Dynamical, biological and anthropic consequences of equal lunar and solar angular radii

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The nearly equal lunar and solar angular sizes as subtended at the Earth is generally regarded as a coincidence. This is, however, an incidental consequence of the tidal forces from these bodies being comparable. Comparable magnitudes implies strong temporal modulation, as the forcing frequencies are nearly but not precisely equal. We suggest that on the basis of palaeogeographic reconstructions, in the Devonian period, when the first tetrapods appeared on land, a large tidal range would accompany these modulated tides. This would have been conducive to the formation of a network of isolated tidal pools, lending support to A. S. Romer’s classic idea that the evaporation of shallow pools was an evolutionary impetus for the development of chiridian limbs in aquatic tetrapodomorphs. Romer saw this as the reason for the existence of limbs, but strong selection pressure for terrestrial navigation would have been present even if the limbs were aquatic in origin. Since even a modest difference in the Moon’s angular size relative to the Sun’s would lead to a qualitatively different tidal modulation, the fact that we live on a planet with a Sun and Moon of close apparent size is not entirely coincidental: it may have an anthropic basis.

1. Introduction

The fact that the solid angles subtended by the Sun and Moon at the Earth are nearly equal is generally regarded as a coincidence, one that leads to the phenomenon of total solar eclipses of agreeably short duration. The purpose of this article is to propose an anthropic explanation for why the near equality of solar and lunar angular sizes may not be entirely coincidental, and in the
process lend support to an old idea of Romer [1] on the evolutionary role of tidal pools. The idea is that the near match of angular sizes is a mathematical, but incidental, by-product of the presence of a strongly modulated tidal forcing by the Sun and Moon. It is the latter that is the true biological imperative.

The two earliest known tetrapods with more than fragmentary remains, *Acanthostega* and *Ichthyostega*, are thought to have been fully (perhaps only predominantly in the case of *Ichthyostega*) aquatic creatures [2]. The coastal and estuarial waters such organisms and their immediate ancestors are believed to have inhabited would have been subject to sizeable and irregular tides, leaving an inland network of pools. The farthest inland of these pools would on occasion have been left exposed weeks at time, ultimately evaporating. A creature caught in one of these isolated inland pools would consequently have faced dehydration or suffocation. But given a sense of direction to its flailing, there would have been plenty of inviting pools closer to the sea. These would be refreshed progressively more often than pools deeper inland. In addition, any fish left stranded in these inland pools would have been easy prey for those predators adapted to directed terrestrial motion [2]. The exigencies and advantages of large motor control in a network of tidal pools would surely have been an important evolutionary impetus to evolve weight-bearing chiridian limbs. This simple and important argument, which ties together evolutionary biology with established tidal theory, deserves to be much more widely known. In this paper, we illustrate by explicit calculation the sensitivity of the equilibrium tidal height to the relative lunar and solar angular sizes and point out that the continental configuration associated with Devonian plate tectonics may have been particularly conducive to a large tidal range.

The argument associating tidal modulation with perceived lunar and solar angular sizes is very simple. Isaac Newton himself was aware of it: in the *Principia*, he shows that one may use the ratio of the spring to neap tides to deduce the fact that the Moon’s tidal force is stronger than the Sun’s, and that the Moon therefore must be the denser body. The relation is also clearly discussed in Tolbert & Sarazin (1992, unpublished manuscript), which goes on to note some of the biological implications that we discuss more fully in this work.

The tidal force, which arises from the quadrupole term of the two-body potential of the disturbing source and its host, is proportional to the mass of the disturber and the reciprocal cube of the distance between the centres of mass. Assume for the moment that the Sun exerts a tidal force on the Earth which is a fraction \( f \) of the Moon’s tidal force. Then,

\[
\frac{M_S}{r_S^3} = f \frac{M_m}{r_m^3}, \tag{1.1}
\]

where \( M_S \) is the mass of the Sun, \( r_S \) the Earth-to-Sun centre-of-mass distance and \( M_m \) and \( r_m \) the corresponding quantities for the Moon. The masses, in turn, are proportional to the average internal density times the cube of the body’s diameter. With \( \rho \) and \( D \) standing for average density and diameter, respectively, subscripts \( S \) and \( m \) for Sun and Moon, we have

\[
\rho_S \left( \frac{D_S}{r_S} \right)^3 = f \rho_m \left( \frac{D_m}{r_m} \right)^3. \tag{1.2}
\]

But \( D/r \) is just the apparent angular size \( \theta \) of the object subtended at the Earth. This means, for example, that the total tidal potential at latitude \( l \) and time \( t \) may be written

\[
\Phi = GR_E^2 \left[ \rho_S \theta_S^3 A(l,t) + \rho_m \theta_m^3 B(l,t) \right], \tag{1.3}
\]

where \( G \) is the gravitational constant, \( R_E \) the radius of the Earth and \( A \) and \( B \) angular functions of order unity (\( t \) serves as a longitudinal variable). The relative Sun and Moon contributions are thus extremely sensitive to their relative angular sizes. Equation (1.2) implies

\[
\theta_S = \left( \frac{f \rho_m}{\rho_S} \right)^{1/3} \theta_m. \tag{1.4}
\]

Were the densities the same, equal angular sizes would mean equal tides. With \( (\rho_m/\rho_S)^{1/3} = 1.34 \), we see that values of \( f \) even roughly near 0.5 will translate to nearly equal angular sizes for the Sun
and Moon subtended at the Earth. The question of why these angular sizes should be so closely matched now becomes one of why the Sun’s tides should be something like half of the Moon’s. The ground has shifted from perception to dynamics, and dynamics has calculable consequences.

2. Analysis

(a) Semi-qualitative considerations

There are many characteristic frequencies in the tidal problem, the precise number depending upon the level of accuracy and time baseline sought. The three most important frequencies are associated with the diurnal rotation period of the Earth, the sidereal orbital period of the Moon and the yearly passage of the Sun along the ecliptic. We experience events on the rotating surface of the Earth, which boosts the effective forcing frequencies of the Moon and Sun by $2\pi/(1\ \text{day})$. For the problem at hand, this is a large number, and the difference between the effective lunar and solar forcing frequencies is small compared with their average. When two processes with close but unequal frequencies superpose, the net response is carried at this average frequency, with a modulation envelope at the difference frequency. In the case of the tides, the modulation is particularly rich, because there are many different modulation frequencies that enter. By contrast, were one of the solar or lunar tides heavily dominant, very little of this modulation richness would be present. It is this feature of the problem that compels one to consider the importance of comparable tidal contributions from the Sun and Moon.

The close match of the Sun and Moon angular size combined with the density ratio implies that the solar tidal contribution is somewhat smaller than the lunar. Amplitude modulation of the tidal forcing would still be present if the inequality of magnitudes were reversed; might it just as easily have occurred that the Moon’s contribution was smaller than that of the Sun? At an orbital radius of 1 AU, the net tide would then of course be considerably smaller, and if the Earth is in fact near the inner edge of the Sun’s habitable zone as some current estimates suggest, a more distant orbital location would make the tides yet smaller. If a putative moon with a mass comparable to the true Moon had to form close to the Earth by impact or otherwise, there is a natural link between relative and absolute tidal amplitudes. The early moon’s tidal contribution, putative or real, would have been overwhelming, moving the Earth’s crust through kilometre-scale upheavals. The lunar orbit would evolve rapidly at first, with the satellite spiralling outward via tidal dissipation to several $10^5\ \text{km}$, where the orbital recession would slow to a comparative crawl, conveniently measured in centimetres per year. In the process, not only would the tides greatly diminish to below environmentally friendly metre-scale displacements, at the same epoch the Sun would also become a player in the tidal game. In other words, for any Moon-like satellite, orbital dynamics lead to something resembling the present tidal environment: the Moon dominant but not overwhelmingly so.

The scenario might be different if a moon formed farther out and evolved inward, but this is not possible if the host planet rotates more rapidly than the moon orbits, as presumably would be the case on a planet capable of supporting life. If the planet rotates more rapidly, the effect of tidal dissipation on the perturber’s orbit is to cause outward migration. (It is generally thought the absence of any moons associated with the two slowly rotating inner planets Venus and Mercury is due to the resultant inward tidal migration of any primordial moons circling these bodies [3].)

(b) Tidal potential

(i) Coordinate expansion

To calculate the actual height of the oceanic tides at a particular location is a difficult task. The answer depends on the details of the coastline in question (especially whether resonances are present), the depth of ocean as a function of position (bathymetry), the hydrodynamics of ocean-propagating long waves (shallow water waves modified by the Earth’s rotation) and coefficients
known as the Love numbers, used to extract the difference between the oceanic and solid crust tidal response. We surely do not know Devonian bathymetry or the the Laurussian coastline in sufficient detail to perform a precise calculation of this type.

Fortunately, extreme accuracy is not required. A quantity known as the equilibrium tide will suffice. This is simply the displacement of a local equipotential surface caused by the introduction of the tidal potential and is directly proportional to this potential. The displacement is calculated by setting the associated work done against the Earth’s gravity equal to (minus) the disturbing tidal potential.

Let be this potential and be the Earth’s gravitational field. The height of the tide is then simply

\[ h = - \frac{\Phi_t}{g}. \]  

(2.1)

The equilibrium tide is a reasonable measure of the scale of the response. In any case, we are less interested in as an actual height, then the fact that it is proportional to \( \Phi_t \), the driving potential of the problem. We are particularly interested in the temporal behaviour of \( \Phi_t \), and in effect use \( h \) as a convenient normalization.

The calculation of \( \Phi_t \) is a standard exercise [3] and not difficult. We briefly review it here to keep the presentation self-contained. Let the centre of mass distance between the Earth and Moon be \( r_m \). At the centre of the Earth, we erect a \( u = (u, v, w) \) coordinate system, where \( w \) is the distance along the line connecting the centres of mass, and \( u \) and \( v \) are orthogonal axes oriented so that \( u, v, w \) is a standard right-handed Cartesian system. The potential at the coordinate location \( u, v, w \) is

\[ \Phi = - \frac{GM_m}{|(r_m + w)^2 + u^2 + v^2|^{1/2}}. \]  

(2.2)

It is important to note that while the origin of our \(uvw \) system is fixed to the Earth’s centre, the axes are not fixed to the Earth. They are defined by the Moon’s instantaneous location (see below.)

As \( r_m \) is large compared with \( u, v \) or \( w \), we expand \( \Phi \) through second order in small quantities

\[ \Phi = \frac{GM_m}{r_m} \left[ -1 + \frac{w}{r_m} + \frac{1}{2r_m^2} (u^2 + v^2 - 2w^2) \right]. \]  

(2.3)

The first term is an additive constant contributing nothing to the force \(- \nabla \Phi \). The gradient of the second term returns the dominant \( 1/r^2 \) force along the \((w \text{ axis})\) centres of mass, and the third term is the desired leading order tidal potential \( \Phi_t \), giving rise to a force vector proportional to \((-u, -v, 2w)\). Relative to the Earth’s centre, the \( w \) force is repulsive, and the \( uv \) forces are attractive. We thus find

\[ h_m = \frac{GM_m}{2gr_m^3} (2w^2 - u^2 - v^2). \]  

(2.4)

The more cumbersome calculation arises when one relates these \(uvw \) coordinates, defined by and moving with the Moon’s orbit, to coordinate axes fixed to the rotating Earth. Let us refer to these Earth body axes as \( x_b = (x_b, y_b, z_b) \), with their origin at the Earth’s centre and the \( x_b \)-axis parallel to the North Celestial Pole. With \( \phi_m(t) \) equal to the azimuthal angle of the Moon in its own orbital plane, \( i_m \) the Moon’s orbital inclination relative to the equator, \( \alpha \) the shift in the azimuth of the line of nodes (i.e. the line formed by the intersection of the equatorial and lunar orbital planes), \( \Omega_E \) the Earth’s diurnal angular rotation rate and \( T \) denoting transpose (so the vectors are in column form) the transformation is given by

\[ u^T = R_x(\phi_m)R_y(i_m)R_x(w)R_x(-\Omega_E t)x_b^T, \]  

(2.5)

where \( R_x(\theta) \) is a \( 3 \times 3 \) rotation matrix about the \( x \)-axis

\[ R_x(\theta) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & \sin \theta \\ 0 & -\sin \theta & \cos \theta \end{pmatrix}. \]  

(2.6)
and $\mathcal{R}_Y(\theta)$ is a $3 \times 3$ rotation matrix about the $y$-axis

$$
\mathcal{R}_Y(\theta) = \begin{pmatrix}
\cos \theta & 0 & \sin \theta \\
0 & 1 & 0 \\
-\sin \theta & 0 & \cos \theta
\end{pmatrix}
$$

(2.7)

(Note that $i_m$, $\alpha$ and $\phi_m$ are in effect Euler angles.) By substituting (2.5) into (2.4), we may determine the potential at a particular terrestrial location. Exactly analogous formulae hold for the solar orbit.

(ii) Eccentricity

A complication of practical importance is the eccentricity of the Moon’s orbit. Its present value is \[ \epsilon_m = 0.0549. \] (2.8)

The $1/r^3_m$ behaviour of the tidal amplitude means that there is modulation from this effect alone. A more minor modification is that the temporal advancement of the azimuth in the orbital plane is no longer uniform. With $\Omega_m$ equal to the average orbital frequency, the first-order correction is

$$
\phi_m(t) = \Omega_m t - \omega + 2\epsilon_m \sin(\Omega_m t - \omega),
$$

(2.9)

where $t$ is time, and $\omega$ is the longitude of the pericentre. The current solar eccentricity is $\epsilon_s = 0.0167$ [4]. The separation $r_m$ is given by the usual formula [5]

$$
r_m = \frac{r_0}{1 + \epsilon \cos \phi_m(t)},
$$

(2.10)

where $r_0$ is the semilatus rectum of the orbit. Analogous formulae hold for the Sun.

(c) Equilibrium tide

In figure 1, we show the total equilibrium tide, $h(x_b) = h_m(x_b) + h_S(x_b)$. For this canonical case, we have chosen parameters for the solar orbit to be those of today. For the lunar orbit, we use an estimated Devonian semilatus rectum of 365 000 km [3,6]. (The Earth’s rotational frequency has accordingly increased to conserve total angular momentum.) We have used the current orbital inclinations and eccentricities. It is certainly possible that these have evolved for the Moon [7], and the Milankovitch cycles affect the Earth’s orbit about the Sun, but our results are not sensitive to non-pathological values. The lunar and solar longitudes of the pericentres have been chosen arbitrarily ($0.63\pi$ and $-0.17\pi$, respectively); the precise values are inconsequential. The $\alpha$ angle currently rotates with an 18.6-year period. Its precise value is also not critical, though small values show particularly sharp modulation. The canonical value is thus $\alpha = 0$. The latitude chosen, $35^\circ$ S, is supposed to be representative of the Late Devonian Laurussian coast. The most striking feature of $h$ is the presence of many different incommensurate frequencies, the most important of which are diurnal, semi-diurnal and twice the lunar orbital frequency. Note the asymmetry between the diurnal and semi-diurnal components, which results in a ‘shading’ effect in the lower portion of the figure. (The asymmetry is caused by the orbital inclinations.) A higher time resolution detail is shown in figure 2 between 1000 and 2000 h. The strength of the diurnal equilibrium high tide can vary by a factor of 5: it is highly modulated.

There is a self-evident repeating pattern of a build-up of the tidal strength to a maximum, corresponding to the deepest inland penetration of the sea line, followed by a recession, which can be sharp, in which the inland penetration diminishes each day. It is not the height of the spring tide (say, at 600 h) that is relevant here. Rather, it is the rapid rate of change of the ‘modulation envelope’ (at about 700 h). Being a maximum, the spring tide changes little from one local peak to the next, but the changes of the high water mark just after the spring tide become treacherous. The waxing and waning shoreline would have left behind a series of tidal pools of increasing depth (or at least more frequent replenishment) with decreasing distance from the sea. Any aquatic
Figure 1. Representative Devonian equilibrium tide ($h$ in cm) at latitude $35^\circ$ S for a lunar semi-major axis of 365 000 km, a plausible value for the Late Devonian Period. Other orbital parameters correspond to current values, except for arbitrarily chosen longitudes of the pericentres. (See text.) The displayed baseline is 150 days. Note that the driving is indeed highly modulated. (Online version in colour.)

Figure 2. Detail of figure 1 between 1000 and 2000 h. (Online version in colour.)
Figure 3. Equilibrium tide without the Moon’s contribution. The contrast with figure 1 is evident. (Online version in colour.)

tetrapod stranded in a shallow inland pool that was adapted to squirming to a nearby reservoir would clearly have been favoured over those less mobile. This selection pressure was likely to have presented itself relentlessly.

This should be contrasted with the equilibrium tide that would obtain if there were no (or a tidally unimportant) Moon (figure 3). This tide would be one-third of the amplitude and much less variable. Local topography (and weather!) might still lead to the stranding of aquatic life forms of course, but probably not with an extensive network of pools leading back to the sea. Whether this would lead to a different course of evolution is a matter of speculation, but there is a real qualitative difference in tidal ponds and estuarial flooding in these two scenarios.

Finally, in figure 4, we show for comparison the equilibrium tide for the cases corresponding to a lunar angular diameter is half that of the Sun’s, without changing the Moon’s average density. There is some modulation, but far more gentle than and qualitatively different from our canonical case. It is only when the angular sizes become close that we start to see highly sculpted modulation.

3. Discussion

(a) Tidal receptivity

Any discussion of continental reconstruction prior to 200 Ma must begin by noting that this is an unavoidably speculative undertaking. Nevertheless, there seems to be some consensus on major features.

At the time of the middle Silurian (430 Ma), the broad intercontinental seaway comprising the Rheic Ocean separated the (southern) Gondwanan and (northern) Laurussian land masses. The Early Devonian marked the beginning of the closure of this seaway, a protracted geological event. The squeezing of the Rheic was not uniform along its length, however. Some reconstructions show the eastern Rheic squeezed down to brackish swampland, while in the west the Rheic
maintained a very broad opening of several thousand kilometres before giving on to the great Panthalassa Ocean. More recent reconstructions suggest a western closure preceding the eastern [8]. In either scenario, a tapered, horn-shaped configuration of the intercontinental seaway was maintained throughout most of the Devonian, before the Rheic became closed off at the start of the Carboniferous, eventually uniting the Laurussian and Gondwanan land masses, forming the Pangaeanean supercontinent of the Permian.

From the point of view of tidal dynamics, the Devonian is distinctive. The intercontinental seaway dividing Laurussia from Gondwana had the same generic form as the current Bay of Fundy, Bristol Channel or northwest coast of Australia: a broad opening onto a deep ocean, tapering to shallower seas. These are all regions known for their large tidal range. The propagation speed of water waves is greater in deep water than in shallow seas, going roughly as the square root of the water’s depth [9]. In the case of interest, this means that the shallows would not have responded as rapidly to tidal forcing as would the deeper water in the opening to the ocean. The resulting tidal surge propagates into the shallows, the flow convergent because of the tapering of the channel. The consequence of this behaviour is a greatly enhanced rise of the propagating tide. A correspondingly rapid egress occurs at low tide. This behaviour accounts for the famously large tidal ranges of the modern regions noted above.

The Devonian, we therefore expect, was likely to have seen dramatic tides along the Rheic Ocean, with both significant modulation of the high tide level and a great tidal range. It is not difficult to imagine the resulting rich network of coastal tidal pools that is likely to have been present. It is therefore highly suggestive that the earliest identified tetrapod trackways are thought to have originated in the Eifelian stage of the Devonian, significantly predating body fossil tetrapod remains, at a palaeogeographic location corresponding to a tight constriction of the central Rheic seaway [10]. The southern tropical coasts of the Devonian Earth may well have been a massive swamp.
(b) A brief overview of Devonian tetrapodomorph habitats

One of the richest sources of Devonian tetrapodomorph fossils is a huge area extending through parts of modern day Lithuania, Latvia, Estonia and Russia. In Devonian times, it was a massive delta region, with clear evidence of tidal influence in the form of currents and facies [11]. Yet more telling, from the point of view of this work, is the evidence of interruption of river current sediment deposition by tidal currents. The delta plane was graded. In the upper plane region, the evidence indicates sporadic interruption during spring tides; the lower plane region shows a much more regular pattern of tidal currents. (This is analogous to the modern day River Severn, which hosts tidal bores at spring tides [9].) The Baltic Devonian Delta thus preserves explicit evidence for the environmental influences of modulated tidal forcing. The formation existed for some 30 Myr, and for much of this time provided habitats for tetrapods and near-tetrapods [11,12].

More generally, the distribution of Devonian tetrapodomorph fossils indicates a preference for marginal marine environments [2]; the extent of the distribution implies an ability to cross narrow seaways. It is of interest to consider also elpistostegids, such as Pandrichthys, Livoniana and Tiktaalik, the fish group from which the tetrapods are thought to have evolved. While they retained paired fins (not limbs), they probably enjoyed some terrestrial maneuverability. Elpistostegid fossils extend further back in time than the earliest true tetrapod body fossils, but do not predate the earliest known tetrapod trackways [10]. Evidently, there was an extended period of coexistence between the two groups. From the mid-Devonian, fossils of the more primitive tetrapodomorph Eusthenopteron have been found in coastal marine sediments [2,13] (Eastern Canada), as have Pandrichthys and Livoniana fossils (Latvia) [14]; Tiktaalik remains are found in non-marine fluvial deposits (Ellesmere Island, Canada) from the same period [15]. The former environment would very likely have been subject to tidal influences; the latter is less certain but by no means impossible. The case for a tidally influenced environment also applies to the tetrapods Elginopteron [16] (non-marine fluvial deposits, Scotland) and Tulerpeton [17] (coastal lagoon, Russia). By contrast, Ichthyostega [18] and Acanthostega [19], the earliest known tetrapods with fairly complete body fossils (later than Elginopteron, for which only fragmentary remains are known) are associated with a non-marine inland basin (Greenland), a more ambiguous tidal zone. Remains of the approximately contemporaneous tetrapod Ventastega [20] were found in river bed tidal deposits (Latvia). Note that Ventastega, Pandrichthys and Livoniana all left remains in the massive Baltic Devonian Delta system described above. Finally, the Eifelian trackway is an important datum, as it represents the earliest known evidence of tetrapod activity. The trackway was found in sediments associated with a coastal lagoon (Poland) [10].

The fossil record generally supports the notion that tidal modulations contributed to the shaping of the environment of tetrapodomorphs.

4. Conclusion

The very near angular sizes of the Moon and Sun as seen from the Earth are a mathematical by-product of the existence half-metre, highly modulated, quasi-periodic equilibrium tides associated with a planet of order 1 AU from a Sun-like star. These conditions have been examined quantitatively in this work by explicit calculation of the equilibrium tides under a variety of different assumptions. It is probably rare for a planet to harbour highly complex macroscopic organisms (though hard data on this are of course scarce!), and it must also be unlikely for a planet to have a large moon nearly matching the central star in angular diameter. If these outlandish features are unrelated, why should the same planet just happen to have both? What is certain is that the Sun and Moon both are able to contribute significantly to the net tide, that this introduces very strong amplitude modulation effects that would otherwise be absent, and that early tetrapods would have had to cope with becoming stranded in a constantly changing network of shallow inland tidal pools. The uncertainty is whether these ineluctable consequences of strong tidal modulation were essential, or merely incidental, to creating an evolutionary pathway leading to a contemplative species.
It may be just a coincidence that our planet has all these features in common for no particular reason. But this line of argument does not sit well and is in any case totally sterile. In terms of the sheer number of phyla and diversity of species, the Earth’s intertidal zones are among the richest habitats on the planet [2]. Despite their ostensible stranding hazards, these regions stimulated diversity, not avoidance. It seems reasonable to consider the notion that not just the existence of the tide, but its particular form, may have influenced the course of evolution, selecting for (among other things), efficient maneuverability and motility in networks of shallow tidal pools.

A. S. Romer’s classic vision of trapped tetrapods striving for accommodating pools is supported by the apparent coincidence in angular sizes of the Sun and Moon. The fact that the resulting tidal pools would not have been in arid zones—one of the early criticisms of part of Romer’s theory that has allowed it to fall into disfavour—is irrelevant, if isolated shallow pools are common because of the tidal dynamics. As has been noted elsewhere [21], aridity is really not an issue. Puddles can drain or be rendered unsuitable for habitation under humid conditions as well. For Romer’s purposes, what is really needed is a developed network of ponds, and this is what the dynamics of modulated tides provides. A striking contemporary example of pond-searching is evinced by the so-called ‘climbing perches’, \textit{Anabas testudineus} [22], air breathing fish who literally save themselves by terrestrial locomotion from one drying puddle to a deeper pool. These fish, whose behaviour constitutes a sort of Romerian ideal, inhabit wetlands in southeast Asia, hardly an arid climate. It is not a great conceptual leap to envision a similar survival imperative (with no contemporaneous land-based predators) in Devonian swamps.

There may also be interesting geophysical consequences of non-commensurate modulated tides acting over billions of years that have yet to be explored—the Earth’s Love numbers, by which one measures the solid planetary response are by no means tiny. Yet further afield, it is of interest to note that the search for the moons of extrasolar planets (‘exomoons’) is now in its infancy and is expected to return significant results in the next few years [23]. The discussion of this paper suggests a special role for those moons providing a tidal force comparable to the planet’s host star. For if it is necessary to have the sort of heavily modulated tides we experience on the Earth in order to influence a planet’s evolutionary course in a manner constructive for evolving complex land-based organisms, the mystery of nearly equal angular sizes of the Sun and Moon would evaporate, rather like an inland Devonian tidal pool.

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