CHAPTER 1

Tidal science before and after Newton

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1. Introduction

I was asked to write on how ideas on the tides have changed through history. That would have been an interesting challenge had David Cartwright's excellent book on the history of tidal science not already existed. That book provides a comprehensive overview of investigations into tides from antiquity to the present day (Cartwright, 1999). Rather less well known is his later journal paper which attempted to make up for omissions in the book due to space limitations (Cartwright, 2001). That paper was concerned with findings during the classical era and up to the 13th century. The two publications of Cartwright taken together provide as much detail as most people would require on the history of investigations into tides up to the Middle Ages.

Not much of note on tides occurred between the 13th and 16th centuries, although the heliocentric theory of Nikolaus Copernicus (1473–1543), published in the *De Revolutionibus Orbium Coelestium* (*On the Revolutions of the Celestial Spheres*) just before his death, was an essential precursor to the Copernican Revolution and so to the work on tides by Kepler, Galileo, and Newton that followed.

Therefore, in the present chapter, I have decided to focus on two contrasting periods in later years (i.e., during the 16–17th and 18th centuries) when there was activity, if not progress necessarily, by a small number of researchers on the tides. These two periods are either side of the great leap forward in tidal insight provided by Isaac Newton. In the first period, science without decent physical theories and without the rigor of mathematics was little more than speculation by a well-resourced few. It was made worse by some investigators forgetting, or choosing to ignore, findings from observations on the tides which had been known for centuries. By the second period, science had benefited from the theoretical insight provided by Newton, although his theory was still not accepted universally.

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Nevertheless, there was now more mathematical rigor to the work, instead of the earlier plethora of (reasonable or unreasonable) speculation, and there was greater attention to observational data. In fact, one example to be discussed, the use of Bernoulli's development of a generic tide table leading to practical tables for northern European ports, involved a combination of both theory and measurements. Nevertheless, there were still important aspects of the tides that had been established previously but were still being forgotten (or ignored) by some people.

Before discussing these two periods in Sections 3 and 5 (with some mentions of Newton in Section 4), Section 2 provides a summary of the main "bullet points" concerning the tides which would (or should) have been known to European researchers after the 14th century. Of course, the tides were also of interest elsewhere, such as in India with its history of astronomy (Kak, 1996), which saw the construction of the first "wet dock" at Lothal in the Indus Valley in the third millennium BCE (Pannnikar and Srinivasan, 1971; Nigam, 2006). However, the focus of the present paper will be on research in Europe. Section 6 provides a contrast of the before and after Newton periods, while conclusions are presented in Section 7.

2. Aspects of the tides known since antiquity

This section summarizes some of the main findings on the tides which had been accumulated up to the 14th century.

- Herodotus (c.484–425 BCE) reported in 440 BCE in his *Histories* that in the Red Sea "there is an ebb and flow of the tide every day" contrasting with the small tides of the Mediterranean (Wright, 1923).
- Aristotle (c.350 BCE) famously tried to understand the four times a day reversals of currents through the Strait of Euripus between Boeotia (mainland Greece) and Euboea Island. Although tidal elevations in most of the Mediterranean are only decimetric, tidal currents in straits can be large (e.g., exceeding 2 m/s in the Strait of Messina, the probable source of the Charybidis whirlpool of Greek mythology). However, in this case and as we know now, weather disturbances would have complicated Aristotle's investigations, as was fully appreciated only recently (Tsimplis, 1997). Aristotle knew that larger tides were to be found in northern Europe than in the Mediterranean.
- From the remarkable (some might say incredible) voyage of Pytheas of Marseille (c.350–285 BCE) in about 325 BCE, from the Bay of Biscay, circumnavigating the British Isles and into the North Sea, and possibly as

far as Iceland, one learned that the tides of the Atlantic were considerably larger than in the Mediterranean. The tides around the British coast were said to have a height of 120 ft (36 m), a gross overestimate which Huntley (1980) claims was typical of tidal observations until the 17th century. Pytheas also observed that there were two high tides per lunar day and that their amplitude depended on the phases of the Moon (spring tides). These findings were published in his book *On the Ocean*, now lost but quoted by other authors. At almost the same time (325 BCE), the army of Alexander the Great was surprised by the large tides of the Indian Ocean and was almost destroyed by a tidal bore on the Indus River.

- Seleucus of Seleucia (Baghdad) or of Seleukia (Red Sea) (190–150 BCE) was an eminent astronomer and an arguer for a heliocentric system. His original writings are now lost but were reported by Strabo and others. He remarked that the two tides each day in the Erythrean Sea (Arabian Sea) were not equal (diurnal inequality) and that the inequality was largest when the Moon was off the equator. Therefore, the tides obviously had some dependence on the Moon.
- Posidonius (135–51 BCE) travelled in about 100 BCE to Gades (Cadiz) on the Atlantic coast of Spain to study the large tides to be found outside the "Temple of Hercules." He found them to be twice daily "in strict accordance with the motion of the Moon." In addition, they were "regular" or "irregular" depending on the Moon's declination (diurnal inequality), with what are now called spring tides separated by neap tides corresponding with New and Full Moons. In these things, he concurred with Seleucus. Based on information from local people, he also concluded (wrongly) that tides are largest at the summer solstice; this implies however that some knowledgeable local person had made an extended set of measurements. His original writings were lost in the fire of the library at Alexandria in 47 BCE but were included in those of Strabo.
- Strabo (63 BCE–24 CE) reported in his *Geography* of 23 CE on many of the previously mentioned findings, and especially on those of Seleucus and Posidonius, for example, that the tides of the Persian Gulf are diurnal and not semidiurnal. He denigrated the reports of Pytheas, calling him "that arch-falsifier," although Pytheas had been supported earlier by the respected geodesist and mathematician Eratosthenes of Cyrene (276–195 BCE). Cartwright (2001) suggests that Strabo's sarcasm of Pytheas probably contributed to the vanishing of his book. Strabo also provided what is arguably the first description of earth tides (water level motion in a well due to tidal strain) based on measurements made by

Posidonius at Cadiz; these observations were unexplained until the work of Chaim Pekeris in 1940 (Ekman, 1993).

- Pliny the Elder (23–79 CE) in his *Natural History* encyclopaedia also examined findings from Seleucus and Posidonius, concluding that the effect of the Sun's tides vary through the year resulting in large equinoctial spring tides. He noted the regular time difference between lunar transit and the next high tide and that the maximum tidal range occurs a few days after New Moon (the age of the tide).
- Harris (1898) mentions that several other Roman writers, including Julius Caesar (100–44 BCE), made the connection between spring tides and Full Moon, with Seneca (3–65 CE) remarking that equinoctial spring tides, when Moon and Sun are in conjunction on the equator, tend to be larger than other spring tides.
- The Greek astronomer and mathematician Claudius Ptolemy (100–170 CE) attributed the phenomenon of the tides to a virtue or power exerted by the Moon on the waters (Hecht, 2019; Wikipedia, 2022a).
- The Venerable Bede of Jarrow Abbey (672–735 CE) made many important observations in a section called On the Harmony of the Sea and Moon in his *De Temporum Ratione* (*The Reckoning of Time*) of 725 (Wallis, 2004). He noticed that in 12 lunar months of 354 days the sea rises and falls 684 times and not 708, so the tide relates primarily to the Moon and not the Sun. He remarked on the progression of the tide down the east coast of England, flowing from the "boundless northern sea," and he observed that every location has its own timing relative to the Moon (now known as its establishment or phase lag). Bede was also aware of the ability of the wind to alter both the time and height of high water. His findings on the relationship between the Moon and the tide were demonstrated in beautiful "tidal rota," which were in effect tide tables (Fig. 1.1) (Edson, 1996; Hughes, 2003).
- Similar notions to those of Ptolemy were espoused by the Persian astrologer Abū Ma'shar (787–886) (Hecht, 2019), while in a book on the *Wonders of Creation*, the Arabian scientist Zakariya al-Qazwani (1203–83) attempted to explain that the flowing tide is caused by the Sun and Moon heating the waters and making them expand. However, he failed to explain the dominant role of the Moon (Ekman, 1993).
- Gerald of Wales (1146–1220) observed that the tides had the same or opposite timings at locations on the Irish Sea coasts in Britain and Ireland, depending on the individual locations, each one with a particular

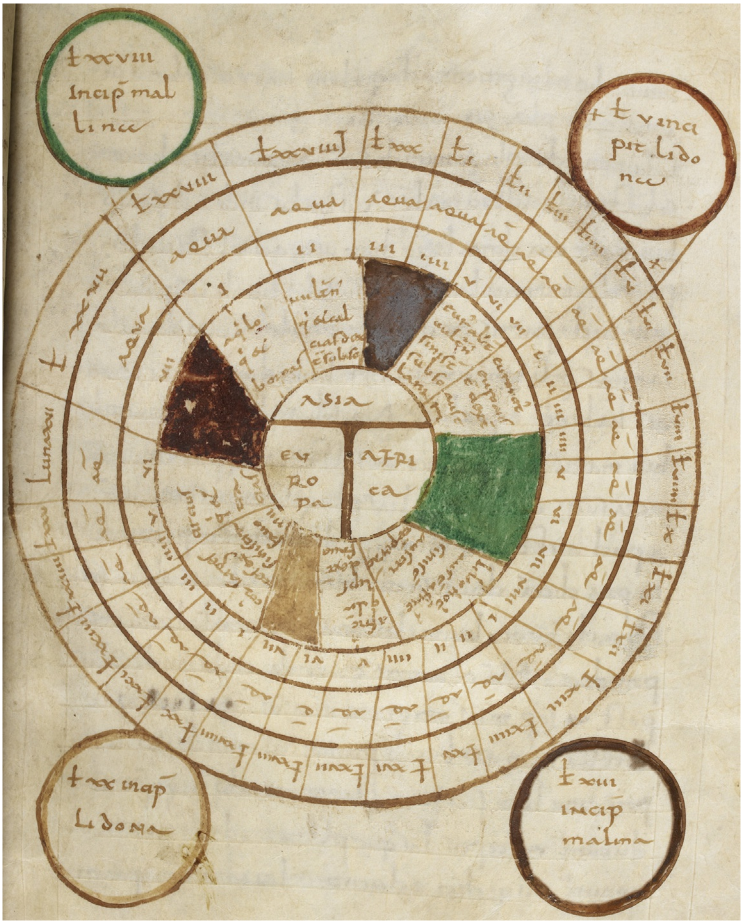


Fig. 1.1 A rota showing the relationship between the Moon and the tide. While Bede's actual text did not refer to diagrams, in some rota "ut Bede docet" (Bede teaches) is printed below them. This rota probably came from the library at Fleury in France in the late ninth century. In the interpretation of Edson (1996), the Earth is in the center, divided into its three continents and surrounded by the winds. The scribe has filled in the names of eight winds, although 12 spaces are provided. The next ring is numbered with the 29 days of the lunar month divided into four parts representing cycles of the tide of 7 or 8 days. The ring beyond labeled "Aqua" may simply be indicating that the tides are the subject of the diagram. The outer ring contains the Moon's age, from 1 to 30 days (L. xxii is missing). The four circles in the corners are marked to show when the highest tides (malina, days 13 and 28) and lowest tides (ledona, days 5 and 20) occur each month. See also the description of this particular rota in Hughes (2003). *(© The British Library Board (MS Harley 3017, f.135r).)*

relationship to the time of passage of the Moon across the meridian. These suggestions were consistent with Bede's ideas of tidal progression along coastlines.

- This leads to the "St. Albans Tide Table" of John of Wallingford for the "flood at London Bridge". Lubbock (1837, 1839) refers to the Benedictine monk John of Wallingford as Abbot John (d. 1213), information that was repeated by Harris (1898), Huntley (1980), and Cartwright (1999). However, it is claimed that this was an error in Lubbock's 19th century sources, resulting in a confusion between the monk John (d. 1245), the actual collector of the manuscript which contained the tide table, and his earlier namesake the Abbot John (d. 1213/4) (Wikipedia, 2022b). Strictly speaking, this was not a tide table based on any observations but assumed the tide to be 3 h 48 min after lunar transit at New and Full Moon, incrementing by 48 min each day. Nevertheless, this demonstrates the unambiguous association now known to occur between the Moon and the tides.

Some of the previously mentioned observations on the tides were accompanied by ad hoc theories for their generation. Seleucus ascribed tides both to the Moon and to a whirling motion of the Earth modified by a "pneuma" (breath or wind). Bede suggested a physical mechanism involving the "Moon blowing on water." Other theories similarly invoked some kind of "breathing," "heating," or "pressing of the atmosphere." For example, Leonardo da Vinci speculated "as man has in him a pool of blood in which the lungs rise and fall in breathing, so the body of the Earth has its ocean tide which likewise rises and falls every six hours, as if the world breathed." Many of these theories implied a somewhat implausible change in the total volume of water in the ocean through the tidal cycle, rather than the transfer of water from place to place during that cycle. Harris (1898), Deacon (1971), Cartwright (1999, 2001), and Parker (2010) may be consulted for more on tidal ideas in antiquity. In particular, Harris (1898) contains an extensive set of notes of tidal work and knowledge before the time of Newton (Chapter 5, pp. 386–409), Newton to Laplace (Chapter 6, pp. 410–421), and Laplace (Chapter 7, pp. 422–437). Although written more than a century ago, Cartwright (1999, Chapter 1) considered Harris (1898) to have been the most thorough review of early ideas on tides. Another historical review written at almost the same time can be found in Chapter 4 of Darwin (1899).

One would like to think that later researchers would have carried away a few basic facts from this earlier body of work, in particular that tides in most places are twice daily and more closely associated with the Moon than the Sun. After all, sailors had known since ancient times that there was some connection between the Moon and the tides, and following the evidence is how science tends to progress. However, this was not always the case, as demonstrated by the set of researchers who preceded Newton in our first period. The work of that small number of investigators is covered by only a few pages in Chapter 4 of Cartwright (1999) so they are worth revisiting.

3. Investigations of the tides before Newton

Our story can start with Johannes Kepler (1571–1630), one of the key figures in the scientific revolution of the 17th century. Kepler is famous for his three laws of planetary motion which modified and extended the heliocentric theory of Copernicus and which were later shown by Newton to be consistent with his own three laws of motion and the law of universal gravitation. Harris (1898) mentions that Kepler was forming objections to the tidal ideas of Galileo (see later) as early as 1598. In his *De Fundamentis Astrologiae Certioribus* (*On The More Certain Fundamentals of Astrology*) of 1601, Kepler noted that "all things swell up with the waxing Moon and subside when she is waning". In this book, Kepler made what is thought to be the first mention of a 19-year variation in the tides (see Thesis 47 in the translation of Brackenridge and Rossi, 1979). Whether he had in mind the nodal or, more likely, the metonic cycles of the Moon (periods of 18.6 and slightly more than 19 years, respectively) is not clear. Both would have been known since antiquity, but in fact only the former is important for tides. Nowadays, a book on astrology by such a famous astronomer might seem strange. However, at that time astrology and astronomy were treated together. Kepler himself earned a living from reading horoscopes. However, he was not completely convinced by them, maintaining that "If astrologers sometimes do tell the truth, it ought to be attributed to luck" (CDSB, 2008). In Kepler's last book, a novel called *Somnium* (*Dream*), published posthumously in 1634 but actually written in 1608, he speculated in a clear modern-sounding way "the causes of the ocean tides seem to be the bodies of the Sun and Moon attracting the ocean waters by a certain force similar to magnetism. Of course, the body of the Earth likewise attracts its own waters, an attraction which we call 'gravity'."

A year later, Kepler's axioms for a "true theory of gravity" in his *Astronomia Nova* of 1609 included the need for attraction between the Earth and Moon. For this, he looked to a form of magnetic attraction, having been inspired by the publication of William Gilbert in 1600 concerning the magnetic field of the Earth (Ekman, 1993; Fara, 1996; Hecht, 2019; Wikipedia, 2022a). As for the tides, he stated "If the Earth ceased to attract (to itself) the waters of the sea, they would rise and pour themselves over the body of the Moon." As a result, he claimed that the tides would be excited "insensibly in enclosed seas, but sensibly where there are broad beds of the ocean."

Kepler's interpretation later took an apparently backward step when the expression of his astrological views in the *Harmonices Mundi* (1619) led to him interpreting the tides in terms of the mystical breathing of terrestrial animals and especially the breathing of fish. The CDSB (2008) states that at this time "swept on by his fantasy, Kepler found animistic analogies everywhere". In addition, Scientific American (1858) reported that Kepler "believed that the earth was a real living animal, that the tides were due to its respirations, and that men and beasts were like insects feeding on its back" but ignored his earlier support for an attraction such as magnetism. However, it does not follow that Kepler had renounced his earlier views of attraction (magnetic or gravitational) (Harris, 1898).

There is much more to be said about Kepler. Recent reviews of his life and works can be found in Hecht (2019) and Wikipedia (2022c). It is important to realize how difficult it was for other thinkers to grapple with the idea of attraction or "action at a distance" by some mysterious force such as that proposed by Gilbert or Kepler. For some it almost smacked of the occult ("Occult" is an Aristotelian and early modern term used when distinguishing qualities which are evident to the senses from those which are hidden (Roos, 2001).). In particular, the idea was ridiculed by Galileo who considered it "to be a lamentable piece of mysticism which he read with regret in the writings of so renowned an author as Kepler" (Thomson, 1882).

Galileo Galilei (1564–1642) was a champion of the Copernican revolution (Wikipedia, 2022d). He has been called the "father of the scientific method" which, to modern ears, suggests greater attention to reconciling theory with data than was the case with his theory of the tides published in the *Discourse on the Tides* of 1616 and the *Dialogue Concerning the Two Chief World Systems* of 1632. Galileo completely dismissed Kepler's belief that tides were caused by the Moon, a simple fact that had been known since antiquity.

Galileo's theory of the tides has been discussed in the literature far more extensively than have most incorrect theories (e.g., Aiton, 1954, 1963; Burstyn, 1962, 1963; Aiton and Burstyn, 1965; Shea, 1970; Palmieri, 1998). Roos (2001) commented that "there is a virtual academic industry on Galileo and the tides." The many publications are undoubtedly a reflection of

Galileo's otherwise considerable scientific achievements. Galileo persisted with his theory of the tides over many years, even though it is likely that he knew it may be incorrect (Wikipedia, 2022e). The theory has since been categorized, rather kindly, as a "fascinating idea" as a result of the overriding need to provide evidence for the motion of the Earth (Einstein, 1954). Otherwise, it has been described as "Galileo's big mistake" (Tyson, 2002).

In trying to defend the Copernican theory, Galileo suggested that the tides were due to the Earth's rotation around its axis and its orbital motion around the Sun (Fig. 1.2). The principal causes of them were said to be (1) "… the determinate acceleration and retardation of the parts of the Earth, depending on the combination of two motions, annual and diurnal; …" and (2) "… the proper gravity of the water, which being once moved by the primary cause, then seeks to reduce itself to equilibrium, with repeated reciprocations..". See Aiton (1954) and Cartwright (1999) for explanation of how such an argument is confused by the mixture of reference frames. Galileo correctly pointed out that large tidal ranges tend to be accompanied by weak tidal currents (and vice versa), characteristic of standing waves, and somehow advanced this observation on the "varieties of tides" as a

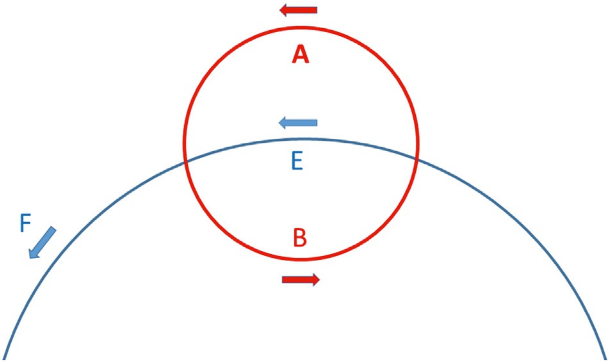


Fig. 1.2 Galileo's theory of the tides was based on his observations of the seiche-like motions of water slopping in a barge when subjected to an acceleration. He attempted to explain the tides by suggesting that the ocean "cavities" (or basins) were similarly subject to such accelerations. EF represents part of the Earth's orbit around the Sun (period one cycle per year) and its rotation is shown by the arrows (period one cycle per sidereal day). At point A, the annual and diurnal motions are in the same sense, while at point B they are opposite. The absolute speed (relative to the Sun) is therefore greater at A than B, and consequently each part of the Earth's surface is alternately accelerated and decelerated. *(Adapted from Aiton, E.J. 1954. Galileo's theory of the tides. Ann. Sci., 10, 44–57, https://doi.org/10.1080/00033795400200054.)*

confirmation for nonuniform movement (accelerations) implied by his theory (Harris, 1898).

The most obvious problem with Galileo's theory was that it suggested one (and not two) tides per solar (and not lunar) day. In other words, it suggested the tides to be dominated by what is nowadays called an S1 (solar diurnal) rather than an M2 (lunar semidiurnal) component. The theory therefore failed on two major counts, as had been pointed out to Galileo by Kepler. Galileo hand-waved these problems aside. Cartwright (1999) explained that Galileo was not convinced of the evidence for two tides per (lunar) day at most locations, thereby ignoring the findings of Posidonuius and others, and instead could have been influenced by the tide at Venice having a strong diurnal component. Polli (1952) lists the amplitudes of the M2, S2, K1, and O1 constituents at Ponta della Salute as 23, 13, 16, and 5 cm, giving a Form Factor for the Venice tide of 0.58, which implies a "mixed, mainly semidiurnal" tidal regime (Pugh and Woodworth, 2014).

Harris (1898) points out that, to be fair, Galileo had been contemplating a treatise on the theory of the tides, but that the religious persecution of the time would not have enabled him to continue with his scientific work. So we have to wait until much later (1666) when an extended version of Galileo's theory was proposed by John Wallis (1616–1703), Professor of Geometry at Oxford (Deacon, 1971). Wallis was concerned by the lack of association of the tides to the Moon in Galileo's theory. He observed correctly that it was the center of gravity of the Earth-Moon system which orbits the Sun. As a consequence, the tides result from the Earth's rotation combined, not only with the Earth's motion around the Sun but also with rotation around the center of gravity. Wallis's suggestion thereby inferred one tide per lunar day, an improvement on Galileo's one tide per solar day, but still not two tides. Wallis (1666), published in the first volume of the *Philosophical Transactions of the Royal Society*, has the distinction of being the first paper on tidal theory to appear in a scientific journal.

A contemporary of Gilbert was Sir Francis Bacon (1561–1626), Lord High Chancellor of England 1617–21 (SEP, 2021; Wikipedia, 2022f). Bacon claimed that "knowledge is power" and was a deep-thinking individual with a vast range of scientific interests. (There was also a 19th century suggestion called the "Baconian Hypothesis" that Bacon was the real author of Shakespeare's plays.). He is sometimes called the "father of empiricism" and his ideas published in his influential novel *New Atlantis* in 1626, for example, are considered as guiding spirits leading to the founding of the Royal Society in 1660 (Fig. 1.3). He believed that knowledge should be

Fig. 1.3 An etching by Wenceslaus Hollar, after John Evelyn, frontispiece to *The History of the Royal-Society of London* by Thomas Sprat (1667). On the left is William Brounckner, a mathematician and the first President of the Royal Society; in the center, King Charles II (1630–85); on the right Francis Bacon, 1st Viscount St Alban (1561–1626), philosopher and Lord Chancellor. *(©National Portrait Gallery, London.)*

based only on careful observations of nature and on inductive reasoning. The Baconian Method, the first formulation of what is now called the scientific method, was introduced in his *Novum Organum* (*New Method*) of 1620 and is still of research interest regarding tides and other phenomena (Schwartz, 2017). He is said to have lost his life to pneumonia while researching the effects of freezing on meat preservation.

Bacon began his essay of 1623 *On the Flux and Reflux of the Sea* by recognizing the daily, half-monthly and monthly cycles of the tides, and a half-yearly cycle with greater tides at the equinoxes than at the solstices (Shea, 1970). He suggested that the apparent monthly and annual variability in the tides would be similar everywhere, as is the case. He also noted the progressive wave nature of the tides as they propagated south to north along the eastern coast of the North Atlantic, similar to the observations of Bede along the east coast of England. He made the case for observations elsewhere. Galileo made similar comments on tidal progression although Bacon is believed to have arrived at his own conclusions before news of Galileo's theory reached him (Aiton, 1954). Aiton (1954) states "This idea that the tides depend on the progressive movement of water and not on any alteration of its physical state is the only positive contribution made by either Bacon or Galileo to the solution of the problem of the tides."

Bacon was one of Galileo's earliest opponents because of the former's Ptolemaic Earth-centered, rather than Copernican, perspective. However, in common with Galileo, he seems to have ignored the evidence of tidal cycles and the role of the Moon when it came to devising his theory for the tides. Bacon asserted "I am fully persuaded, and take it almost as an oracle, that this motion (the tides) is of the same kind as the diurnal motion (of the Earth)." As a result, his explanation for the tides involved diurnal motion only, rather than the diurnal and annual combination of Galileo. He observed that all (or most) heavenly bodies moved from east to west every day and the motion was greatest in the heavenly sphere of the fixed stars. Each sphere was considered to affect the motion of the sphere below (i.e., the various planets) with motion decreasing downwards. One eventually reached the level of the atmosphere with its east to west movement of the Trade Winds. Similarly, he considered that ocean currents (however generated) would be a simple westward flow in the absence of continents. The tides occur in this theory as a result of the obstruction of these currents by the continents, where they are reflected and so cause the observed ebb and flow. Because of the westward motion, tides in gulfs or bays which open toward the east on the western sides of ocean basins should have larger tides than elsewhere. In common with Galileo, he had no explanation for the observed two lunar tides per day, claiming that the period was nothing to do with the Moon but was determined by the dimensions of the Atlantic in some kind of resonance akin to the sloshing of water which had led to Galileo's theory. This sort of idea was not new. The Italian scientist Julius Caesar Scaliger (1484–1558) had suggested some kind of trans-Atlantic resonance (or "seiche") mechanism in 1557 (Ekman, 1993) (See Harris (1898) for more information on Scaliger.). Aiton (1954) provides a discussion of the theories of both Bacon and Galileo and the widespread controversy about them at the time. He points out that while Galileo's theory of the tides was a failed attempt to prove, once and for all, the validity of the Copernican system, so Bacon's theory was ultimately a failed attempt to provide conclusive evidence for the Ptolemaic (or Aristotelian) perspective.

Some years later (1651), a theory of the tides by William Gilbert (1544–1603, Wikipedia, 2022g) was published posthumously (in Latin) in *A New Philosophy of Our Sub-Lunar World*. Gilbert had previously proposed that the Earth acts like a large magnet, as published in *De Magnete* in 1600 (Fara, 1996). He now suggested that the orbits of the planets and the tides were determined by magnetism, and similarly "The Moon produces the movements of the waters and the tides of the sea…" (Ekman, 1993; Hecht, 2019). Bryant (1920) states that Gilbert did not suggest explicitly that there was an attraction between the Moon and water, but more vaguely that "subterranean spirits and humors, rising in sympathy with the Moon, cause the sea also to rise and flow to the shores and up rivers." Although the lunar, rather than solar, connection was recognized here, the twice daily character of the tides remained unexplained.

It is perhaps surprising from a modern perspective to find magnetism, rather than gravity, discussed so much in the context of history of the tides, and to find that Gilbert and then Kepler, among others, had been inspired to propose magnetism as a mechanism for them. However, Fara (1996) explains how the *De Magnete* of Gilbert was adopted widely as a "magnetic philosophy" that was a central part of 17th century thinking. In addition, Athanasius Kircher (discussed later) was an expert on many philosophical (and apparently magical trickery) aspects of magnetism including a magnetic map of the world (Glassie, 2012; Udías, 2020). Newton's writings included only passing references to magnetism, and yet he was interested enough to own a magnetic signet ring mounted with a powerful chip of lodestone. On a more practical level, by the 18th century we find William Hutchinson, the Liverpool dockmaster, making the case for better magnets in compasses for negotiating the tides (Hutchinson, 1777).

It is interesting that, after all this body of work and only a couple of decades before Newton's *Principia* was published, respected (in some places) investigators were still coming up with what are now seen to be absurd ideas for the tides. In his book, Cartwright (1999) remarks that it would be "unnecessary [for him] to enlarge on some quite unscientific theories of the tides.”. However, to omit them completely would present a perspective of investigation at that time through a filter of modern insight. Therefore, it seems worthwhile to mention a couple of them here who had a following at the time.

Anthanasius Kircher (1602–80) has been described as either “a master of a hundred arts” in his own opinion, or “more of a charlatan than a scholar” in that of René Descartes (Brauen, 1982; Findlen, 2004; Glassie, 2012; Wikipedia, 2022h). Either way, he was a fascinating and influential character with interests in many things (especially geology as mentioned later), extremely well-read and a prolific writer with over 30 books, making use of an enormous amount of scientific evidence (real or manufactured) sent to him in Rome by other Jesuits around the world. In line with the religious doctrine of the time, he opposed the Copernican heliocentric proposition and its assumption in the astronomical work of Gilbert and Kepler. He considered their scientific fallacies “pernicious to the Christian Republic and dangerous to the faith of the church” (Baldwin, 1985). Nevertheless, he communicated with a large number of the most important scientists of the mid-17th century via what was called the *Republic of Letters* (Wikipedia, 2022i). His name is largely forgotten today, probably because, it has to be said, most of his ideas were ridiculous.

In the *Mundus Subterraneus* (*Underground World*) of 1665, Kircher covered a vast range of Renaissance science and pseudoscience, seeking rational causes for various phenomena through an understanding of natural laws derived from observations rather than miraculous explanations (Wikipedia, 2022j). This lavishly illustrated publication can be inspected at Internet Archive (2022). The mythical whirlpool of Charybdis in the Strait of Messina near the Scylla rock in Calabria, first mentioned by Homer, is discussed at the end of Book 2 (of 12) in terms of winds driving water through an underground channel linking the two sides of Sicily in which they are heated by Mount Etna. Book 3 of 12 is concerned with wider aspects of hydrography. Section 1 discusses general properties of the ocean including its general east to west motion. Tides are covered in Section 2 in which it is clear that Kircher appreciated the basic astronomy of the Moon returning to its apparent position after about 25 h and the combined roles of Moon and Sun in the cycle of New, Quarter, and Full Moons. He knew that the tides had a diurnal and monthly character to them (from which we understand semidiurnal and semimonthly), and he was aware of the large tides outside the Mediterranean such as those experienced by Alexander the Great. He suggested that tides were caused by the effect of the Moon on the light of the Sun. The pure light of the Sun would be infected with a "nitrous quality" as it is reflected off the Moon and, passing to the Earth, causes turbulence and a rise in the level of the sea. As a result, the "nitrous effluvia of the Moon" causes water to be pushed and pulled through a global network of "hidden and occult passages" (a main topic of the *Mundus Subterraneus* discussed at length in the *Pyrographicus* of Book 4).

Section 2 of Book 3 also contains descriptions of different tides at several places including the high tides of London, which he describes (quite reasonably) as due to the tides of Atlantic restricted by passage up the English Channel. It is believed that Kircher probably got his information about the London tides from Sir Robert Southwell (a diplomat, later to be President of the Royal Society) or an earlier English visitor to Rome such as the diarist John Evelyn (1620–1706), another of the founders of the Royal Society (Brauen, 1982; Reilly, 1974). In addition, he refers to the tidal vortex (maelstrom) off the north coast of Norway, located adjacent to another supposed underground passage beneath Scandinavia connecting the Atlantic with the Gulf of Bothnia.

He maintained that proof of all this could be demonstrated by observing the "nitrous quality" of the Moon in a small benchtop experiment involving the Moon shining on a basin of sal ammoniac (ammonium chloride). He claimed that an infusion of that volatile salt "placed obliquely to receive the Influence of the Moon ... did Increase and Decrease as it held of an equal Correspondence, by an uninterrupted Chain of Atoms, with the Flowings and Ebbings of the Marine waters." Furthermore, the effect would be stronger on a moonlit night when the two luminaries (Sun and Moon) were in conjunction or opposition. Roos (2001) suggests that behind his idea might have been the fact that ammonium chloride is hygroscopic. However, the experiment was tried at the Royal Society by Henry Oldenburg (its first Secretary and the first editor of the *Philosophical Transactions*) and Robert Boyle (one of the founders of modern chemistry), with a visit by Sir Robert Moray (one of the founders of the Society) to see how successful it was (Reilly, 1974; Glassie, 2012; Roos, 2001). Moray had dissolved an ounce of "Bay Salt" and another of niter (saltpeter) in two-and-a-half pints of water and, after staring at it for half an hour, was rewarded with only a few bubbles. Boyle then had his assistant repeat the experiment for two full nights, again a failure. Moray told Oldenburg that he should not bother to communicate such negative experimental results to the *Philosophical Transactions* "knowing your moments may be better employed," while Oldenburg concluded that, this first of experiment of Kircher having been a failure, it was likely that all the others in *Mundus Subterraneus* would be also.

A similar-sounding idea was proposed by the English poet and writer Thomas Philipot (d. 1682). His idea can be considered as independent of Kircher's, and Philipot would probably have been unaware of the Royal Society experiments. He produced his 1673 essay on a chemical theory of the tides, partly as a (justifiable) criticism of Galileo and Kepler and most of the other theories that preceded Newton. The essay included a review of the many competing ideas at that time. He proposed that the "flux of the tide" (its rise) was due to volatile salts "armoniack salt or spirit, that is wrap'd up in the Bowels of the Sea" that were released by the "Impressions of the Sun and Moon." For the "reflux of the tide," (its fall) he invoked the action of the "spring of the air," which was Boyle's term for air pressure. One should read Roos (2001) for an explanation of the justifications for his theory in the context of the time. His arguments can be considered as a contribution to the then general interest in the chemistry of salts involving Boyle and others, and, as Philipot himself remarked, his theory of the tides was no less absurd than the breathing animal of Kepler.

But to return to Kircher, one aspect of tides for which he does deserve credit is his suggestion of the use of a float and stilling well for tidal measurements, a simple technology that remains in use at many locations around the world (Woodworth, 2022). A drawing can be found in Book 3 of the *Mundus Subterraneus* (Fig. 1.4). The same suggestion was made at almost the same time by Sir Robert Moray in a paper that was also published in the first volume of the *Philosophical Transactions* (Moray, 1666). Moray is usually given the credit for the idea, but the two suggestions may not have been a coincidence. Moray is known to have read Kircher's 1641 book *Magnes Sive de Arte Magnetica* (*The Lodestone, or the Magnetic Art*), while a prisoner of the Duke of Bavaria in 1643–45. Glassie (2012) states that this began a set of correspondence between Moray and Kircher which lasted decades. For example, Moray's observations of the tides in the Hebrides, published in the same first volume of the *Philosophical Transactions* (Moray, 1665), is mentioned in Book 3 of the *Mundus Subterraneus*. Therefore, it is quite possible that they corresponded about the stilling well idea.

Lalande mentions Moray's tide gauge and the instructions for its use (Lalande, 1781). Lalande also mentions a similar instrument which had been described in an Italian journal in 1675. A summary and diagram derived from that report can be found in the *Journal des Sçavans* of 22 April 1675 (page 118, https://gallica.bnf.fr/ark:/12148/bpt6k56526h/f107.item). This was the earliest academic journal in Europe, starting in January 1665 shortly before the *Philosophical Transactions* in March.

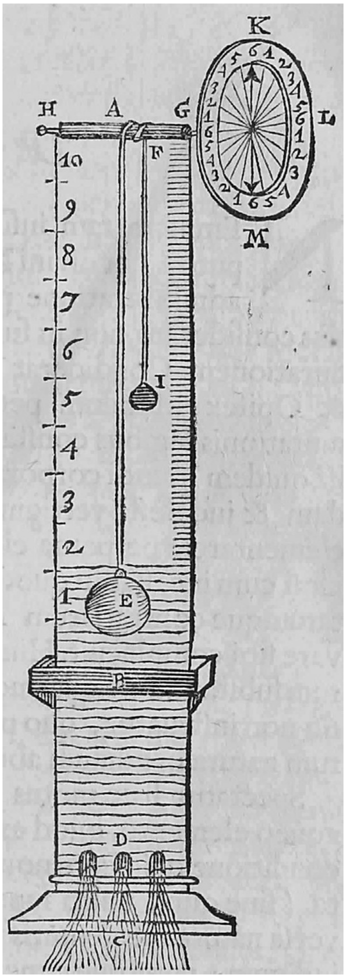
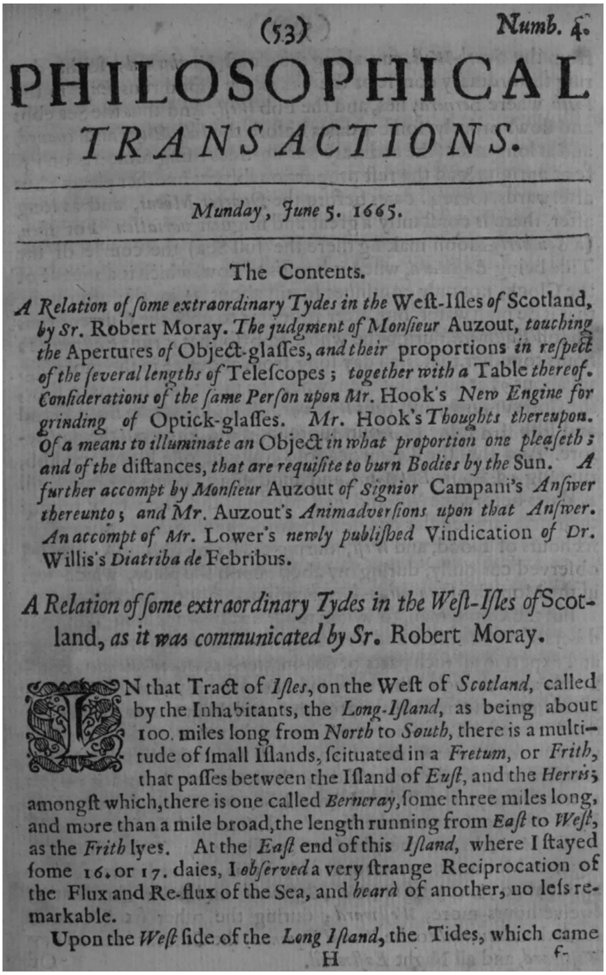


Fig. 1.4 A diagram of a float and stilling well tide gauge on page 157 of Book 3 of the *Mundus Subterraneous* by Athanasius Kircher (Kircher, 1665). *(Image courtesy of the Herzog August Bibliothek, Wolfenbüttel, Germany.)*

Moray (1665) was the first paper on tides to appear in a scientific journal (Fig. 1.5), while Wallis (1666) could be said to be the first paper on tidal theory. Moray (1665) pointed to tidal currents between islands in the Hebrides, as observed by himself and local fishermen, being diurnal in an otherwise semidiurnal tidal regime, an aspect which was not fully understood until recently (see Chapter 13 of Cartwright, 1999). Moray was apparently not pleased that Kircher had printed the contents of a letter informing him of



(53) **Numb. 4.**

PHILOSOPHICAL TRANSACTIONS.

Munday, June 5. 1665.

The Contents.

A Relation of ſome extraordinary Tydes in the Weſt-Iſles *of* Scotland, *by Sr.* Robert Moray. *The judgment of Monſieur* Auzout, *touching the* Apertures *of* Object-glaſſes, *and their* proportions *in reſpect of the ſeveral lengths of* Teleſcopes; *together with a* Table *thereof. Conſiderations of the ſame Perſon upon Mr.* Hook's *New Engine for grinding of* Optick-glaſſes. *Mr.* Hook's *Thoughts thereupon. Of a means to illuminate an* Object *in what proportion one pleaſeth; and of the* diſtances, *that are requiſite to burn Bodies by the* Sun. *A further accompt by Monſieur* Auzout *of Signior* Campani's *Anſwer thereunto; and Mr.* Auzout's *Animadverſions upon that Anſwer. An accompt of Mr.* Lower's *newly publiſhed* Vindication *of Dr.* Willis's *Diatriba de* Febribus.

A Relation of ſome extraordinary Tydes in the Weſt-Iſles of Scotland, *as it was communicated by Sr.* Robert Moray.

IN that Tract of *Iſles*, on the Weſt of *Scotland*, called by the Inhabitants, the *Long-Iſland*, as being about 100. miles long from *North* to *South*, there is a multitude of ſmall Iſlands, ſcituated in a *Fretum*, or *Frith*, that paſſes between the Iſland of *Euſt*, and the *Herris*; amongſt which, there is one called *Berneray*, ſome three miles long, and more than a mile broad, the length running from *Eaſt* to *Weſt*, as the *Frith* lyes. At the *Eaſt* end of this *Iſland*, where I ſtayed ſome 16. or 17. daies, I *obſerved* a very ſtrange Reciprocation of the Flux and Re-flux of the Sea, and *heard* of another, no leſs remarkable.

Upon the *Weſt* ſide of the *Long Iſland*, the Tides, which came

H ſ-

Fig. 1.5 The first page of Moray (1665), the first paper on tides in a scientific journal.

the Hebrides tides. Oldenburg wrote to Moray that he was disappointed that Kircher had been unable to explain their strange character and probably considered that the measurements were defective (Reilly, 1974).

If there had been a prize for best theory of the tides at this time, similar to that discussed in Section 5, then the possible winner would have been René Descartes (1596–1650), often called “the father of modern philosophy” (Wikipedia, 2022k). His theory of 1644 was the only one to suggest two tides per lunar day, based on a decent attempt at a physical theory of attraction. Aiton (1954, 1955a) and Cartwright (1999) explain how the heliocentric theory accepted by Descartes had the planets pulled along in their orbits by a vortex of a rotating ether-like medium generated in turn by a rotating Sun. Similarly, the Earth's rotation inputs its own local vortex into the ether which carries the Moon along in its monthly orbit. The tides were due entirely to the Moon and occurred through the center of the vortex being displaced slightly from the center of the Earth (a suggestion that was over 20 years in advance of Wallis's concept of an Earth-Moon center of gravity displaced from the center of the Earth). Rather than explaining the spring-neap cycle as a combination of lunar and solar attraction, Descartes invoked what was then a well-known but small solar perturbation in the Moon's orbit called "variation." This perturbation is now known to lead to a minor tidal constituent called μ2, much too small to account for the observed spring-neap cycle. One problem with the theory was that it suggested the passage of the Moon to be accompanied by a low, rather than high water. However, given the known lags in the real tide behind the Moon, this was not necessarily seen as a problem.

Newton later demonstrated the theory of Descartes to be incorrect, being inconsistent with Kepler's third law of planetary motion, and with the fact that any planet carried along by a vortex would have to have the same density and motion as the vortex medium itself. Nevertheless, unlike the hand-waving of some other previous investigators, this was enough of a theory to lend itself to ongoing discussion and development. It survived even after Newton's death, being the basis of the theory of Antoine Cavalleri in the 17th century (Section 5), its "action by contact" approach being more palatable for some than the "action at a distance" of Newton's theories.

Some of the previously mentioned investigators realized that if progress was to be made then more measurements of the tides were required. Several of the more important of these associated with the Royal Society in London and by the *Académie Royale des Sciences* in Paris are described in Chapter 6 of Cartwright (1999). For example, Wallis had failed to see why tides should be larger at the equinoxes, a feature of the tides which seems obvious now. Instead, he persisted with reports of them being larger in February and November. This controversy following his 1666 publication led to a call for more measurements of both high and low water heights through the year at ports as close to the open sea as possible (Deacon, 1971). A number of other reports had been inconclusive, largely because of the difficulty of separating tides from the effects of winds and river runoff in short and imprecise sets of measurements. In particular, the publication of Joshua Childrey (1670) rejected Wallis's claim of tides being larger in February and

November, suggesting also that those observations had been the effect of winds rather than tides. He stated that English seamen as a rule believed the largest tides to occur at the equinoxes. In addition, he was the first to observe that high tides also tend to occur when the Moon is close to perigee, in addition to the spring-neap periodicity, resulting in “perigean spring tides.”

The first systematic observations of the tides for scientific purposes in the UK, preceding those associated with the Royal Society, were probably those of Jeremiah Horrocks (1618−41) at Toxteth near Liverpool. His tidal measurements are thought to have spanned several weeks in 1640, with the hope of collecting a much longer record. This was prevented by his death in 1641, and his tidal records did not survive the Civil War. Horrocks is most well known for his prediction and observation of the Transit of Venus in 1639. The insight of Horrocks into the orbits of comets and planets and the Moon provided a bridge between the work of Kepler and Newton and undoubtedly contributed to Newton’s thinking in the *Principia*.

Cartwright (1999) refers to some of these individuals (but not Horrocks) as “early amateur observers,” although their observations were in retrospect as important as those of the distinguished scientists of the day. The stir caused at the Royal Society by Wallis’s publication led the Society to charge William Brouncker (its first President) and Moray with organizing a program for measurements at as many locations as possible, such as in the Thames and Bristol Channel where tides are large. That measurement campaign itself never happened. Nevertheless, the standards for measurements which Moray laid down and his suggestions for the use of stilling wells (see previously mentioned) laid the groundwork for future measurements. Reidy (2008) provides a readable account of the controversies at the Royal Society at this time as a result of Wallis’s publication.

As for tidal prediction, Henry Philips made a modification to prediction of the time of high waters at London through the spring-neap cycle by introducing (as we would explain now) an addition to the familiar 48 min increment per day of a cosine term with period of 15 days and amplitude 45 min. John Flamstead, the first Astronomer Royal, made use of measurements of the times of high water at Tower-Wharfe in late 1661 and Tower-Wharfe and Greenwich in summer 1682, together with his astronomical insight into the orbits of the Moon and Sun, to produce a tide table for the times of London tides for 1683–88 and, by means of simple adjustments, (somewhat imprecise) times of tides elsewhere.

4. Isaac Newton's *Principia Mathematica*

As we have seen, up until this point there had been little constraint on advancing theories on the tides that conflicted with well-established evidence. Any theories tended to be descriptive and lack mathematical rigor. In fact, as Glassie (2012) points out, although Europe had many so-called professors of Mathematics (Kircher was one), mathematicians had traditionally been viewed with condescension by natural philosophers and theologians. In their opinion, mathematics could be used to measure and describe and had some practical applications, but it had nothing to say of the causes or nature of things. All this was to change, as demonstrated by the Restoration in England leading to the founding of the Royal Society in 1660 as a "College for the Promoting of Physico-Mathematical Experimental Learning."

Attention to scientific evidence and use of the power of mathematics were the two keys to the triumph of Isaac Newton's *Philosophiæ Naturalis Principia Mathematica* published in 1687. As Cartwright (1999) remarked, scientific measurements would provide the foundation on which theoretical ideas would be built. Newton stated later "Instead of the conjectures and probabilities that are being blazoned about everywhere, we shall finally achieve a natural science supported by the greatest evidence." Harper (2011) describes in detail Newton's "experimental philosophy" or what would now be called his "scientific method" as applied to his arguments for universal gravity. Central to that method is the need to test hypotheses using observations of any consequences which flow from them. Mathematics had been essential for Newton reaching the conclusions in the *Principia*, having been obtained by means of his "infinitesimal calculus," although for its publication Newton had reworked his arguments in the more widely understood language of geometry.

As a result, we arrive at Books One and Three of Newton's *Principia* in which he explained in a few pages, and in a supplement called *The System of the World*, the main features of the tides using the theory of universal gravitation. These features included the following: spring-neap tides resulting from the gravity of both Moon and Sun with spring tides happening at syzygy; spring tides being larger still when lunar perigee coincides with syzygy; diurnal inequality occurring from the Moon and Sun being above or below the equator; solar tides being greatest in winter (perihelion); the anomalous diurnal tides in the South China Sea (see later); and at the end of Book 3, a calculation of the magnitude of tidal motions from first (mathematical) principles. We have Edmond Halley to thank for paying for the publication of the *Principia*, the finances of the Royal Society having been strained by the publishing failure of the *History of Fishes* by Francis Willughby.

We tend to think now that Newton's explanations of gravity and tides were accepted rapidly after the publication of the *Principia*, but that was far from the case for at least the next half century (van Lunteren, 1993). In fact, *The Gentlemen's Journal* in 1692 listed 10 competing explanations for the tides and made the reasonable statement that their proliferation was leading to confusion (Roos, 2001). Of course, Newton's theory was promoted energetically by his supporters in the scientific world such as Edmond Halley, and it eventually became the "standard model," but there was still to be more general reaction from other directions. Important in England was the Hutchinsonian movement named after John Hutchinson (1724–70) (Wilde, 1980; Aston, 2008). This was a loose collection of individuals in church and state who opposed the cultural dominance of Newtonian physics which, in their eyes, constituted the "Religion of Satan" (Fig. 1.6). Instead, they claimed that the truth lay in the original Hebrew text of the Old Testament. Hutchinson's main personal objection to Newtonian philosophy was over the use of force as an explanatory concept without assigning a mechanical cause, an aspect of gravity which had concerned Newton himself (Aiton, 1969; Wilde, 1980). It would take a century after Newton's *Principia* for the Hutchinsonian movement to die out.

5. Essays for the *Académie Royale des Sciences*

In 1740, the *Académie Royale des Sciences* in France awarded four recipients with a prize for the best philosophical essay on the "flood and ebb of the sea" (Cartwright, 1999). One was Colin Maclaurin, Professor of Geometry at Edinburgh University, and another was Daniel Bernoulli, Professor of Anatomy and Botany at Basel. Maclaurin and Bernoulli can serve as examples of how well-connected scientists now were and of how their developments of Newton's theory were to lead to practical improvements in the provision of tidal information.

Maclaurin proved what Newton had assumed intuitively, that the shape of an otherwise spherical ocean in static equilibrium with the tidal force induced by a disturbing body (i.e., either the Moon or Sun) is a prolate spheroid (a shape like a rugby ball with one elongated axis of symmetry), the major axis of which points toward the body. Bernoulli's *Traité Sur le Flux et le Réflux de la Mer* in effect extended Maclaurin's essay, although at the

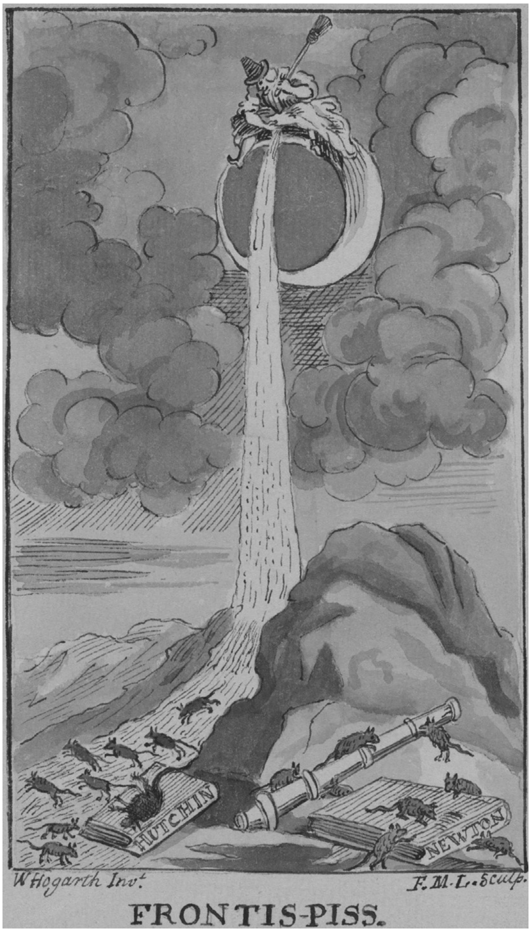


Fig. 1.6 William Hogarth designed this frontispiece for a pamphlet against the Hutchinsonians in 1763. A witch sitting on top of a crescent moon is urinating a cascade onto the rocks below, on which there is a bound copy of "Hutchin" (i.e., the *Moses's Principia* of 1724 and 1727 by John Hutchinson), and so drowning a group of black rats (i.e., the followers of Hutchinson). Some of the rats are vainly trying to gnaw at Newton's philosophy, represented by a bound copy of "Newton" (i.e., his *Principia*) and a telescope. Pen and ink with gray wash. *(© The Trustees of the British Museum.)*

time he was unaware of Maclaurin's contribution (Aiton, 1955b). His essay introduced the so-called Equilibrium Theory, which describes the temporal and spatial structure of the equilibrium tide due to the Moon and Sun in combination. In other words, Bernoulli combined the two individual prolate spheroids into one overall shape and introduced the lunar and solar orbits

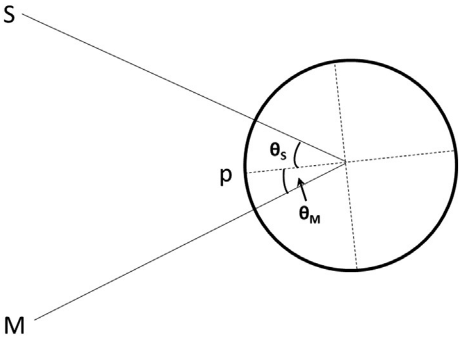


Fig. 1.7 Bernoulli's diagram for the parameters of the combined equilibrium tide due to the Sun (S) and Moon (M). The combined tide at point *p* is given by $h\ (\cos^2\theta_s - 1/3) + H\ (\cos^2\theta_m - 1/3)$. For a practical tide table, one simply has to know the relative proportions of the solar and lunar semidiurnal tide at that location (*h* and *H*, respectively) with the angles θ_s and θ_m obtainable from the *Nautical Almanac. (Adapted from a diagram in Cartwright, D.E. 1999. Tides: A Scientific History. Cambridge University Press: Cambridge. 292 pp., a similar diagram can be found in Aiton, E.J. 1955b. The contributions of Newton, Bernoulli and Euler to the theory of the tides. Ann. Sci., 11, 206–223, https://doi.org/10.1080/00033795500200215.)*

and Earth rotation into the discussion, so that the time dependence of the equilibrium tide at any point on the Earth's surface could be parameterized (Fig. 1.7). Bernoulli had also found that Newton had overestimated the ratio between the lunar and solar tides; using French observations, he arrived at a value of 2.5, close to modern estimates (Ekman, 1993).

As we know now, the *spatial* variation of the tide in the real ocean is much more complicated than that of the equilibrium tide because of the ocean dynamics, but Bernoulli found that its *temporal* variation at any location with predominantly semi-diurnal tides (which includes most of the European Atlantic coastline) can be parameterized in terms of the equilibrium tide to a good approximation with a small number of adjustments. As a result, he was able to compute a generic tide table for such locations (see Fig. 5.4 of Cartwright, 1999).

An important factor with respect to the Bernoulli method was the publication of the *Nautical Almanac* under the direction of the fifth Astronomer Royal Nevil Maskelyne, who had his own interests in ocean tides. As is well known, the *Nautical Almanac* was published primarily for the purpose of navigation at sea using the method of "lunar distances." However, the tables of lunar and solar parameters contained in the 1767 and subsequent editions were in an ideal form for application to Bernoulli's method.

Another requirement is the availability of some observations of heights and times of high waters at the location in question in order to make the necessary small adjustment to Bernoulli's generic method. In practice, this involves a scaling factor for the average range of the tide at that location, an adjustment for its age of the tide (when one has maximum high water following a New or Full Moon), and an additional one for the relative importance of the Moon and Sun (which can be obtained from inspection of the real spring-neap variation in high waters). As a result, shortly after the first *Nautical Almanac* was published one finds the first reliable, publicly accessible tide table being produced for the port of Liverpool by Richard and George Holden, tuned up from Bernoulli's generic method thanks to the availability of 4 years of observations by William Hutchinson, the Liverpool dockmaster. The Holden family tried to keep the details of their method secret for many years. However, it was finally shown by Woodworth (2002) to be simply a version of that specified by Bernoulli (Fig. 1.8).

The important connections between the individual characters in this story can be demonstrated by reference to James Ferguson who was an astronomer, elected Fellow of the Royal Society in 1763. He wrote several astronomical treatises, of which one contains an "exercise" for the construction of a tidal clock (Ferguson, 1773). He made part of his living by travelling around the country and presenting lengthy series of lectures on scientific

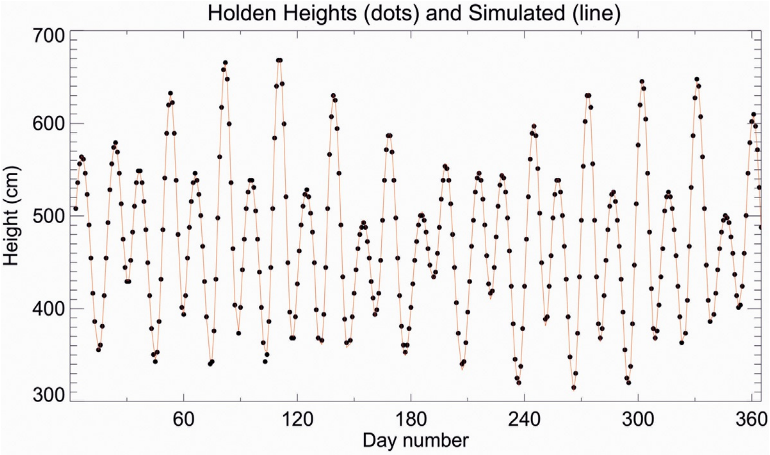


Fig. 1.8 Heights of daytime high waters for 1795 from the Holden tables (dots) and as computed by the author using the Bernoulli method (line). *(From Woodworth, P.L. 2002. Three Georges and one Richard Holden: the Liverpool tide table makers. Trans. Hist. Soc. Lancashire Cheshire, 151, 19–51.)*

subjects. He visited Liverpool on several occasions and usually stayed at Hutchinson's house. Ferguson is believed to be the person who encouraged Hutchinson to begin his tidal measurements. He was a lifelong friend of Maclaurin whom he had first contacted on aspects of astronomy. Ferguson and Maclaurin were also linked through Murdoch Mackenzie, a native of the Orkneys and a "much travelled marine surveyor." Mackenzie had started his career in hydrography on Maclaurin's advice, and Maclaurin had recommended him for the task of surveying the Orkneys, where he made his own observations on the tides (Mackenzie, 1749). Ferguson and Mackenzie met in Edinburgh and were very close, Ferguson naming his third son after Mackenzie, and both being called protegés of Maclaurin (Millburn, 1988). Mackenzie is thought to have been the person who introduced Ferguson to Hutchinson. In turn, Hutchinson was either a friend or close colleague of Richard Holden, as demonstrated by their common interests in astronomy and the invention of lighthouse reflectors (Woodworth, 2002).

While the essays of Maclaurin and Bernoulli can be seen to have led to practical benefits, those of Leonhard Euler, Professor of Mathematics at St. Petersburg, and Antoine Cavalleri, Professor of Mathematics at Cahors, were in retrospect less useful. However, all four essays could at least be said to have the merit of having learned from what had come before. Euler showed that it was the horizontal, and not vertical, component of the force field which leads to tidal motion (Aiton, 1955b). Cavalleri's essay built on the work of Descartes, although he disagreed with the earlier theory because of its lack of a major contribution from solar tides. He also disagreed with Newton's theory of gravitation and instead persevered on a fruitless development of the Cartesian theory of vortices. Aiton provides a detailed discussion of the vortex theory of planetary motions (Aiton, 1957, 1958a, 1958b). He remarks that Cavalleri had nothing really new to add to this subject (Aiton, 1958b).

One might note that the essays on the tides were not the only ones at this time. For example, both Bernoulli and Euler had essays on magnetism in 1746. Bernoulli was awarded the grand prize of the Paris Academy 10 times in all, and Euler 12 times, for essays on various topics (Fara, 1996). Maclaurin was arguably also the first to identify what is now called the Coriolis Effect (Harris, 1898).

6. Before and after Newton

In this chapter, I have tried to present the contrasting approaches to ideas on the tides in the periods before and after Newton. Theories in the earlier period tended to be little more than hand-waving speculations with an absence of mathematical or any other rigor. Just half a century later, as we have demonstrated by the Paris essayists (especially Bernoulli and Maclaurin but all four to some extent), there was a greater willingness to base theories on observations and to learn from the earlier work of others. And in Bernoulli's case, a major benefit of the research was the generic tide table capable of application to anywhere in the world with a semidiurnal tidal regime. Of course, such a comparison could be said to be a false one given what the second set would inevitably have learned from Newton. Nevertheless, the contrast is quite apparent.

However, we have shown that acceptance of Newton's theories was not universal and immediate. In addition, it is disappointing that after the achievements of Newton and Halley, investigations of tides became largely a continental European and not English pursuit, culminating at the end of the century in the dynamical tidal theory of Laplace with tides considered as fluid in motion on a rotating Earth. Laplace's *Traité de Mécanique Celeste,* written in five parts between 1798 and 1825, can be regarded as almost as important to the study of tides as Newton's *Principia*. In fact, it has pointed out that the Laplace Tidal Equations (Laplace, 1775, 1776) can be regarded as the first formulation of an ocean model, in this case a tide model (Arbic, 2022).

Meanwhile, in England, there was a "doldrums of UK tidal science" until the work during the 19th century by the UK scientists mentioned in the Conclusions later (Rossiter, 1971). Initiatives in tidal measurement, as well as in tidal theory, passed to continental Europe (especially France) after Newton. Notably, the times and heights of high and low waters were recorded at Brest between 1711 and 1716 which were sent for analysis by Jacques Cassini at the Académie Royale des Sciences. Later measurements were also made at Brest and neighboring ports. Cassini interpreted these data as support for the Descartes theory of the tides. Cartwright (1972) and Wöppelmann et al. (2006) discuss their use in modern analyses. Extended measurements of high waters in England had to await those of William Hutchinson at Liverpool in 1764–93.

The practice of forgetting findings of earlier investigators was repeated through the years. For example, we have shown that some areas of the ocean were known by the investigators in the ancient world to have diurnal, rather than semidiurnal tides. It was remarked on subsequently regarding locations far from Europe. One case concerns the communication by Francis Davenport of the East India Company to the Royal Society in 1678, referring to the anomalous diurnal tides of the Gulf of Tonkin (South China Sea).

The matter was taken into consideration by Halley in 1684, after a delay of 6 years, inconveniently to some extent just before the publication of the *Principia* (Cartwright, 2003; Hughes and Wall, 2006).

However, tides continued to be understood to mariners of powerful north-western European countries in the 18th century in terms of only the two parameters suitable for describing the predominantly semidiurnal tide: rise and fall, which was essentially twice the tidal amplitude, and high water full and change, which would later be known as establishment. The latter parameter is the lag between the Moon's transit of the meridian at the location in question and the next occurrence of high tide, at times when the Moon, Earth, and Sun are aligned (syzygy). Such information was to be collected and made available in the tables of Lalande (1781). Therefore, the mariners carried this picture of the tide with them when they embarked on their wider voyages of exploration. For example, Woodworth and Rowe (2018) discuss how puzzled James Cook was by diurnal inequality in the tide along the Queensland coast, a factor which led to the near sinking of the *Endeavour* in June 1770.

One might have thought that the possibility of diurnal tides at distant locations would have been known to most captains by the time of Cook's voyage a century later than Davenport's report. The Holden tide table makers at around this time certainly knew of the night-time tides at Liverpool being lower than day-time ones for November–April (and vice versa), primarily due to the local phase lag of the K1 diurnal constituent with an amplitude of 11 cm, and made an appropriate adjustment for their "Bernoulli predictions" (Woodworth, 2002). Diurnal inequality was later to be an important aspect of tidal research by Whewell and others in the 19th century.

7. Conclusions

Newton has been represented in this chapter as a separation between one era in the history of tidal science and the start of another (with admittedly a number of omissions such as the work of Halley). However, with the benefit of hindsight, one can identify other eras during the following centuries. These include the dynamical work of Laplace in the late 18th and early 19th centuries; the development of the harmonic method by Kelvin and Darwin, the drawing of global cotidal charts by Whewell, Airy, Bache, Harris, and others, and the technological developments of tide gauge networks (the data from which are now important for long-term climate studies) and tide prediction machines (Woodworth, 2020) during the 19th century; and the theoretical work of Proudman and developments in tidal prediction by Doodson at the Liverpool Tidal Institute (LTI) in the mid-20th century (Woodworth et al., 2021). It is obvious that there are many omissions and simplifications in such a list. Nevertheless, it seems that when Cartwright produced the manuscript for his book in 1996, he thought that he was marking the end of another era (Chapter 1, page 4). The postwar decades of the 20th century had seen the deployment of bottom pressure recorders for tidal measurements in many parts of the ocean (in which Cartwright himself had been a leading participant), and the publication of comprehensive global tidal models involving many constituents, notably the model of Schwiderski (1980).

However, Cartwright (1999) also noted that research on tides was hardly at an end, especially given the potential provided by satellite altimetry and other technologies. This was already made clear at a meeting at the Royal Society in 1996 to celebrate his 70th birthday, with many papers subsequently published in a special issue of Progress in Oceanography (Ray and Woodworth, 1997). The TOPEX/POSEIDON and JASON series of satellite altimetry missions has since revolutionized the development of regional and global tide models (Stammer et al., 2014), and for some tidal researchers, this is very much the "age of altimetry." However, there is still a need to understand the tides better in coastal waters and at high latitudes, and the altimeters of recently launched and upcoming missions such as CryoSat-2, Sentinel-3, Sentinel-6, and SWOT should meet these challenges to a great extent. Tides continue to be important factors in a wide range of research that is of both scientific and practical importance, as noted by the various papers in a special issue of Ocean Science to mark the centenary of the founding of the LTI in 2019 (Woodworth et al., 2021). Cartwright himself had been Assistant Director at the Institute of Oceanographic Sciences (Bidston), as the LTI was known at the time.

It seems that the ocean tides will never cease to fascinate. Ideas for alternative theories of the tides continue to appear on a regular basis; Doodson and Warburg (Admiralty Manual of Tides, 1941) remarked that "There are few subjects which have been more associated with fantastic theories and speculations." But that is fine, each theory and speculation presents an intellectual challenge, and it is always possible that new perspectives may be obtained by discussing them. Of course, the essential aspect of any new theory should be that it explains all available data as well as an existing theory and in addition comes up with predictions that differ from the earlier theory that can be tested by measurement (the Baconian Method).

In summary, I hope this article has interested the reader enough to purchase David Cartwright's book for an excellent treatment of the history of research into the tides through the years. To avoid major overlap with the chapters in his book, I have tried to include as many relevant references as possible since that book was published. For example, there is now an extensive amount of information in Wikipedia and elsewhere on the internet (which Cartwright would probably not have regarded as respectable). Otherwise, I would recommend the reader to consult Harris (1898), the "concise history" of Ekman (1993) and the many papers of Aiton in Annals of Science.

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