Journal of Physics:
Conference Series

PAPER • OPEN ACCESS

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To cite this article: Philip L. Woodworth 2024 *J. Phys.: Conf. Ser.* **2877** 012035

Journal of Physics: Conference Series **2877** (2024) 012035 doi:10.1088/1742-6596/2877/1/012035

Associating the Moon and the tide

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Abstract. The Moon is important to us. It has played a major role in the evolution of our planet, most obviously by causing a reduction of the rotation rate of the Earth through tidal friction. It is even possible that the Moon and hence the tides could have provided one mechanism for the origin of life on Earth through the repeated flooding and drying out under the Sun of primitive organisms in inter-tidal pools [1], [2]. In addition, the Moon has been an important factor in the religions and cultures of many societies.

The Moon and the tide

An association of the Moon with the ocean tides and also with those in the solid Earth seems obvious to us now; the tidal forces of the Sun are known to be less than half of those of the Moon [3]. As a consequence, the predominant component of the ocean tide around the UK coast (and most if not all other coastlines) has a period of 12 hours 25 minutes, being half of a lunar rather than a solar day. This component is known by tidal scientists as M2 [4].

These facts have been known implicitly for centuries by coastal dwellers, who have made use of the tide in fish traps, tide mills etc. In addition, it is known now that many components of coastal ecosystems depend on the tides. For example, in North America the reproductive cycles of grunion fish and fiddler crabs take advantage of spring tides when the tides due to the Moon and Sun coincide. These things will have been well known by coastal societies, qualitatively at least. In addition, there was a considerable amount of folklore associated with the tide, for example the belief that no animal dies when the tide is ebbing, which goes back to Aristotle [4]. Therefore, it seems inconceivable that an association of the tides with the Moon would not have been obvious. The first of what might be called tide tables was made around 1000 AD for the tidal bores occurring around spring tides in the Qiantang River near Hangzhou in China [5], while the 'St. Albans Tide Table' of John of Wallingford produced in the early 13th century was a modified lunar calendar [6]. These examples imply a well-understood connection between the tides and the Moon.

Nevertheless, although most considerations of the tides in antiquity did associate them with the Moon, this was not always the case. A list of many such observers of and commentators on the tides from the Greek, Roman, Persian and other civilisations can be found in [6] and in the excellent history of the tides by Cartwright [7], [8]. The most notable person not to do so, but rather to explain the tides as being due to the Sun, was Galileo Galilei (1564-1642) in his *Discourse on the Tides* in 1616 and *Dialogue concerning the Two Chief World Systems* in 1632. Galileo dismissed Johannes Kepler's belief that tides were caused by the Moon, a simple fact that had been known since antiquity. Instead, he suggested that the tides were due to the Earth's rotation around its axis and its orbital motion around the Sun (figure 1). See [7] and [9] for an explanation of how this argument is confused by a mixture of reference frames.

Galileo's theory implied that there would be one (and not two) tides per solar (and not lunar) day. In other words, it suggested the tides to be dominated by what tidal scientists call an S1 (solar diurnal) rather than an M2 (lunar semidiurnal) component. Therefore, Galileo's theory failed on two counts, as had been pointed out to Galileo by Kepler. Reference [10] mentions that 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. The implication is that he may have changed his mind. In 1666 John Wallis (1616-1703), Professor of Geometry at Oxford proposed an extended version of Galileo's theory. He observed that it was the centre of gravity of the Earth-Moon system which orbits the Sun. Consequently, 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 centre 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. His publication (1666) 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.

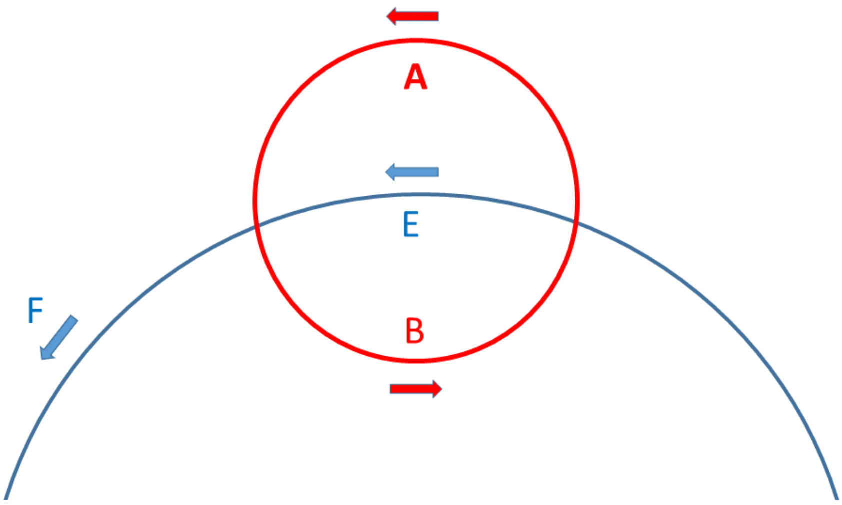

Figure 1. Galileo's theory of the tides was based on his observations of the seiche-like motions of water slopping in a barge when subjected to an acceleration. He attempted to explain the tides by suggesting that the ocean 'cavities' (or basins) were similarly subject to such accelerations. EF represents part of the Earth's orbit around the Sun (with a period of one cycle per year) and its rotation is shown by the arrows (with a period of 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 [9]. (From reference [6] © Elsevier.)

Reference [6] discusses the various attempts to account for the tides by Kepler, Francis Bacon, William Gilbert, René Descartes and others, as well as by Galileo, in the lead up to the *Philosophiæ Naturalis Principia Mathematica* of Isaac Newton, published in 1687. For the first time there was a decent theory of the tides which could be tested and built upon, instead of the sets of speculations that had been published before (e.g. the quite outlandish suggestions of Anthanasius Kircher and Thomas Philipot). In Books One and Three of the *Principia*, and in a supplement called *The System of the World*, Newton explained the main features of the tides using his theory of universal gravitation. These features included: 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 and at the end of Book 3 a calculation of the magnitude of tidal motions from first (mathematical) principles.

It is hard to imagine science without the *Principia* and one is indebted to Edmond Halley for paying for its publication, the finances of the Royal Society having been strained by the publishing failure of the *History of Fishes* by Francis Willughby. Halley made his own systematic measurements of tidal streams in the English Channel on the Admiralty "pink" *Paramour* and he studied the anomalous (diurnal) tides of the Gulf of Tonkin [11].

By now an association of the tides and the Moon was accepted by just about everyone if it had not been before. One tends to think that Newton's explanations were accepted rapidly. However, that was far from the case for at least the next half century [12]. There was still to be reaction from other directions, such as in England in the Hutchinsonian movement named after John Hutchinson (1724-1770) [13]. It would take a century after Newton's *Principia* for the Hutchinsonian movement to die out.

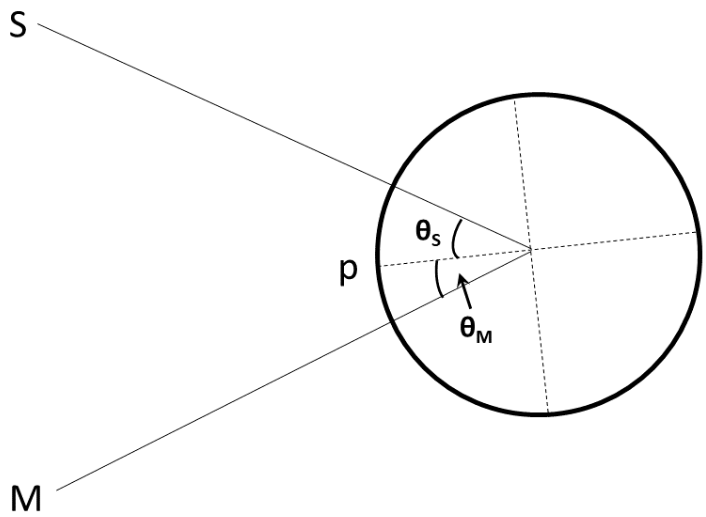

Figure 2. Bernoulli's diagram for the parameters of the combined Equilibrium Tide due to the Sun (S) and Moon (M). The combined tide at point *p* is given by $h\ (cos^2\theta_s - 1/3) + H\ (cos^2\theta_m - 1/3)$. For a practical tide table one simply has to know the relative proportions of the solar 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 [7], a similar diagram can be found in [14]. (From reference [6] © Elsevier.)

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' [7]. One was Colin Maclaurin, Professor of Geometry at the University of Edinburgh and another was Daniel Bernoulli, Professor of Anatomy and Botany at Basel. Maclaurin proved what was an intuitive assumption to Newton, 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 towards the body. In effect, Bernoulli's *Traité Sur le Flux et le Réflux de la Mer* extended Maclaurin's essay, although at the time he was unaware of Maclaurin's contribution [14]. 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 and Earth rotation into the discussion, so that the time

Journal of Physics: Conference Series **2877** (2024) 012035 doi:10.1088/1742-6596/2877/1/012035

dependence of the Equilibrium Tide at any point on the Earth's surface could be parameterised (figure 2).

An important factor with regard to practical implementation of the Bernoulli method was the publication of the *Nautical Almanac* from 1767 under the direction of the fifth Astronomer Royal. Nevil Maskelyne. Shortly after its first publication, one finds the first reliable, publicly accessible tide tables being produced for the port of Liverpool by Richard and George Holden, tuned up from Bernoulli's generic method thanks to the availability of four 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 in [15] to simply be a version of that specified by Bernoulli (figure 3).

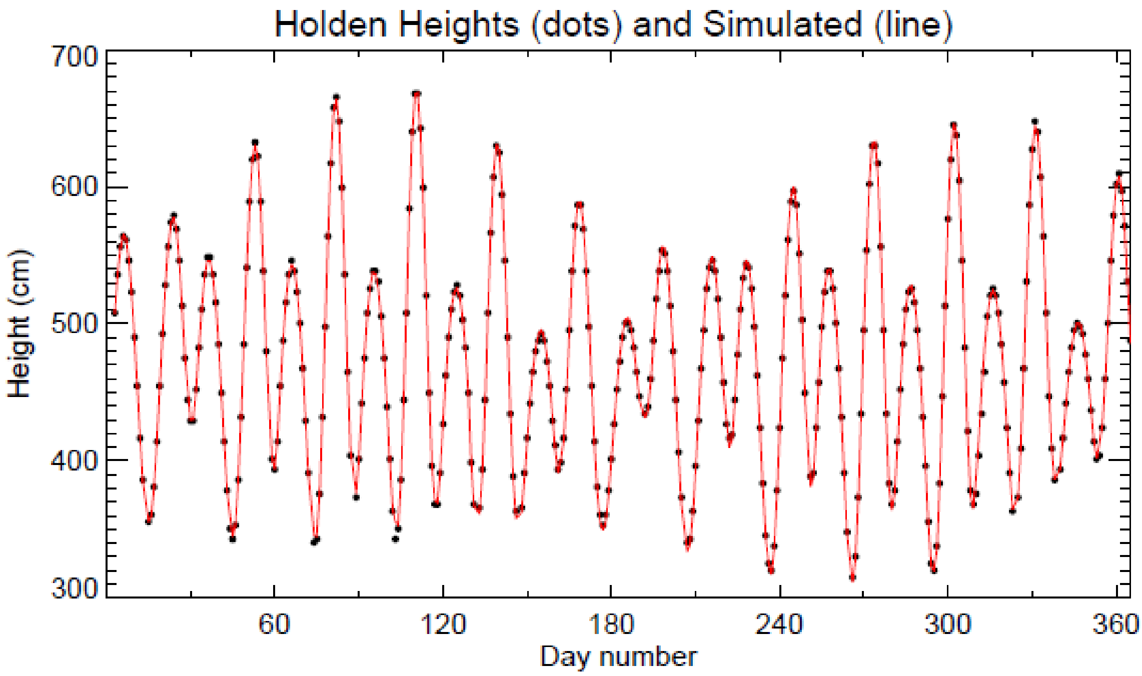

Figure 3. Heights of daytime high waters for 1795 from the Holden tables (dots) and as computed by the author using the Bernoulli method (line). (From reference [6] © Elsevier.)

It is disappointing that after the achievements of Newton and Halley, investigations of the tides became largely a continental European and not English pursuit, culminating at the end of the 18th century in the dynamical tidal theory of Pierre-Simon 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.* Meanwhile, in England there was a 'doldrums of tidal science' until work during the 19th century by scientists such as Lord Kelvin, William Whewell and Charles Darwin [16].

The 19th and 20th centuries saw the development of new instrumentation for measuring the tides (many types of tide gauge, bottom pressure recorders and satellite radar altimetry), devices for analysing the data and making tidal predictions (analogue tidal analysers and tide prediction machines) and computational methods for studying the data (harmonic analysis, response method and other techniques). Early in the 19th century the first co-tidal charts were produced, enabling the spatial dependence of the tides to be studied as well as its temporal characteristics at particular locations. In the 20th century modern digital computers provided the means to collect and analyse measurements and to undertake various types of numerical tidal modelling. As a result the M2 component is known throughout the deeper parts of the world ocean to centimetric accuracy [17], [18]. Much remains to be learned about the tides, such as their complexities in shelf and coastal waters and at high latitudes [19], [20]. But at least enough is known now to unambiguously associate the tides primarily with the Moon.

Acknowledgements
I am very grateful to Dr Jo Ashbourn for the chance to speak at the HAPP One-Day Conference on "*A History of the Moon*" in 2016. This paper has referred to some aspects of the tides mentioned in [6] which might be consulted for a more detailed discussion; that chapter was included in a book on tides edited by Mattias Green and João Duarte, and I am grateful to them for that opportunity.

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