order was put to work, consider Newton's very first extant letter, written in Cambridge in spring 1669 to his college friend Francis Aston. Here Newton copied out another virtuoso's instructions concerning the inquiries travellers should

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15 Steven Shapin, *A Social History of Truth: Civility and Science in Seventeenth-century England* (Chicago: Chicago University Press, 1994), 243-58; Brendan Dooley, *The Social History of Skepticism: Experience and Doubt in Early Modern Culture* (Baltimore: Johns Hopkins University Press, 1999), 12-18.

16 Pamela H. Smith and Paula Findlen (eds.), *Merchants and Marvels: Commerce, Science and Art in Early Modern Europe* (London: Routledge, 2002); Londa Schiebinger and Claudia Swan (eds.), *Colonial Botany: Science, Commerce and Politics in the Early Modern World* (Philadelphia: Pennsylvania University Press, 2005); James Delbourgo and Nicholas Dew (eds.), *Science and Empire in the Atlantic World* (London: Routledge, 2008). For the global trade networks of Newton's chemical colleague and dealer Giovanni Francesco Vigani, see Larry Stewart and Simon Schaffer, "Vigani and after: chemical enterprise in Cambridge 1680-1780," in M.D. Archer and C.D. Haley (eds.), *The 1702 Chemistry Chair at Cambridge: Transformation and Change* (Cambridge: Cambridge University Press, 2004), 31-55.

make about navigation, mining, pendulum clocks and metallurgy. Newton then added notes from a favoured alchemical text edited by Michael Maier, so asked about transmutations and for news of a medical chemist ("I think he usually goes clothed in green") whose repute in Holland he wished to judge. Alchemy provides a noteworthy case of the links between professed solitude and artful commerce, since without global supply chains much alchemical labour would lack its indispensable materials. Historians' readings of this 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.[17]

In tracing such networks of trade and knowledge through their regulative work, we might rather follow the suggestions of recent historians of the process, such as Hal Cook and Steven Harris. In his provocative analysis of the interaction between Dutch merchant enterprise and natural history, Cook rightly points out how collective and creditworthy accumulation of goods and information characterised the Dutch economic system and its knowledge regime too. Inventory investment, the invention of maintenance technologies of storage, classification and warehousing were simultaneously systems of knowledge accumulation and of world making whether in libraries, botanic gardens, pharmacies or museums. Harris uses the career of the Dutch VOC, alongside those of Spanish and Jesuit long-range knowledge networks, to chart the

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[17] Newton to Aston, 18 May 1669, *Correspondence of Isaac Newton*, ed. H.W.Turnbull, J.F. Scott and A.R.Hall, 7 vols. (Cambridge: Cambridge University Press, 1959-77), vol. 1, 9-11; R.S.Westfall, *Never at Rest: a Biography of Isaac Newton* (Cambridge: Cambridge University Press, 1980), 193; Manuel, *Portrait of Newton*, 162; Hessen, "Social and Economic Roots," 171-3.

ways in which travel, expropriation and accumulation provided both the social modes of existence of the early modern capitalist system and the information networks and genuinely "big sciences" of these crucial European institutions.[18] The economic systems of global European commercial networks vouchsafed the scope of the information order. The information order also underwrote the power of those systems. This is how an information order could help make a world. In this regime the divinely sanctioned reasons of creation were supposed to guarantee the possibility of knowing it and relying on its products. Credit was how such goods were got and how they were defined as goods.

There was thus a fundamental link between the colonial information order and the empiricist knowledge regime forged in the final decades of the seventeenth century, between a certain kind of epistemology, of providentialism and a form of domination. New worlds discovered were apparent on shipboard and through the optical devices stashed in the Royal Society – the microscope and the telescope. 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."[19] This was both conceptually

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[18] Harold J. Cook, "Time's Bodies: Crafting the Preparation and Preservation of Naturalia," in Smith and Findlen (eds.), *Merchants and Marvels*, 223-47 and Cook, *Matters of Exchange: Commerce, Medicine and Science in the Dutch Golden Age* (New Haven: Yale University Press, 2007), 267-76, 325-9; Steven J. Harris, "Long-distance Corporations, Big Science and the Geography of Knowledge," *Configurations* 6 (1988), 269-304.

and chronologically correct. 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.[20] The enterprise became an extra-parliamentary source of income for the crown. Its agents were called "spirits" in London slang. Leaders of the Royal Society such as its treasurer Abraham Hill, its president John Vaughan 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.[21]

Such remarkable information systems as those run by the Society of Jesus, the VOC and the Royal Africa Company, and in London by Oldenburg and 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.[22] What counted were the criteria with which plausibility could be assessed. How to discriminate,

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19 "An Introductory Discourse containing the whole History of Navigation," *A Collection of Voyages and Travels*, 2 vols. (London: Churchill, 1704), vol. 1, lxxiii.

20 Thomas Sprat, *History of the Royal Society* (London: Martyn and Allestry, 1667), 406-7.

21 Mark Govier, "The Royal Society, Slavery and the Island of Jamaica 1660-1700," *Notes and Records of the Royal Society* 53 (1999), 203-17; Larry Stewart, "The Edge of Utility: Slaves and Smallpox in the Early Eighteenth Century," *Medical History*, 29 (1985), 54-70; James Delbourgo, "Slavery in the Cabinet of Curiosities: Hans Sloane's Atlantic World," (www.britishmuseum.org/PDF/Delbourgo%20essay.pdf) accessed March 2007.

22 Stewart, "Global pillage," 828-38; Daniel Carey, "Compiling Nature's History: Travellers and Travel Narratives in the Early Royal Society," *Annals of Science* 54 (1997), 269-92.

for example, between the various reports from eastern Asia that reached London in the early eighteenth century, whether those of Engelbert Kaempfer on Japan, managed into print by Sloane, or those of Lemuel Gulliver in the same waters published at the same time, seemingly edited by Jonathan Swift?[23] (**figure 2**)

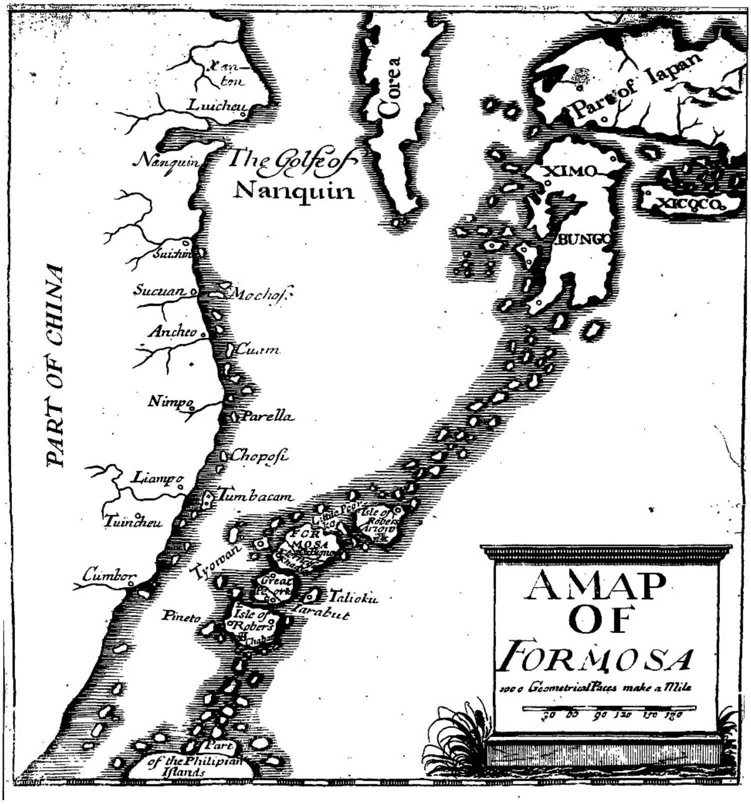

Figure 2a. *Map of Formosa from George Psalmanazar, An Historical and Geographical Description of Formosa, 2nd edition corrected, London, 1705.*

23 Robert Markley, *The Far East and the English Imagination 1600-1730* (Cambridge: Cambridge UP, 2006), 241-68.

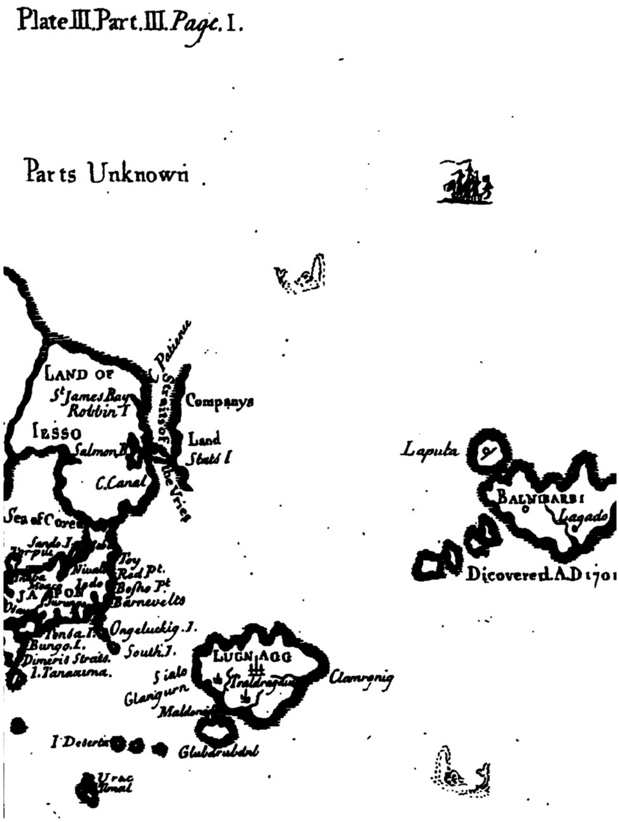

Figure 2b. *Map of Laputa, Balnibarbi, Luggnagg, Glubbdubdribb and Japan, from Jonathan Swift, Travels into Several Remote Nations of the World by Lemuel Gulliver, 2 vols. London, 1726, vol.2. Map of Laputa, Balnibarbi, Luggnagg, Glubbdubdribb and Japan, from Jonathan Swift, Travels into Several Remote Nations of the World by Lemuel Gulliver, 2 vols. London, 1726, vol.2.*

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, 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 all the more credible. Hans 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 Isaac 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.[24] 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.[25]

This perverse exercise in the manipulation of credit in ethnographic curiosity 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.

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24 Chamberlayne to Newton, 2 February 1704, *Correspondence of Newton*, vol.4, 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: Institute of Physics, 1995-2002), vol. 3, 100-101, 182. See Rodney Needham, *Exemplars* (Berkeley: University of California Press, 1985), 75-116.

25 Frank Lestringant, *Une Sainte Horreur, ou le Voyage en Eucharistie XVIe-XVIIIe Siècle* (Paris: PUF, 1996), 311-30. The Psalmanazar literature is vast: Needham gives a bibliography in *Exemplars*, 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: University of Wisconsin UP, 1989), 44-73; Richard Swiderski, *The False Formosan: George Psalmanazar and the Eighteenth-century Experiment of Identity* (San Francisco: Mellen Research UP, 1991); Peter Mason, *The Lives of Images* (London: Reaktion Books, 2001), 56-79; Michael Keevak, *The Pretended Asian: George Psalmanazar's Eighteenth-century Formosan Hoax* (Detroit: Wayne State UP, 2004).

Historians of the Royal Society have often discussed Sloane's succession to Newton's presidential chair in 1727 as a moment when the energies of mathematical physics started to dissipate in trivial accumulation of *naturalia*. Some contemporary Augustan satirists, well 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.[26]

Even Harris' otherwise brilliant exploration of long-range corporations in the networking of early modern knowledge regimes draws exactly such a distinction. He invites us to map the provenance of all the constituents of an early modern scientific text because he wants to show how the "unprecedented early modern explosion in mobility," especially under the aegis of the Society of Jesus and the long range trade corporations, decisively helped make the information order of the period. He describes the vast extent of natural history texts, such as Nehemiah Grew's *Musaeum Societatis Regalis* (a copy of which, as it happens, Newton gave to his college library). But then Harris contrasts this extent with what he imagines the "very small region of the globe" traced by the provenance routes of Newton's Principia. And in this last point, Harris uncharacteristically errs.[27] (**figure 3**) By relocating Newton's masterpiece we can perhaps hope not only to correct the errors of an historiography which draws a harsh distinction between the

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26 Krzysztof Pomian, *Collectors and Curiosities: Paris and Venice 1500-1800* (1987; Cambridge: Polity Press, 1990), 53-64, 125-35; Barbara M. Benedict, *Curiosity: a Cultural History of Early Modern Inquiry* (Chicago: Chicago UP, 2002), 52-70; Margaret 'Espinasse, "The Decline and Fall of Restoration Science," *Past and Present* 14 (1958), 71-89. 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: William Andrews Clark Memorial Library, 1983), 35-40.

27 Harris, "Long-Distance Corporations," 274. In 1680 Newton presented a copy of Grew's *Musaeum Societatis Regalis* to his college: John Edleston, *Correspondence of Sir Isaac Newton and Professor Cotes* (Cambridge: Deighton, 1850), xxix.

successive presidents of the Royal Society, between curiosity and natural philosophy, and between astronomy and natural history. We can also, it is to be hoped, better map the information order of the early modern period's knowledge regimes.

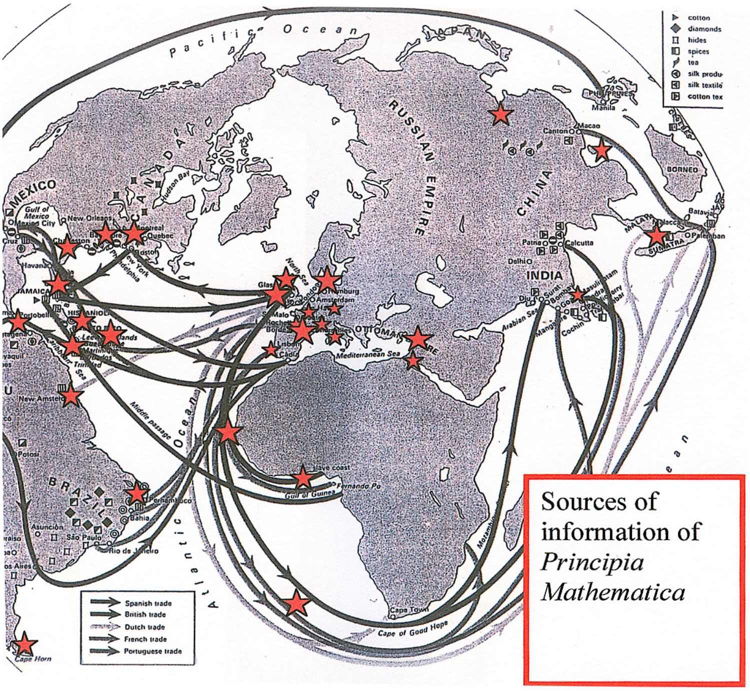

Figure 3. *Sources of information for Newton's Principia Mathematica and the trade networks of early modern European empires*

Tides and Currents: A Tonkin Resolution

Isaac Newton's very first signed publication, in 1672, was a new edition of the definitive geography textbook of the age, the *Geographia generalis* (Amsterdam, 1650) of the great Leiden scholar Bernhard Varenius. Varenius identified geography within mixed mathematics. Newton followed suit, welding the work into a general account of the cosmos. This gives the right geographical reorientation of our image of Newton's programme in its true location.[28] From 1696 he administered the Royal Mint and from 1703 the Royal Society, soon to give him troublesome responsibility for many of the affairs of the Royal Observatory downriver at Greenwich and its brilliant and recalcitrant manager Flamsteed, whose data were vital resources for Newton's work. Newton also stood at the centre of the dramatic 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 work of coiners and clippers, 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. This metropolitan coinage crisis was but one aspect - though a fundamental one - of the settlement of the new Anglo-Dutch regime after the Glorious Revolution of 1688. That regime relied on stable values in its capital, London, 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

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28 Isaac Newton (ed.), *Bernhard Vareni Geographia Generalis* (Cambridge: Cambridge UP, 1672); William Warntz, "Newton, the Newtonians and the *Geographia Generalis Varenii*," *Annals of the Association of American Geographers* 79 (1989), 165-91 on 177. Compare Newton's planned role in John Adams' 1681 English meridian survey: Thomas Birch, *History of the Royal Society*, 4 vols. (London: Millar, 1756), vol. 4, 65-66 (19 January 1681).

29 Simon Schaffer, "Golden Means: Assay Instruments and the Geography of Precision in the Guinea Trade," in Marie-Noelle Bourguet, Christian Licoppe and H. Otto Sibum (eds.), *Instruments, Travel and Science: Itineraries of Precision from the Seventeenth to the Twentieth Century* (London: Routledge, 2002), 20-50 on 35-37; 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: Routledge, 1996), 365-88; Westfall, *Never at Rest*, 623, 862. For communication networks see Burke, *Social History of Knowledge*, 149-76; Ian K. Steele, *The English Atlantic 1675-1740: an Exploration of Communication and Community* (Oxford: Oxford UP, 1986); Daniel Headrick, *When Information Came of Age: Technologies of Knowledge in the Age of Reason and Revolution, 1700-1850* (Oxford: Oxford UP, 2000).

in the engineering of distance, isolation and withdrawal.[29] Such principles also governed the information order of the *Principia Mathematica*.

Expert in monarchical law and MP 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. The final book of Newton's *Principia Mathematica* was where this interpretation counted, in assays of degrees, seconds, miles, inches, observers, experimenters and readers. This account of the "system of the world" was initially and significantly designed to make the *Principia* more popular. Unlike the 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 very wide range of observers.[30] Newton did not achieve the major insights and techniques of his cosmology and celestial mechanics until the early 1680s. The *Principia* was first written during the twelve months to autumn 1685. 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." The Atlantic astronomer and voyager Halley, Newton's first editor, reckoned 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."[31]

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30 Isaac Newton, *The Mathematical Principles of Natural Philosophy*, 2 vols. (London: Motte, 1729), vol. 2, 200 and Newton, *The Principia*, ed. I. Bernard Cohen and Anne Whitman (Berkeley: University of California Press, 1999), 793.

31 Newton, *Mathematical Principles*, vol.2, 201 and Newton, *Principia*, 793; Halley to Newton, 7 June 1686, *Correspondence of Newton*, vol. 2, 434. For composition of the work, see D.T.Whiteside, "Before the Principia: the Maturing of Newton's Thoughts on Dynamical Astronomy, 1664-1684," *Journal of the History of Astronomy* 1 (1970), 5-19; I. Bernard Cohen, *Introduction to Newton's Principia* (Cambridge: Cambridge UP, 1971), 132-35; Westfall, *Never at Rest*, 443-44, 458-62.

After very briefly contemplating omitting all this material, Newton soon made it into the third book of the first edition of his *Principia*. He applied the geometrical principles of unresisted motion under central forces to planetary, lunar, tidal and cometary motions. So it was here that Newton faced the problems of handling numerical observations gathered by others - astronomers, Jesuits, professors, academicians and mariners. In London lectures on the puzzles of cometary observations in the 1660s, Robert Hooke set out exactly the problem of ordering information that Newton must also face: "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."[32]

It was the management of such confounding perplexities and the identification of diligent accuracy in the *Principia*'s final book that drew most attention when the brilliant Cambridge mathematician Roger Cotes began to rework the entire *Principia* between 1709 and 1713. At exactly the same moment, Cotes was working hard with his colleague James Jurin to revise Newton's Varenius edition. The young Cambridge scholars, concerned with geographical knowledge, were also concerned with assessing observers' credit, especially their reports of the lengths of pendulums beating seconds, from which the length of a degree and the Earth's shape could in principle be derived. Jurin even called this puzzle "the French dilemma," because of the variation between different measures of pendulum length reported by French observers.[33]

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32 Robert Hooke, *Lectures and Collections* (London: Martyn, 1678), 22.

33 For Cotes' work as editor, see Westfall, *Never at Rest*, 703-12, 729-51; Cohen, *Introduction*, 227-35. For the French dilemma see James Jurin (ed.), *Bernhardi Varenii Geographia Generalis* (Cambridge: Cambridge UP, 1712), appendix (separate pagination), 3-4 and 40; Warntz, "Newton," 188.

It is suggestive, then, that the enterprises of the Principia's final book raised so clearly issues of the reader response to Newton's work. Consider as an example drawn from a very nearby informant of seemingly undoubted credibility some typically fraught exchanges with the precise, pious and irascible Flamsteed in 1694-5. Newton and his allies wanted at last an adequate lunar theory based on gravitational analysis. They already understood that such a theory would have important implications in navigational astronomy. Newton and his colleague David Gregory visited the Royal Observatory at Greenwich to obtain good lunar data from the Astronomer himself. In the next eight months Flamsteed supplied at least fifty such observations. It seemed hard to persuade Flamsteed of the relation between analysis and observation. "All the world knows I make no observations my self," Newton told the Astronomer, "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 told Flamsteed that the virtues of the *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 fraught. Within a few months, relations collapsed: "I want not your calculations but your observations only," Newton thundered, before exchanges were broken off.[34] 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, and 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

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[34] Newton to Flamsteed, 16 February and 29 June 1695, in *Correspondence of Newton*, vol. 4, 87-88, 134; Westfall, *Never at Rest*, 540-48; Iliffe, ed., *Early Biographies*, xxii-xxiv, 15-17, 186.

proved too great." By 1713 Newton excised two references to Flamsteed that had appeared in the first 1687 edition.[35] This was how hard it was to establish the right relation between calculation and observation, between authorship and gratitude. Similar travails affected most of the data with which Newton's group worked as they sought to make the third book "exact."

In the *Principia* the analysis of lunar motion was set firmly within Newton's remarkable analysis of phenomena of the tides. 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 universal grip of his gravitational model of lunar pull, Newton here faced characteristic troubles of trust in travelers' 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 defensively in 1685, "and it is probable that the Pacific Sea is agitated by the same laws." He had reliable reports about Pacific waters 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."[36]

It is now known that Newton's estimate of the ratio of lunar and solar tides is two times too large. He erred in claiming tides are determined entirely by the vertical component of the disturbing

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35 D. T. Whiteside, "Newton's Lunar Theory: From High Hope to Disenchantment," *Vistas in Astronomy* 19 (1975-6), 317-28. For the removal of Flamsteed's name, compare *Correspondence of Newton*, vol. 4, 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: Cambridge UP, 1972), 658; and Newton, *Principia*, 869-71. For the many 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: Cambridge University Press, 1989), 233-74, on 262-67.
36 Isaac Newton, *A Treatise of the System of the World* (composed 1685; London: Fayram, 1728), 71-72; compare Newton, *Principia*, 835.

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.[37] To estimate numbers meant using the global information order to amass testimony. In the 1710s, faced with threatening rivals to his 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 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.[38]

Tide observations had of course long been an important element in the Atlantic information order. Robert Moray, Scottish traveler and eminent FRS, had already encouraged such 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 tide-mills on the Danube.[39] In their *Directions for Sea Men* published in 1666, the Royal Society demanded tidal measures from as far as New England, St Helena and Bermuda.[40] The same year,

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37 E.J.Aiton, "The Contributions of Newton, Bernoulli and Euler to the Theory of the Tides," *Annals of Science* 11 (1955), 206-23 on 210-13; Newton, *Principia*, 238-46.

38 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*, vol. 5, 243-4, 263-9, 273-5, 278-80.

39 Moray to Bruce, 8 January 1658, in David Stevenson (ed.), *Letters of Sir Robert Moray to the Earl* of *Kincardine* (London: Ashgate, 2007), 113 and Robert Moray, "A Relation of Some Extraordinary Tydes in the West-Isles of Scotland," and Moray, "Considerations and Enquiries concerning Tides," *Philosophical Transactions*, 1 (1665-6), 53-55 and 298-301; Margaret Deacon, *Scientists and the Sea 1650-1900* (London: Academic Press, 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: Cambridge UP, 1983), 404; Newton's notes on these tidal reports in *Philosophical Transactions* are at Cambridge University Library MS Add 3958.1, fol. 9.

40 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* 20 (1965), 28-50, on 32.

in response to a complex philosophical model of tide patterns in the Channel developed by the mathematician John Wallis, Moray proposed a routinised tidal observatory using instruments made by the Royal Society's operator Richard Shortgrave and distributed along the Thames and the Channel coasts.[41] Appraisal of local expertise, in ways made familiar to us in Steven Shapin's account of the trust economy of Restoration England, 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. Across the Marsh, so he learnt,

> " the Sea being kept out with great earthen walls, that it do not at high water overflow the level, and the inhabitants' livelihood depending most on grazing or feeding sheep, they are (as you may believe they have reason to be) very vigilant and observant, at what times they are most in danger of having their lands drowned. And I find them generally agreed by their constant observations (and experience dearly bought) that their times of danger are about the beginning of February and November."[42]

The Baconian astrologer Joseph Childrey similarly appealed to Thames-side inhabitants and to his experience of riverbank flooding. Moray's observatory programme would have relied on "any waterman or other understanding person."[43] When the adept Plymouth observer Samuel Colepresse began his own tide survey,

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41 Moray, "Considerations and Enquiries," 299-301 and Moray, "Patternes of the Tables Proposed to be Made for Observing of Tides," *Philosophical Transactions* 1 (1665-6), 311-13; Deacon, *Scientists*, 99-100.

42 John Wallis, "An Essay Exhibiting his Hypothesis about the Flux and Reflux of the Sea," *Philosophical Transactions* 1 (1665-6), 263-81, on 275-6; Shapin, *Social History of Truth*, 258-66.

43 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* 5 (1670), 2061-8 on 2062-3; Moray, "Considerations and Enquiries," 297-8; Deacon, *Scientists*, 102-8.

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 crucial 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."[44]

It was the data of Colepresse and Sturmy that played a crucial role in the *Principia*'s third book. To calculate the precession of the equinoxes, Newton there 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 quadrature. Here the reliability of putatively local informants was vital. Flamsteed accompanied his own 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." This mattered, because in the 1680s Flamsteed and Newton discussed in some detail whether a soli-lunar model of tidal causation was remotely plausible, and Halley was certainly dubious of Flamsteed's own tide data.[45] When Halley presented a copy of Principia to the monarch James II in 1687, it was tidal

[44] Deacon, *Scientists*, 101-2; Samuel Sturmy, "An Account of Some Observations Made this Present year in Hong-Road within Four Miles of Bristol," *Philosophical Transactions* 3 (1668), 813-17, on 815.

[45] John Flamsteed, "A Correct Tide Table," *Philosophical Transactions* 13 (1683), 10-15, on 12; William Molyneux, "An Account of the Course of Tides in the Port of Dublin," Philosophical Transactions 16 (1686), 192-3; Flamsteed to Newton, 26 September 1685, in *Correspondence of Newton*, vol. 2, 427-8; Flamsteed to Towneley, 12 February 1687, in *Correspondence of Flamsteed*, vol.1, 338.

theory and its global extent that occupied pride of place. 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 his friend John 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.[46] Manipulation of the numbers reported by coastal mariners such as Sturmy and Colepresse dominated these sections of Newton's programme for decades. He could average the numbers from Bristol and Plymouth, as he did in 1685-7; or instead suppress Colepresse's numbers, as he and Cotes did in 1712. "In the calculation of the Moon's force," Newton told his young editor, "your scruple may be eased (I think) by relying more upon the observation of the tide at Chepstow than on that at Plymouth." Newton also decided to "rely" on carefully managed numbers for the varying density of the Earth, working hard until with his assays of the worth of the mariners and the Earth's structure he had a number for the precession which 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 most expert biographer R. S. Westfall. Newton could not tolerate difference between divinely warranted order and such numbers.[47]

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46 Edmond Halley, "The True Theory of the Tides," *Philosophical Transactions* 19 (1697), 445-57 (composed 1686); Alan Cook, *Edmond Halley: Charting the Heavens and the Seas* (Oxford: Oxford UP, 1998), 284-90; 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: University of California Press, 1990), 171-202, on 196.

47 Newton to Cotes, 26 February 1712, in *Correspondence of Newton*, vol. 5, 241. For the manipulation of these tide data, see Richard S. Westfall, "Newton and the Fudge Factor," *Science* 179 (1973), 751-8, on 756-8.

The same kind of 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 period of a fortnight. When the Moon was near the equator, twice a month, there was a period of two days with no tides at all.[48] The writer who first presented these numerical details of the tidal heights at Tonkin 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 yet the best of them all cannot wholly be relied on."[49]

Good East India Company numbers would, perhaps, supplant dodgy 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 Robert Hooke and

48 David E. Cartwright, "The Tonkin Tides Revisited," *Notes and Records of the Royal Society* 57 (2003), 135-42.

49 Davenport to James, 12 July 1678, in "Tonqueen Journal Register," (1678-9), British Library, India Office Records MS G/12/17, part 5, fol. 233v; compare "Tonqueen Journal transcribed 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."

supplier of the Royal Society with its first samples of oriental ganja. The numbers were confirmed, too, when an East India ship, the *Smyrnaote*, was wrecked on the Tonkin bar in early 1683. News of these episodes reached the Royal Society via the London merchant Arthur Bailey FRS in spring 1684.[50] Edmond Halley, a close ally of the Company after his successful St Helena Voyage of 1678, then reprocessed Davenport's data for Royal Society consumption. Halley 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.[51]

Thus the London analysts were presented at a decisive moment in their computations with testimony about one of the most perverse tidal systems in the world. In 1688 the global navigator William Dampier observed on his journey there that "the most irregular tides I did ever meet with are at Tonqueen described at large by Mr Davenport."[52] But by the time Newton turned

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50 Thomas Birch (ed.), *History of the Royal Society*, 4 vols. (London: Millar, 1757), vol. 4, 289-90 (23 April 1684).

51 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* 14 (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. 237-240.

52 William Dampier, *A New Voyage round the World* (London: Knapton, 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.

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 very much in question in fierce London pamphlet wars of 1687-8 that raged after White's piracy brought about the destruction of the entire 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."[53]

Not for the last time, a dubious report from the Gulf of Tonkin by a disreputable American had to be checked for its creditworthiness. Halley, a veteran of the East India Company's ships, and thus Newton, had indeed to depend directly 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.[54] What Newton, Cotes

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53 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: Faber, 1936), 95-99 and 293-6: Davenport "became one of the best-known names in London."

54 Newton, *Principia*, 839; I. Bernard Cohen, "The First Explanation of Interference," *American Journal of Physics* 8 (1940), 99-106, on 105-6; Cartwright, "Tonkin Tides," 137-8.

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

The demonstrations that comets move like planets in conic sections with the Sun in one focus occupied the final propositions of the *Principia* and provided one of its most important achievements. Cometography first drew Newton's attention to the puzzles of astronomy in the 1660s. In the decisive years between 1681 and 1685 his compilation of puzzling catalogues of many 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; as he started compiling natural histories and catalogues of cometary marvels, he began gradually to develop such a notion.[55] His colleagues and informants were exceptionally 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

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55 Henry Guerlac, *Newton on the Continent* (Ithaca: Cornell UP, 1981), 34-40; Simon Schaffer, "Comets and Idols: Newton's Cosmology and Political Philosophy," in Paul Theerman and Adele F. Seeff (eds.), *Action and Reaction* (Newark: University of Delaware Press, 1993), 206-32 on 215-18; Sara Schechner Genuth, *Comets, Popular Culture, and the Birth of Modern Cosmology* (Princeton: Princeton UP, 1997), 133-42; J. A. Ruffner, "Newton's Propositions on Comets: Steps in Transition, 1681-84," *Archive for History of Exact Sciences* 54 (2000), 259-77.

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.[56] As Hooke and Flamsteed, understood, judging credibility mattered a great deal in cometography. 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 up the *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 1664-5 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 Christiaan Huygens to the Royal Society.[57] 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.[58]

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56 Flamsteed to Towneley, 11 May 1677, in *Correspondence of Flamsteed*, vol. 1, 552.

57 Juan Casanovas and Philip C. Keenan, "The Observations of Comets by Valentin Stansel, a Seventeenth Century Missionary in Brazil," *Archivum Historicum Societatis Iesu* 62 (1993), 319-30 on 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: Kluwer, 2003), 249-70, on 260-2 and Camenietzki, "Baroque Science," 316.

58 Newton, *Principia*, 927.

Such critical judgement of past observers was decisive. The historic method Newton concocted relied completely on comparisons between long past observations of cometary transits, especially of shape, position and direction. The aim was to forge a cometary cosmology in which activity and light travelled throughout the heavens, restoring vitality to Earth and confirming the truths of the most ancient philosophy. In late 1682, when Newton and Halley launched this project, Robert 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."[59] In a natural history of comets, appraisal of testimony became indispensable. This mattered especially for Newton, because he was the first to urge the theological and astronomical view that all comets moved round the Sun in elliptical orbits for which parabolas might be good approximations.

Reflect on how he made this claim in his final book of *Principia*. Newton's most important cometary data came from his young editor, Edmond Halley, either directly or via the Astronomer Royal Flamsteed. (**figure 4**) In summer 1679 Halley visited the observatory of Johannes Hevelius in Danzig. The aim of the visit was to allow the Royal Society and the Astronomer Royal to judge the quality of Hevelius' controversial open-sighted instruments *in situ*. This was an assay trip. "Had I not seen," Halley told Flamsteed

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59 Robert Hooke, "A Discourse of the Nature of Comets," (1682) in Richard Waller (ed.), *Posthumous Works of Robert Hooke* (London: Smith and Walford, 1705), 149-90, on 151.

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."[60]

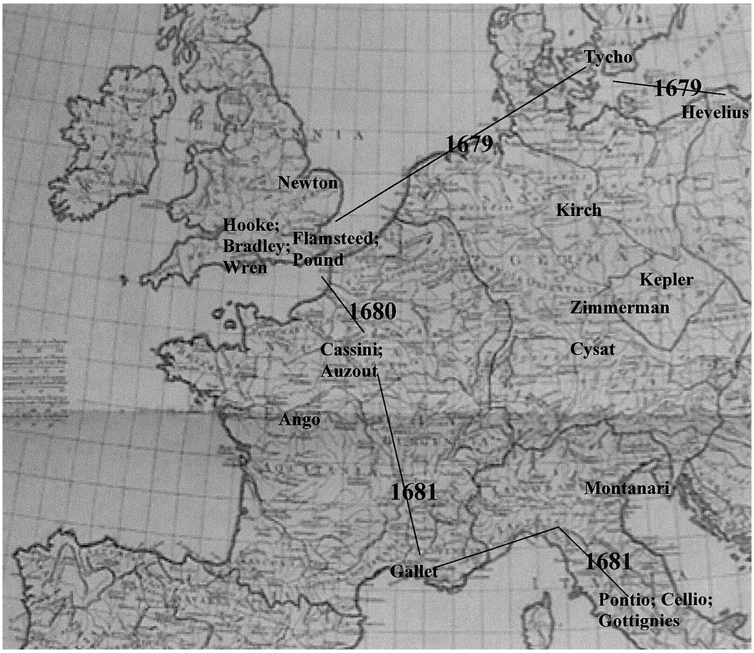

Figure 4. *Edmond Halley's European journeys of 1679-1681 and the sources of cometary observations in Newton's Principia Mathematica.*

Despite this, there remained major queries about Hevelius's work. As Steven Shapin has carefully shown, these doubts were often used to judge the virtue of his cometary and lunar data. "It is our common concern to vindicate the truth from the aspersions of an old peevish gentleman," Halley wrote as late as spring 1686, "who would not have it believed that it is possible to do better

60 Halley to Flamsteed, 7 June 1679, in Eugene Fairfield MacPike, *Hevelius, Flamsteed and Halley: Three Contemporary Astronomers and their Mutual Relations* (London: Taylor and Francis, 1937), 86-7.

than he has done."[61] Halley was despatched to Tycho's ruined observatory at Uraniborg and also went on a tour of France and Italy in 1680-2. In Paris in early 1681 he worked closely with the royal astronomer Jean Dominique Cassini, then much concerned with the great comet of 1680-1681 that Halley himself had first seen on the road to the French capital and whose report Newton then 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 discussed as "remarkable for its size and dreadful in the eyes of the vulgar." Halley himself tried to make a path that would satisfy all the phenomena he got from his Parisian informants, but failed. Here discussions of theories of cometary motion, such as the dubious claim of Cassini that it orbited the Earth with a period of 2 ½ years, were fully integrated into the culture of virtuosity and the lettered.[62]

Halley also gathered from his French colleagues important information about Jean Richer's 1672 expedition to the French base at Cayenne, where Richer found his pendulum clock needed to be shortened to make it beat seconds. Further travels also helped garner key data. At Avignon, Halley met Jean-Charles Gallet whose observations of the 1680 comet there were also to be used in the *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 own astronomers at Ciampini's academy, including Marco Antonio Cellio and Giuseppe Pontio, provided Halley with

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61 Shapin, *Social History of Truth*, 272-87; Halley to Molyneux, 27 March 1686, in Eugene Fairfield MacPike, *Correspondence and Papers of Edmond Halley* (Oxford: Clarendon, 1932), 60.
62 MacPike, *Correspondence and Papers of Halley*, 48-52; Cook, *Halley*, 105-115..

further cometary positions. The clever intelligencer Halley sent Cassini all his latitude data on the road from Paris to Rome, and all the Roman comet observations too. Many of these reached Flamsteed and Newton.[63] All this material was then used in the *Principia*. Back in London by early 1682, Halley then threw himself into astronomical observations and the debates with Hooke that eventuated in Halley's portentous visit to Cambridge in summer 1684.[64] 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 comets' positions and cometary observers.

In his notebooks of 1681-2 Newton soon went back over records from Aristotle, from medieval chronicles and those from informants whom Halley and Flamsteed had appraised themselves. 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."[65] In many cases Newton would seek to exclude data that failed to fit his models, then find rationales from judgements of informants that would help this hostile attitude; sometimes, he would adapt 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

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63 Cook, *Halley*, 119-24, 127; *Correspondence of Flamsteed*, vol. 1, 751-55; Eric G. Forbes, "The Comet of 1680-1681," in Thrower (ed.), *Standing on the Shoulders of Giants*, 312-23, on 313-17. For the Roman milieu see Susanna Åkerman, *Queen Christina of Sweden and her Circle: the Transformation of a Seventeenth Century Philosophical Libertine* (New York: E.J. Brill, 1991), 176-77, 254-55.

64 Cook, *Halley*, 147-51; Westfall, *Never at Rest*, 402-7.

65 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"; Flamsteed to Newton, 25 September 1685 (first draft), in *Correspondence of Flamsteed*, vol.2, 247-8; a later version is at *Correspondence of Newton*, vol.2, 421-8.

proper motion of stars, for example.[66] In the final propositions of the *Principia*, these techniques really counted. Small differences between ellipses and parabolas would only emerge if the database were reliable. Many of the emendations to successive versions of the final sections of the *Principia* were due to the elimination of results that Newton and his collaborators found dubious. 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. "I was the more scrupulous in examining this scholar," Newton wrote, "because I knew not what 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." Newton thus decided to quiz his colleague Humphrey Babington about observations of the comet over the roof of King's College Chapel, showing the tail was 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.[67]

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66 Allan Chapman, "Edmond Halley's Use of Historical Evidence in the Advancement of Science," *Notes and Records of the Royal Society of London* 48 (1994), 167-91.

67 Newton to Crompton for Flamsteed, 28 February 1681, in *Correspondence of Newton*, vol.2, 340-7; compare Flamsteed to Halley, 17 February 1681, in *Correspondence of Flamsteed*, vol.1, 760-763; Flamsteed to Crompton for Newton, 7 March 1681, in *Correspondence of Newton*, vol.2, 348-55. For the redrafts involving French and Roman observers, as well as Hill and Babington, see Koyré and Cohen (eds.), *Principia with Variant Readings*, 717-32.

These were the circumstances in which Newton also helped himself to cometary observations by Flamsteed's correspondent Thomas Brattle in Cambridge Massachusetts, which had been collated in London by Halley before the Harvard astronomer came in person to London in 1682-9.[68] Similar information came from Newton's former Grantham schoolmate Arthur Storer, Babington's nephew. Storer had maintained a 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 1680-1. "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 reported. His observations of what is now known as Comet Halley, that of 1682, are certainly 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.[69] Similar strategies were in play in the case of the Paduan astronomer Geminiano Montanari, a notable disciple of Galilean natural philosophy. Montanari was nevertheless criticised 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

68 Brattle to Flamsteed, 4 June 1681, in *Correspondence of Flamsteed*, vol. 1, 789-90.

69 Peter Broughton, "Arthur Storer of Maryland: His Astronomical Work and his Family Ties with Newton," *Journal of the History of Astronomy* 19 (1988), 77-96, on 92; Newton, *Principia*, 913, 927.

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."[70]

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, and finally to check back predictions from this ellipse against the observations. This was the historic method commended by Newton and practised by Halley throughout the 1690s. This strategy allowed 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 entirely on the conventions of an information order in which knowing positions involved decisions about knowing persons.[71]

The links between assay of locally reliable instruments, persons and God's creation were even clearer in the Newtonian work on the length of isochronic pendulums in Europe, America and in

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70 Hooke, *Posthumous Works*, 154; Koyré and Cohen (eds.), *Principia with Variant Readings*, 730.
71 Shapin, *Social History of Truth*, 287; Edmond Halley, *A Synopsis of the Astronomy of Comets* (London: Senex, 1705), 19 and 21-22.

Africa too. This was treated in proposition 20 of the third book on the weights of bodies in different parts of the Earth and the apparent shortening of such pendulums near the Equator. (**figure 5**) 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."[72]

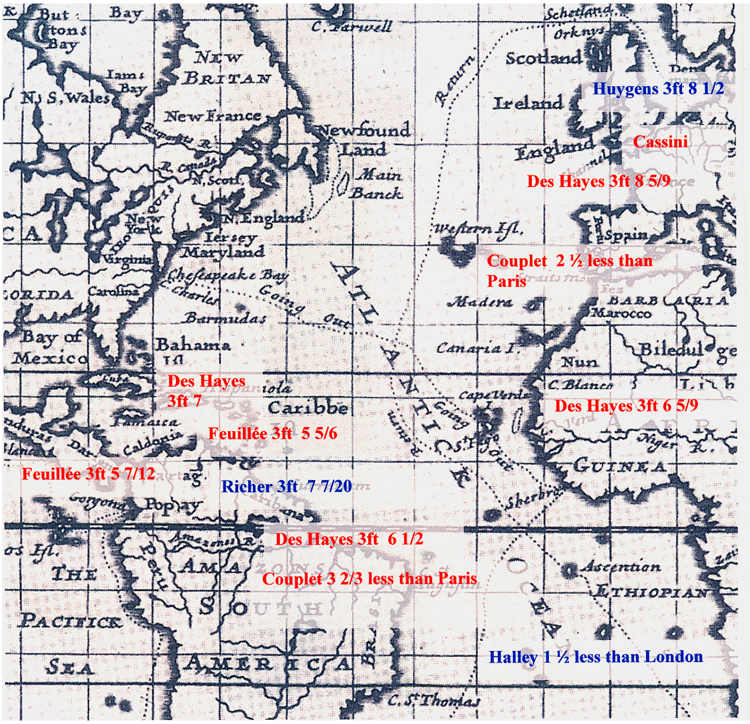

Figure 5. *Sources of information for the length of a pendulum beating seconds, used in Principia Mathematica. Names in red refer to sources mentioned in later editions; numbers refer to estimates of length: Newton claimed these numbers showed a systematic shortening of the seconds pendulum nearer the equator.*

72 Newton, *Principia*, 827.

Newton reworked the proposition with Cotes in spring 1712. Cotes "considered how to make that Scholium appear to the best advantage as to the numbers," notably by crudely averaging across a select sample of 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 an 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."[73] To reach such exactness the *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, when the shortening of the pendulum was first detected, was taken as authoritative in the new *Principia*. His measures allowed the projection from local manipulations of a pendulum clock to the shape of the planet. In the notebook Newton kept in 1681 to collate observations of the great comet of that year, he already recorded the observations that Richer, "sent by the French King," made in Cayenne. These data were very likely passed on directly 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 Royale d'Afrique) "observation was less exact." The delegates sent there, including Jean Deshayes, had bickered. Their confirmatory claim from the tropical slaving fort that pendulums also needed shortening was much doubted

73 Cotes to Newton, 16 and 23 February 1712, in *Correspondence of Newton*, vol. 5, 226, 233.

back in Paris. Richer himself carefully recorded in his 1679 report that in these observations he had even 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 which he then installed at Cayenne on fortuitously placed millstones lying near his observatory.[74] Though, rather like Montanari in Venice, it seemed that Richer's observations had been obscured by clouds, Newton later wrote that this Frenchman's "diligence and caution seems to have been lacking in other observers."[75] One puzzle was the limit that Newton should allow for the difference between pendulum lengths observed in France and at the Equator. Some French numbers fell outside his bound of 2¼ lines (12 lines = 1 Paris inch). In 1684 the chief Parisian astronomer Jean-Dominique Cassini explained the doubt which still surrounded 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."[76]

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74 John Olmsted, "The Scientific Expedition of Jean Richer to Cayenne," *Isis* 34 (1942), 117-28; Nicholas Dew, "*Vers la ligne*: Circulating measurements around the French Atlantic," in Delbourgo and Dew (eds.), *Science and Empire in the Atlantic World*, 53-72, on 60-64, and Dew, "Atlantic Triangulation: the French Scientific Expedition to Gorée and the Antilles, 1681-1683," *International Seminar on the History of the Atlantic World 1500-1800* (Harvard University, 2000), Working Paper 00-19. See Jean Richer, "Observations Astronomiques et Physiques Faites en l'Isle de Caienne," in *Receuil d'Observations Faites en Plusieurs Voyages par Ordre de Sa Majesté* (Paris: Imprimerie Royale, 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*, 116.

75 Newton, *Principia*, 832. Compare Justel to Oldenburg, 16 August 1673, in *Correspondence of Henry Oldenburg*, ed. A.R. Hall and M.B. Hall, 13 vols. (Madison : University of Wisconsin Press, 1965-86), vol. 10, 152-3, cited in Dew, "*Vers la ligne*," 70 n.29.

76 Dew, "*Vers la ligne*," 61-62; Cassini, "Les Elemens de l'Astronomie Verifiez par M. Cassini par le Rapport de ses Tables aux Observations de M. Richer," in *Receuil d'Observations*, 55.

Eventually Newton simply dismissed the astronomer Claude-Antoine Couplet's measures made during a voyage from France via Portugal to Guiana in 1697-8: "he is less trustworthy because of the crudity of his observations." Des Hayes' values from Gorée in West Africa in 1682 and observations at Cayenne in 1700 were once again deemed "less accurate," as were those of the Minim mathematician Louis Feuillée in Martinique and elsewhere in the Antilles in 1704. Feuillée reported that at Porto Bello the differences he found in the pendulum's length "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 which I believed came closest to the true one, 3 feet 5 7/12 lines."[77]

Tropical heat and wind might affect pendulum length, as Newton and Cotes well knew. 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." In 1712-1713 Newton and Cotes agreed that "the differences between the measurements" of the different French authors "are nearly imperceptible" - they amounted to fractions of a line - "and could arise from imperceptible errors in the observations." A decade later, for the final edition of the book, Newton expanded this useful appeal to imperceptible but nevertheless certain local variability. "This disagreement might arise partly from the errors of the observations, partly from the

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77 Newton, *Principia*, 830-2; Louis Feuillée, *Journal des Observations Physiques, Mathématiques et Botaniques*, 3 vols. (Paris: Giffart, 1714-25), vol. 2, 326-7.

dissimilitude of the internal parts of the earth, and the height of mountains; partly from the different temperatures of the air." [78] So the incorrigible variations of humans and of creation were at last used to explain away variations in measures. Then these measures were used to justify a magisterial projection of Newtonian uniformity, to be assayed in its turn by French, Spanish and Swedish surveyors of the Earth's figure in the Andes and the Arctic during the 1730s.[79]

In Heaven as it is on Earth

The way instrumental data were judged in the *Principia* matched the treatment Newton meted out to errant individuals during his period of administration at the Royal Mint. In both regimes, the unreliable and artefactual basis of the system of measures was easy to recognise and important to conceal. Newton's provisional assays of gold and judicious estimates of pendulums were projects in which global uniformities were constructed through precision measures and moral judgments. Making spaces for reliable pendulum measures was like making a space of reliable coin. To pull off such tricks, 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. This was why he sought to make providentialist natural theology the cornerstone of an information order of global scope.[80] So Newton had his own accounts of the relation between mobility, information and reliable informants. At

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78 Newton, *Principia*, 831; compare Cotes to Newton, 23 and 28 February 1712 and Newton to Cotes, 26 February and 3 April 1712, in *Correspondence of Newton*, vol. 5, 234-7, 240-3, 261.
79 Mary Terrall, "Representing the Earth's Shape: the Polemics surrounding Maupertuis' expedition to Lapland," *Isis* 83 (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* 31 (1993), 335-75.
80 Schaffer, "Golden Means," 37-39.

least two projects he pursued from at least the 1680s, at the period when he began composing the *Principia*, helped him make sense of how wide-ranging travel and true knowledge had a divine warrant. He showed that the true cosmology had in ancient times been distributed worldwide by adept voyagers; and he showed that in the millenarian world angelic travellers would freely navigate cosmic space. Neither claim was entirely novel. They drew 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 devised his own 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 the *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.[81] For the *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 judgment he directed at measures of

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81 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: Kluwer, 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: Holmes and Meier, 1982), 15-34; citation from Isaac Newton, "The original of religions," Jewish National Library MS Yahuda 41, fol.4r.

comets, tides and pendulums, and doing so at Cambridge then in London 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 1690s he noted that "the same worship was in use among the Tartars, as William de Rubruquis and John Plancarpinius inform us. And the Indians still keep this sacred fire and call it Human [Vossius]. Benjamin Tudensis found the same fire worshipped in certain islands of the East Indies which he calls Chenerag. And travellers report the same thing of China."[82] 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 1684-5 in the opening sections of Newton's initial drafts of the final book of the *Principia*, "The system of the world," as a lengthy preface to his public treatment of tide and comet data from mariners and mathematicians.[83] The link between the mobile diffusion of cosmic truth under divine inspiration and the restored truth of the Newtonian world was to be made apparent.

We see this process of divine validation of global data management rather well in the most celebrated additions to the second edition of the *Principia*. 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*

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82 Newton, "Original of Religions," fol. 2v.
83 Newton, *System of the World*, 1-4.

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. The *Principia*, in this sense, was a *handbook for travellers*.[84] 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 was "Lord of all" (*universorum dominus*) and that He "ought not to be worshipped under the representation of any corporeal thing." God's supreme authority, rather than His wise plan, was the ultimate guarantee of the constancy and uniformity of Nature: "by existing always and everywhere, He constitutes duration and space, eternity and infinity."[85]

Newton's pragmatic rule of philosophizing 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,

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84 Newton, *Mathematical Principles*, vol.2, 202, and Newton, *Principia*, 198-200, 795. Compare Cohen, *Introduction*, 240-5; Alexandre Koyré, *Newtonian Studies* (1965; Chicago: University of Chicago Press, 1968), 265-6. For the rules in eschatology, see Maurizio Mamiani, "To Twist the Meaning: Newton's *Regulae Philosophandi* Revisited," in Jed Z. Buchwald and I. Bernard Cohen (eds.), *Isaac Newton's Natural Philosophy* (Cambridge, MA.: MIT Press, 2001), 3-14. For application to Atlantic measures see Dew, "*Vers la ligne*," 54-6. Einstein is read as offering a handbook for travellers in Bruno Latour, "A Relativistic Account of Einstein's Relativity," *Social Studies of Science* 18 (1988), 3-44.

85 Newton, *Mathematical Principles*, vol. 2, 390-1 and Newton, *Principia*, 941-2; see Larry Stewart, "Seeing through the Scholium: Religion and Reading Newton in the Eighteenth Century," *History of Science*, 34 (1996), 123-65; Stephen Snobelen, "'God of Gods, and Lord of Lords': the Theology of Isaac Newton's General Scholium to the *Principia*," *Osiris* 16 (2001): 169-208..

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. "If you ask where this heavenly city is, I answer, I do not know. It becomes not a blind man to talk of colours [a phrase to be picked up once again in the General scholium]. Further than I am informed by the prophecies I know nothing…It is not the place but the state which makes heaven and happiness. For God is alike in all places. He is substantially omnipresent, and as much present in the lowest Hell as in the highest Heaven." This was the theme much later reinforced in the 1710s – divine power made the world order knowable through testimony. [86] For Newton, as for his contemporaries, divine uniformity underwrote created variety, and thus underwrote the very possibility of the knowledge regime of which the *Principia* is the towering achievement. Here is how he continued his reflexions on the heavenly city: "As all regions below are replenished with living creatures (not only the Earth with beasts, and sea with fishes, and the air with fowls and insects, but also standing waters, vinegars, the bodies and blood of animals, and other juices with innumerable living creatures too small to be seen without the help if magnifying glasses) so may the heavens above be replenished with beings whose nature we do not understand." The angelic regime outlined by Newton here was an intrinsic component of his information order. This eloquent passage, *ipsissima verba*, gives a rather 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:

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86 Isaac Newton, "The end of the world day of Judgment and world to come," Jewish National Library MS Yahuda 9.2, fols. 139-40.

> "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, 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."[87]

This account of Newtonian information order has some obvious epistemic consequences. Stories about the information order of the *Principia* might help show how such localised distribution ever happens. It might also make sense of the celestial transcendence then attributed to such reasoning. In other words, it would give a better genealogy for the fascinating relation between social mechanisms of testimony and the moral status of solitude. 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.[88] Enlightened and imperial British culture made

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87 Newton, "The end of the world day of Judgment and world to come," fol. 140, transcribed in Frank E. Manuel, *The Religion of Isaac Newton* (Oxford: Clarendon, 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: Collins, 1666), 9. This text was republished in 1681 after Glanvill's death as *Saducismus triumphatus* by Henry More. Newton often reaffirmed his claim that there are "intelligent beings superior to us who superintend these revolutions of the heavenly bodies": see the notes of his conversation with Conduitt in March 1725 in Iliffe, ed., *Early Biographies*, 165.

88 James Thomson, *To the Memory of Sir Isaac Newton*, lines 7 and 190-5; see Fara, *Newton*, 59-97.

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. During the 1780s the radical Anglo-Irish painter James Barry was commissioned to adorn the rooms of the Society of Arts, headquarters of London enlightenment, with images of this order. (**figure 6**)

Figure 6a. *James Barry, "Reserved knowledge", from "Elysium and Tartarus", Great Room, Royal Society of Arts: Newton and an angel in converse with Bacon, Copernicus, Galileo, Descartes and the ancients about the true system of the world.*

Figure 6b. *"Commerce or the Triumph of the Thames", Great Room, Royal Society of Arts: Walter Ralegh, Francis Drake, James Cook and other navigators support the commercial and military triumph of British fleets.*

He depicted on one side *Commerce, or the Triumph of the Thames*, where the paternal deity, wielding appropriate mathematical instrumentation, "connects places the most remote from each other; and Europe, Asia, Africa and America, are thus brought together, pouring their several productions into the lap of the Thames." Opposite and separate was placed an image of what Barry called "reserved knowledge" in *The State of Final Retribution*: there Newton sat conversing with other dead philosophers and an angel about the true model of the world-system.[89] The balance between Newtonian apotheosis and such voyages stayed current.

89 James Barry, *An Account of a Series of Pictures in the Great Room of the Society of Arts* (London: Cadell and Walter, 1793), 59 and 121.

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."[90] The aim here has been to show that the successes of this oddly cognitive voyage depended on the fact that during his voyaging Newton was not and could not be, in any significant sense, alone.

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90 William Wordsworth, *The Prelude* (1850), book 3, lines 60-63. See Thomas and Ober, *A Mind Forever Voyaging*, 47-8.

Author's biographical sketch

Simon Schaffer was trained in natural sciences and the history of science at the universities of Cambridge and Harvard. He was Lecturer in History of Science at Imperial College London between 1981 and 1984 before joining the Department of History and Philosophy of Science at Cambridge where he is now Professor of History of Science. In 1985 he co-authored *Leviathan and the Air Pump: Hobbes, Boyle and the Experimental Life* (Princeton University Press) with Steven Shapin. He has subsequently co-edited books on the history and sociology of experiment, on Robert Hooke, on William Whewell, on the sciences in enlightened Europe and on inquiry and invention in Europe between 1580 and 1820. In 2005 he and Steven Shapin were awarded the Erasmus Prize. Between 2004 and 2009 he was Editor of *British Journal for the History of Science*. In 2008-2010 he holds a Major Research Fellowship from the Leverhulme Trust to research the history of astronomy and British colonialism.

SALVIA SMÅSKRIFTER

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In 2002 the Hans Rausing Professor of History and Science Tore Frängsmyr took the initiative to inaugurate a publication series *Salvia Småskrifter* with the aim to publish lectures arranged by the Office for History of Science at Uppsala University. The coinage *Salvia* is meant in memoriam of Sweden's first scientific book printer *Lars Salvius* (1706-1773) as well as that it refers to a wild growing Swedish plant, *Salvia pratensis*.

Salvia Småskrifter no. 1-9 had been published under the auspices of Tore Frängsmyr. In 2007 the newly installed Hans Rausing Professor at Uppsala University, H. Otto Sibum, took over the editorship.

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   En redogörelse sammanställd av Tore Frängsmyr. (2003)
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