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CORRECTED PROOFS

Early Tides: Response to Varga et al.

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Abstract

Tidal cycling has been causally implicated at the origin of life, but the speed of early tides has not been established. The rotation period of the Earth is the dominant parameter, and a length of day (LOD) of under 6 h at 3.9 Ga was inferred by regression from present values [Lathe, R. 2004. Icarus 168, 18–22]. However, this would imply critical lunar proximity at that time; in their commentary Varga et al. instead argue for a more distant Moon, proposing LOD = 16.8 h. The debate is accentuated because regression from current values requires an Earth–Moon juxtaposition at around 2 Ga, for which there is no evidence. A smooth retreat from a Moon-forming impact at 4.5 Ga is also irreconcilable with the weight of paleotidal evidence. An inflection in the lunar recession curve is required to reconcile current and recent Earth–Moon values with a 4.5 Ga origin, requiring a change in tidal friction during the evolution of the Earth–Moon system. Depending on whether this took place at ∼2–2.5 Ga before present, or more recently (∼0.8–0.2 Ga), LOD values are estimated at between 12 and 16 h, suggesting a compromise figure of LOD = ∼14 h, with tides every ∼7 h, at 3.9 Ga.

Keywords: Cycling; Earth; Moon; Origin of Life; Tide

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1. Introduction

The rate and extent of marine tides at the origin of life (estimated but not so far confirmed (Moorbath, 2005; Lepland et al., 2005) to be at ca. 3.9 Ga or even slightly before (Battistuzzi et al., 2004) is an important issue for theories concerning the emergence of replicating biomolecules (Blum, 1957; Bernal, 1961; Lathe, 2004; Lathe, 2005). The commentary of Varga et al., (2005) is welcomed because it reawakens a long-standing debate (e.g., Kerr, 1983) concerning the dynamics of the early Earth–Moon system and the rapidity of tidal cycling. The central issue concerns the length of day (LOD) and the proximity and orbital period of the early Moon. Fast terrestrial rotation and lunar orbitation has been associated with the event that produced the Moon, ascribed to a large impact at 4.5 Ga or before (Hartmann and Davis, 1975; Cameron and Ward, 1976; Canup and Asphaug, 2001). If true, one must presume that the Moon has now receded from the Earth, with concomitant slowing of the rotation rates of both bodies.

Simulations of the Moon-forming impact event suggest that, immediately following the collision, the rotation period of the Earth must have been short (in the order of 4–7 h), to avoid rapid loss of the nascent Moon through inward tidal decay (Canup and Agnor, 1999), and as fast as 2.5 h in some models (Canup et al., 1999). Tidal friction between the Earth and Moon then requires deceleration of the spin rates of both planet and satellite, slowing of the Moon's orbital period, and recession of the Moon ('despinning'). All these parameters are believed to evolve in parallel, and terrestrial LOD is a rough proxy for lunar rotation, lunar orbital period, and Earth–Moon distance. Early daylength can be therefore estimated by regression from recent data points pertaining to LOD and Earth–Moon distance: for example, G.H. Darwin obtained a terrestrial rotation period under 6 h at the expulsion of the Moon (Darwin, 1879).

A regression plot of LOD (obtained from current and paleontological data) versus time, that pointed to a short LOD (2–6 h) at the origin of life (Lathe, 2004), has been challenged by Varga et al. (2005). In my paper the plot was explicitly intended to illustrate rather than define the brevity of early LOD; it was stated that "a linear relationship between these two parameters is implausible," and the regression "cannot place error limits on the

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early rotation rate, the individual values plotted are estimates, and linear extrapolations unsatisfactory." The only conclusion drawn was that early rotation "may have been rapid" (Lathe, 2004). I am in agreement with Varga et al. that the inferred rotation rate at the origin of life (LOD 2–6 h) is fast, and perhaps even implausibly so. However, equally implausible values are generated by regression plots of Earth–Moon distance. These are important issues. To put the debate on a firmer footing the striking inconsistency between values obtained by regression and what is known of the history of the early Earth is revisited.

2. A conflict of evidence

Two different but equally robust sets of data conflict. The weight of geological and biological evidence firmly points to surface water and stable terrestrial evolution for the last 4 Ga or more. Stable evolution is also true of the Moon: dating of lunar surface rocks yields values from 3.1–3.8 Ga in impact maria with fragments of highland breccias dating to 4.3 Ga. A recent meteorite of lunar origin has been accurately dated to an impact event taking place on the Moon's surface at 3.9 Ga (Gnos et al., 2004). A lunar surface has existed for at least the last 3.9 to 4.3 Ga, consistent with joint origin of the Earth–Moon pair at around 4.5 Ga.

This evidence conflicts with regression from empirical data pertaining to lunar distance and LOD over the last 1–2 Ga. Precise measurement of present day lunar recession obtained by laser ranging (Dickey et al., 1994) has given a figure of 3.82 cm/yr, a value consistent with recent decay rates of the Earth–Moon system inferred from regular laminations in paleobiological and paleogeological residua (fossil corals, bivalves, stromatolites, and notably tidalites; see Panella, 1975; Scrutton, 1978; Lambeck, 1978; Lambeck, 1980; Vanyo and Awramik, 1982; Sonett et al., 1996; Williams, 1997; Kvale et al., 1999; Williams, 2000). These combined data point to steady and predictable evolution of daylength and Earth–Moon distance over the last 1–2 Ga.

The conflict arises because the current recession rate is too fast. Simulations require that recession and orbital decay are fastest at earliest time points, when the Moon was closest to the Earth, with more sluggish decay closest to present. On this basis, mathematical regression of current and recent data provides implausible values for the dynamics of the Earth–Moon system. "The pace of tidal evolution for the past 450 Myr implies an Earth–Moon collision some 1500–2000 MyrBP, an event for which there is no corroborating evidence" (Walker and Zahnle, 1986). A similar conclusion is reached by (Kvale et al., 1999), while Williams (2000) states "the implications of employing the present rate of tidal energy dissipation are catastrophic." Cataclysmic proximity of the two bodies at around 2 Ga is inconsistent with the physical evidence.

To reconcile these data one might attempt to question the overall reliability of the paleotidal and paleorotational data on the grounds that values for fossil growth increments are approximations (Scrutton, 1978), tidalite and fossil data are largely unvalidated (Mazumder and Arima, 2005), and the uncertainties are too great to permit any reasonable estimate of earliest parameters of the Earth–Moon system (Williams, 2000). But, despite these caveats, data over the last 1 Ga are broadly consistent with the present fast recession rate of the Moon (Kvale et al., 1999). Together these recent data constitute a robust body of evidence (see Williams, 2000), and one not easily open to challenge.

3. Fitting the data

Two different approaches address this inconsistency. First, the recent LOD data are adapted to fit the end-points (current LOD and recession rate *versus* the formation of the Moon in a single giant impact at 4.5 Ga). Varga et al. (2005) revisit the four different scenarios depicted in Fig. 15 of Williams (2000) where three of four regression curves for the Earth–Moon distance retropredict catastrophic proximity between 1.5 and 3 Ga. They focus only on the fourth curve because "only scenario #4 is acceptable on geological grounds" (Varga et al., 2005).

Dwelling on this fourth curve of Williams, a LOD of 16.8 h at the origin of life was retropredicted (Varga et al., 2005). However, this curve sets itself apart, not only because it is inconsistent with other data (and is the only curve that removes the Earth–Moon event back to 4.5 Ga), but also because it is centrally based on the age of the Weeli Wolli banded-iron formation, a unit now interpreted as having been deposited from a submarine hydrothermal system rather than explicitly from tide-dependent marine sediments. The meaning of the Weeli Wolli cyclicity is debatable, indeed the diverse tidal and nontidal interpretations enjoy timescales that differ by up to 3 orders of magnitude. Its use in a regression curve was for demonstration purposes (Williams, 2000).

A second approach is to infer an inflection or phase-change during the evolution of the Earth–Moon pair. One wonders if the moon could have decayed in two phases. Complex dynamical considerations point to unstable resonances with discrete phase changes (Touma and Wisdom, 1998). Krasinsky (2002), attempting to resolve the paradox through planetary dynamics, and extrapolating from the same fossil and tidalite data, suggested that decay to about 2 Ga could have been slow, followed by an abrupt change to more rapid decline, thereafter consistent with present day values. In this paper rapid early orbitation of the Moon was also discussed, and a terrestrial rotation period of just over 4 h (with a lunar month of the same magnitude) was proposed for 1.8 Ga.

This is also fraught with some difficulty. A reviewer of the present paper affirms that tidal forces are such that, given known parameters, it is impossible to "store" the Moon for up to 1 Ga any closer to the Earth than ∼30 Earth radii (current distance, ∼60 radii) for any plausible value of tidal dissipation for a solid body, a point endorsed by Varga et al. (2005), though not seen as insurmountable by Krasinsky (2002). Further, the referee advises that the rate of recession of the Moon at close distances is so fast that the Moon must, from what we know, have been at least 30 radii away from the Earth by the origin of life ascribed to 3.9 Ga.

Compromise solutions could be to infer that, for the most part of the Moon's life, tidal friction and orbital decay were significantly slower than today. One reviewer focuses discussion: “there is general agreement among workers in this field that the rate of lunar recession must have been lower during the Archean and early Proterozoic than during later eons.” Another reviewer writes “the current rate of evolution of the lunar orbit cannot have persisted for even 2 Ga; it must have been slower in the past.” Reduced tidal friction seems likely, but no explanation of the rate change was advanced.

4. Mechanism and timing of tidal friction changes

The consensus is that tidal friction must have been significantly lower than today. However, both LOD and the rate of early tides will depend on the timing of the recession rate increase. In definitive overview, Williams (2000) argues for a fairly recent change, and estimated that the mean rate of lunar recession over the last 2.5 Ga could lie between 1.24 and 2.17 cm/yr (in contrast to the current value of 3.82 cm/yr), pointing to very substantially reduced tidal friction in the early part of this period. In this paper it was proposed that a recent increase in recession rates could have been driven by increasing oceanic tidal dissipation with changes in tidal resonances. Lambeck (1980), Sündermann (1982), and Brosche (1984) previously suggested that near-resonance of oceanic free modes and tidal frequencies with recent continent dispersal (∼0.2 Ga before present) may have produced an increase in tidal friction, while Kvale et al. (1999) suggest that both the assembly and the break-up of the Pangea supercontinent is likely to have affected the spin rate of the Earth. Global glaciation (snowball Earth) at 0.73–0.58 Ga may have contributed. Together, these could point to changes in tidal friction in the approximate period between 0.8 and 0.2 Ga before present, and indicate (by graphical regression) a LOD of around 16 h at 3.9 Ga, close to the value advocated by Varga et al.

A problem with this scenario is that the early Earth is thought to have been rather hotter and more fluid than today: higher mantle temperature and a thinner lithosphere would have led to increased dissipation within the solid Earth (Lambeck, 1980), inevitably leading to higher (and not lower) tidal friction, and this consideration could require a more radical change in tidal friction at some time in the Earth’s history.

There is evidence for marked upheavals at the terrestrial surface, so far unexplained, in the period immediately prior to 2 Ga. These include the Shunga event at around 2 Ga (Melezhik et al., 2003) and an abrupt period of mantle overturn or intense plume activity at 2.45 (Kump et al., 2001). There is widespread evidence for intense global glaciation at around 2.45–2.22 Ga that is not found prior to 2.5 Ga or after 2 Ga, until reappearing more recently at ∼600 Ma (Evans et al., 1997; Kirschvink et al., 2000). Significant and sometimes quite exceptional fluctuations in isotope ratios include carbon at 2.11–2.25 Ga (Lomagundi or Jatulian event) (Baker and Fallick, 1989; Aharon, 2005), sulfur at 2–2.45 (Farquhar and Wing, 2003), strontium at 2.3–2.6 Ga (Kuznetsov et al., 2003; Mirota and Veizer, 1994), with a major discontinuity in oxygen isotopes at 2.5 Ga (Knauth, 2005). Although biomass accumulation could contribute (Melezhik et al., 1997), the exact cause(s) of these upheavals are unknown. Though the upheavals appear to have taken place over a protracted period, it was suggested that conditions were extraordinary; the possibility of a catastrophic event not yet understood was also considered (Melezhik and Fallick, 1996). One notes that isotope shift is associated with the K/T event, but the magnitude of the changes taking place in the 2–2.5 Ga timeframe (reviewed by Melezhik et al., 1999) could indicate combined events greater by at least an order of magnitude. Such further events are not inconsistent with what is known of the evolution of the Earth–Moon system, and could suggest a major change in tidal friction occurred at between 2.5 and 2 Ga before present; this would point to a LOD at 3.9 Ga in slight excess of 50% of its current value.

5. Conclusion

Very short lengths of day (LODs) at 3.9 Ga, under 6 h by regression (Lathe, 2004), or 4 h by orbital shifting (Krasinsky, 2002), are held to be implausible as they would imply critically unstable Earth–Moon proximity at that time. Nevertheless, the estimated LOD, 16.8 h, advocated by Varga et al. (2005) omits the uncertainties acknowledged by Williams (2000) and is selective in the empirical data it considers. Instead the data appear most consistent with a significant change in tidal friction and an inflection in the lunar recession curve during evolution of the Earth–Moon system. Although it is impossible to afford any precise or accurate estimate, a change in tidal friction could point to a LOD at the origin of life somewhere between 12 and 16 h, a little lower than the 16.8 h figure advocated by Varga et al. (2005). These figures are compatible with values advocated by a referee of the present paper who argued that the Moon must have been at least 30 Earth radii away at 3.9 Ga, with a LOD of at least 9–12 h (and a diurnal tidal height of not more than ∼10 times the present height).

Many of the concerns of Varga et al. (2005) are therefore accepted, but further complexities and uncertainties are emphasised. As Touma and Wisdom (1998) state, the richness of the dynamics of the Earth–Moon system is far from being exhausted. I wrote earlier: “The only reliable conclusion is that early rotation may have been rapid” (Lathe, 2004) and suggest here that with limited data it is unsafe to attempt to retropredict relative rotation at 3.9 Ga with any accuracy.

All the evidence points to a shorter LOD, a closer Moon, and faster lunar rotation at the origin of life: we cannot escape the conclusion that early tides were higher and more frequent than today. The timing of the origin of life remains uncertain: some of the most compelling DNA sequence evidence points to an origin as early as 4.1 Ga (Battistuzzi et al., 2004); if so, this would further shorten the contemporary LOD to under 12 h. It seems likely that no consensus will be obtained without further investigations to resolve these crucial issues. Until such time, it is suggested that biochemical simulations of early tides might adopt a compromise LOD of around 14 h, somewhat greater than 50% of current values, and with tides every 7 h, at the inferred origin of life, while recognising that this can be no more than an interim estimate based on incomplete and sometimes contradictory data.

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*including Alan W. Harris

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