Precambrian Research, 37 (1987) 95-105
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

A CONSTANT DAYLENGTH DURING THE PRECAMBRIAN ERA?

KEVIN ZAHNLE*

NASA Ames Research Center, MS 245-3, Moffett Field, CA 94035 (U.S.A.)

JAMES C.G. WALKER

Department of Atmospheric and Oceanic Sciences and Department of Geological Sciences, The University of Michigan, Ann Arbor, MI 48109-2143 (U.S.A.)

(Received January 20, 1987; revision accepted April 9, 1987)

Abstract

Zahnle, K. and Walker, J.C.G., 1987. A constant daylength during the Precambrian Era? Precambrian Res., 37: 95-105.

The semidiurnal atmospheric thermal tide would have been resonant with free oscillations of the atmosphere when the day was ~21 h long, c. 600 Ma ago. Very large atmospheric tides would have resulted, with associated surface pressure oscillations in excess of 10 mbar in the tropics. Near resonance the Sun's gravitational torque on the atmospheric tide - accelerating Earth's rotation - would have been comparable in magnitude to the decelerating lunar torque upon the oceanic tides. The balance of the opposing torques may have long maintained a resonant ~21 h day, perhaps for much of the Precambrian. Because the timescale of lunar orbital evolution is not directly affected, a constant daylength would result in fewer days/month. The hypothesis is shown not to conflict with the available (stromatolitic) evidence. Escape from the resonance could have followed a relatively abrupt global warming, such as that occurring at the end of the Precambrian. Alternatively, escape may simply have followed a major increase in the rate of oceanic tidal dissipation, brought about by the changing topography of the world's oceans. We integrate the history of the lunar orbit with and without a sustained resonance, finding that the impact of a sustained resonance on the other orbital parameters of the Earth-Moon system would not have been large.

Introduction

Atmospheric tides differ from their oceanic counterparts in some ways that are basic to a discussion of tidal evolution. A purely gravitational tide gives rise to a torque solely through dissipation; in the absence of dissipation the tide would be in phase with the tide-raising force. This is not the case for the atmospheric tides, the most important of which are thermally excited by absorption of sunlight by water vapor and ozone. At the surface, the largest of these is semidiurnal. It is most prominent in the tropics, where its amplitude is largest (~1 mbar, with pressure maxima occurring at ~10 a.m. and ~10 p.m.) and where it is not masked by the passage of extratropical cyclones.

The observation of relatively large semidiurnal thermal tides led Kelvin (1882) to suggest that the semidiurnal tide was nearly resonant with a natural period of the atmosphere, and hence much amplified with respect to the diurnal tide. Debate over this 'resonance hypothesis' dominated atmospheric tidal the-

---

*National Research Council Postdoctoral Fellow.

0301-9268/87/$03.50

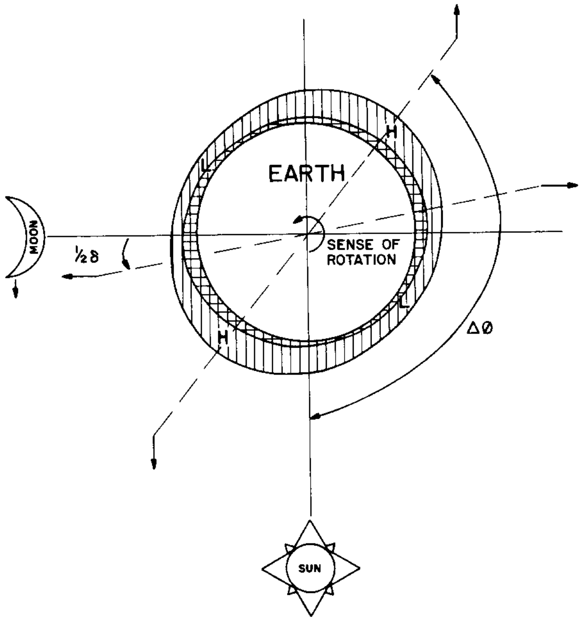

Fig. 1. Cartoon illustrating the opposing effects of torques on the solar thermal semidiurnal atmospheric tide and the gravitational lunar semidiurnal oceanic tide. The viewpoint is from above the north pole. The depiction of the oceanic tide is grossly idealized.

ory until the late 1950s, when accurate measurements of the temperatures in the stratosphere finally ruled out the resonance theory (an entertaining and authoritative account of these matters is given by Chapman and Lindzen, 1970). Kelvin also pointed out that the solar gravitational torque on the semidiurnal thermal tide accelerates Earth's rotation rate (see Fig. 1). He calculated that this 'thermodynamical acceleration' was about an order of magnitude less than the deceleration due to the lunar tides, and thus little more than a curiosity. Later, Holmberg (1952) suggested nonetheless that the two torques were in fact equal and opposite, thus stabilizing Earth's rotation rate and thereby explaining the otherwise implausible version of the resonance hypothesis then extant. (A similar balance of gravitational and atmospheric torques has been advanced to explain Venus's modern rotation rate; see Gold and Soter, 1969; Dobrovolskis and Ingersoll, 1980.) But Kelvin's estimate proved closer to the truth; using modern empirical values the accelerative torque is calculated to be $\sim 2.5 \times 10^{22}$ dyne-cm, while the decelerative torque derived from lunar orbital evolution is $\sim 6 \times 10^{23}$ at present, or $\sim 4 \times 10^{23}$ if averaged over the Phanerozoic (cf. Lambeck, 1980).

Here we revive the resonance hypothesis and Holmberg's idea for stabilizing Earth's rotation rate, but apply them only to the distant past. Two factors work to close the gap between the torques. The first is that near resonance the atmospheric tide would have been much larger. Secondly, the lunar tidal torque must have been, on average, much lower in the Precambrian than in the Phanerozoic – this is required by the stability of the lunar orbit over the life of the solar system. (Extrapolation of the present rate of tidal evolution implies an Earth–Moon collision some 1.5 Ga ago; an event for which there is no good evidence – sometimes known as the 'time scale problem' or the 'Gerstenkorn event'.) The aims of this paper are to find when and for how long the two torques were comparable, and to consider what consequences a prolonged resonance might have had.

Tidal resonance

The theory and observation of the atmospheric tides have been ably reviewed many times (Siebert, 1961; Chapman and Lindzen, 1970; Lindzen and Chapman, 1971; Forbes and Garrett, 1978, Kato, 1980). Classical tidal theory applies to oscillations of a stationary, inviscid, spherically symmetric thin atmosphere; meridional temperature gradients and mean winds are neglected. Subject to these limitations, it can be shown (also Craig, 1965; Lamb, 1932) that the linearized equations of motion governing the atmospheric tides may be reduced to separate equations governing the vertical and the horizontal structure of the wave (the latter is known as 'Laplace's Tidal Equation'). Eigenvalues of the latter may be written in the nondimensional form

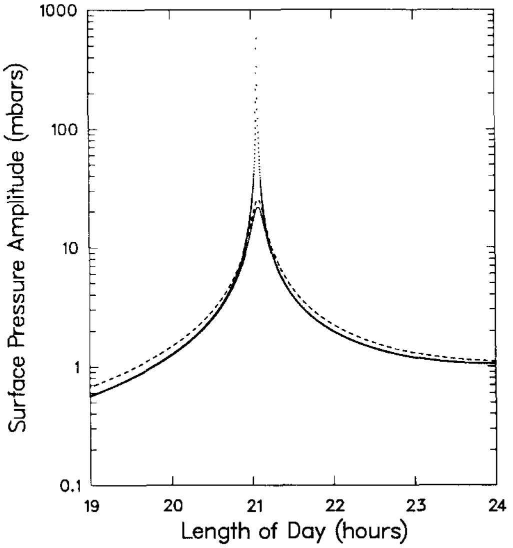

Fig. 2. Equatorial surface pressure oscillations associated with the semidiurnal atmospheric tide as a function of daylength. The solid curve includes dissipation (modeled using Newtonian cooling of 1 °C 24^{-1} h); its dotted extension is without dissipation. This amount of dissipation is consistent with damping of ~ 10 h Lamb waves. The dashed curve includes both semidiurnal latent heat release and dissipation.

$$\beta = \frac{4R_{\oplus}^2 \Omega_{\oplus}^2}{gh} \tag{1}$$

where $R_{\oplus}$ is the radius of Earth; $\Omega_{\oplus}$ is the rotation angular velocity of Earth; and where the separation constant h is known as the 'equivalent depth' of the wave. The equivalent depth of the fundamental symmetric semidiurnal thermal tide is currently $h = 7.852$ km; thus in the geological past it would have been

$$h = 7.852(24/LOD)^2 \; km \tag{2}$$

written here in terms of the length of day (LOD), expressed in hours.

Free oscillations of the atmosphere, or 'Lamb waves', have at present an equivalent depth of ~ 10 km. Evidently the atmosphere would have been resonant with the semidiurnal thermal forcing when the day was ~ 21 h long. This was the case c. 600 Ma ago (cf. Lambeck, 1980), roughly coincident with the end of the Precambrian era.

The resonance is illustrated in Fig. 2, which shows calculated surface pressure oscillations as a function of daylength for the 15 °N standard atmosphere (U.S. Standard Atmosphere Supplements, 1966). The amplitudes of the forced waves have been obtained numerically after the method clearly described by Chapman and Lindzen (1970). Thermal forcing by water vapor and ozone have been calculated as described there. Where included, dissipation is modeled by Newtonian cooling of 1 °C 24 h^{-1}. Although Newtonian cooling itself is not important, damping of ~ 10 h Lamb waves by surface friction has been calculated to be of this order (their fig. 8, Lindzen and Blake, 1972). Where included, possible thermal forcing due to latent heat release follows Lindzen (1978). It is noteworthy that tidal pressure oscillations as large as ~ 20 mbar are quite plausible near resonance.

Aside from dissipation, the resonance in a real atmosphere might also be broadened by mean winds and the meridional temperature gradient – complications neglected in the classical theory. Their import is not easily measured without recourse to a much more sophisticated model than is justified here. However, it may be rather small, since the phase velocity of the semidiurnal tide is very large compared with the mean winds and because the resonant tide would be primarily confined to the tropics, where the meridional temperature gradient is negligible.

The equivalent depth of the atmosphere depends primarily on its tropospheric scale height, which in turn depends on the surface temperature. It is readily shown that the equivalent depth of an isothermal atmosphere is simply γH (e.g. Siebert, 1961), where H is the scale height and γ the adiabatic exponent. The resonance behavior of realistic atmospheres must be found numerically. We consider three types of possible ancient terrestrial atmospheres as a function of surface temperature. The first has modern levels of oxygen and ozone. The third is fully anaerobic, with neither oxygen nor ozone. This type of atmosphere is expected before the advent of oxygenic photosynthesis, and may have persisted for some time thereafter (Walker et al., 1983). The second reflects the transition from the ancient anaerobic atmosphere to the fully aerobic modern atmosphere. Theoretical models predict that ozone reached more or less modern levels for atmospheres that were no more than ~ 1% O_2 (Kasting et al., 1985). Such an atmosphere may have prevailed over a large fraction of Earth history (Walker et al., 1983). For consistency, in all three cases we model the tropospheres by moist adiabats. We have assumed a modern stratospheric temperature profile for those cases with ozone. In the absence of ozone, we have assumed a cold ($T = 180°$ K) isothermal stratosphere, as suggested by detailed radiative-convective models (Morss and Kuhn, 1978; Kasting et al., 1984). Since the equivalent depth of the atmosphere is determined largely by the scale height of the tropical troposphere, our calculations are not greatly compromised by the crudity of our stratospheres.

The results of the exercise are shown in Fig. 3. Plotted are the surface temperatures that correspond to resonances at the indicated daylengths. Abundant molecular oxygen lengthens the resonant daylength almost 0.5 h by decreasing the scale height from that of pure N_2. Abundant ozone shortens the resonant daylength by some 0.3 h by warming the stratosphere – this is apart from ozone's contribution to thermal forcing. Also shown are the resonances of the 15°N and midlatitude spring-fall standard atmospheres (U.S. Standard Atmosphere Supplements, 1966). Because the moist adiabatic temperature gradient is less steep near the ground than the standard atmosphere's 6.5°C km^{-1}, the warmer moist adiabats have shorter resonant daylengths than the standard atmospheres for a given surface temperature. This difference gives rise to an inferred systematic uncertainty in our calculated resonant daylengths of ~ 20 min.

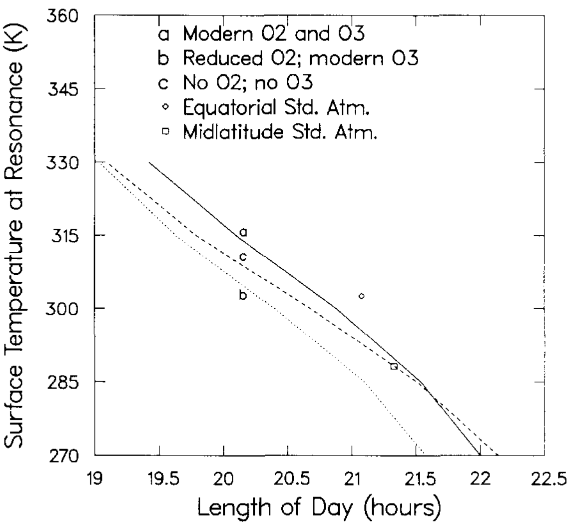

Fig. 3. Daylength at resonance for a variety of real and hypothetical atmospheres as functions of surface temperature. The solid curve (a) assumes modern levels of O_2 and O_3; the dotted curve (b) assumes 2% O_2 coupled with modern O_3; the dashed curve (c) assumes no O_2 or O_3. The diamond represents the modern 15°N standard atmosphere; the square the midlatitude spring-autumn average.

Torque on the resonant tide

The phase of the semidiurnal tide reversed upon passage through resonance, so that before resonance pressure maxima took place near 3:00 and both lunar and solar tides acted to slow Earth's rotation. Neglecting semidiurnal latent heat release, exactly at resonance pressure maxima would have occurred at 12:00, with no net torque. Just after resonance, however, torque on the thermal tide would have been comparable in magnitude and opposite in sign to the lunar torques on the oceanic tides. If obliquity is neglected, the time-averaged solar torque on the resonant component of the atmospheric tide may be written

$$T'_{\oplus 3} = \frac{3\pi G M_{\odot} R^4_{\oplus}}{2a^3_{\odot}} \frac{\delta p(0)}{g} \sin(2\Delta\phi) \qquad (3)$$

where $\delta p(0)$ and $\Delta\phi$ are the pressure amplitude and the phase lag of the tide at the surface (currently ~ 1.16 mbar and ~ 158°, respectively);

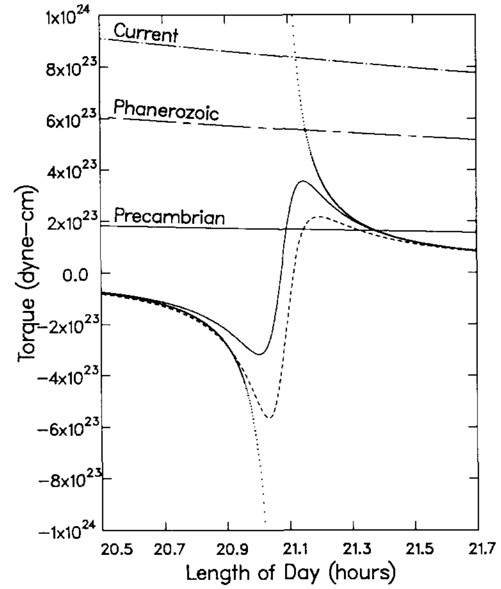

Fig. 4. A comparison of representative lunar torques (slowing Earth's rotation) to opposing solar torques (increasing Earth's rotation) near resonance. The largest of the lunar torques is consistent with contemporary tidal dissipation, the second is for average Phanerozoic tidal dissipation, the lowest is for average Precambrian tidal dissipation. The dependence on LOD presumes constancy of Earth-Moon system angular momentum. The opposing solar torques are for the three cases shown in Fig. 2.

$M_\odot$ and $a_\odot$ are the solar mass and the distance to the Sun, respectively; and $T'_{\oplus 3}$ is the component of tidal torque opposing the Earth's rotation (the notation for torque follows Goldreich, 1966).

In Fig. 4 we compare the thermodynamical acceleration to lunar torques representing contemporary (Lambeck, 1980), average Phanerozoic, and average Precambrian rates of tidal dissipation. The average Phanerozoic torque used here is derived from the lowest of several values for the average rate of Phanerozoic tidal dissipation obtained by Lambeck (1980, pp. 388–389) through judicious use of the available paleontological data (many of which are presented in Figs. 5 and 6). The average Precambrian torque used here we obtained from our interpretation of a 23.3 ± 0.3 year periodicity preserved in the Weeli-Wolli Banded Iron-formation (Trendall, 1973) as the signature of the lunar nodal tide (Walker and Zahnle, 1986). We emphasize that this rate of tidal dissipation is about as large as it could be while still being consistent with the stability of the Moon's orbit over the life of the solar system. Still lower Precambrian tidal torques have been suggested on theoretical grounds (Hansen, 1982; Webb, 1983).

The results shown in Fig. 4 imply that the solar torque would indeed have been large enough to freeze the length of day provided that the competing gravitational tide was near its Precambrian average and that the resonance itself was not very much broader than we have estimated here. Other factors affecting the ability of the resonance to stabilize the daylength would have included the existence of an ozone layer; long-term fluctuations in the average surface temperature, in particular the average surface temperature in the tropics; and the phase of the tide near resonance.

The latter effect is illustrated with the dashed curve in Fig. 4, which shows the tidal torque including the phase shift induced by semidiurnal latent heat release (Lindzen, 1978; Hamilton, 1981). Lindzen has argued that the tide is at present about ten times too small to directly influence cloud formation and precipitation. If so, then near resonance the tide may well have been large enough to do so. If this additional semidiurnal latent heat release occurred in phase with maximum tidal convergence, it would have occurred 3 h before the pressure maxima. At present this would be at ~ 6:00, and is therefore ~ 180° out of phase insolation. At resonance it would have been shifted 90° to ~ 9:00. Thermal forcing at this phase would tend to counteract the thermal forcing peaking at ~ 4:00 due to the pre-existing semidiurnal rainfall. If tidally induced rainfall exceeded and/or suppressed the pre-existing semidiurnal rainfall, or if tidal divergence at ~ 3:00 suppressed it, then at resonance pressure maxima would take place before 12:00 and there would remain a residual accelerative torque. The potential impact of the resonant tide on the tropical climate may be a key to understanding the extensive low-latitude glaciation peculiar to the late Precambrian (cf. Frakes, 1979; Crowley, 1983). Another possible link to the late Precambrian climate might be indicated by the apparent preservation of sunspot cycles (Williams and Sonett, 1985) and the lunar nodal tide (Zahnle and Walker, 1987) in the 680 Ma old Elatina formation. The evident hypersensitivity of the local environment to the sunspot cycle implies enormous amplification of very small changes in climatic forcing – such as might be provided by a nearly resonant atmospheric tide.

Given that the torque on the thermal tide at resonance was large enough to have prevented changes in daylength, the width of the resonance, defined as the region over which the accelerating torque would have been large enough to have balanced the decelerating torque, is probably not much affected by nonlinearities and dissipative processes. Thus it is possible to estimate the width in terms of the parameters – daylength and surface temperature – that determine resonance. This is done in Table I for four representative possible lunar tidal torques. Also given is the minimum length of time required to evolve through a resonance; i.e. if there were no opposing atmospheric tide this is how long it would take the given tidal torque to lengthen the day by a period equal to the width of the resonance. Evidence available at present indicates that Earth's atmosphere has been at least mildly oxygenated for the past ~ 2 Ga (Walker et al., 1983), and should therefore have had ozone concentrations similar to those today (Kasting et al., 1985). It is useful nevertheless to consider the impact of removing ozone's contribution to the thermal forcing.

After some consideration of Table I, it becomes apparent that the easiest way to destabilize the resonance would have been through an abrupt (as measured on the timescale of orbital evolution) global temperature rise of order 3–5 K maintained for a period of order 30–100 Ma, coupled with a modern rate of tidal dissipation. The temperature rise shifts the resonance to a shorter daylength, evading the need to evolve through it. A temperature drop does not work because the resonant daylength is increased, and is therefore met again sometime later.

Apparently just such a climatic event occurred at the end of the Precambrian. Extensive glaciation characterized the 200–300 Ma

TABLE I

Width of resonance

	Lunar Torque (g $cm^2 s^{-2}$)			
	1×10^{23}	2×10^{23}	4×10^{23}	8×10^{23}
With ozone and oxygen				
Change in daylength (min)	32	15	7.4	3.7
Change in surface temperature (°C)	13	5.8	2.9	1.5
Length of time required to evolve through resonance (in Ma)	520	120	31	7.7
Without ozone or oxygen				
Change in daylength (min)	17	8.2	2.0	
Change in surface temperature (°C)	6.1	3.0	0.75	
Time to evolve (Ma)	280	68	4.2	

immediately preceding the Cambrian; paleomagnetic evidence is sometimes taken to indicate that large-scale glaciation occurred even in equatorial regions (cf. Frakes, 1979; Crowley, 1983). The Cambrian was by contrast quite warm. Given that the stabilized resonance was then in effect, the change to the much warmer Cambrian climate, perhaps coupled with the relatively large rate of lunar tidal dissipation expected at that time (Sündermann and Brosche, 1978; Krohn and Sündermann, 1982), would have provided precisely the conditions required to escape the resonance. It may not be simply coincidence that the day was then ~ 21 h long (see Fig. 5), as expected in the scenario outlined here.

An alternative mechanism for escaping the resonance could have been the rise of atmospheric ozone, if this event took place at the end of the Precambrian. Again, the timing is interesting, in this case because it has been suggested that the biological leap into the Phanerozoic may have been triggered by the emplacement of the ozone shield (Berkner and Marshall, 1965). Or it may simply be that the oceanic torque grew large. In any case, it is at least possible that the resonance may have persisted for a long time before it was destabilized. A possible history of the day consistent with a sustained resonant daylength is illustrated by the dashed line in Fig. 5.

Comparison with the geologic record

We have raised the possibility that a resonant ~ 21 h day may have been sustained for a substantial fraction of the Precambrian. The available evidence is equivocal. There are five published data of which we are aware that pertain to the length of the Precambrian day. All are based on the hypothesis that the conspicuous banding observed in Precambrian stromatolites may be interpreted either as daily growth or as the rhythm of the tide, or both. Periodic patterns of the fine laminae are in turn interpreted as modulation by fortnightly and monthly tides, or by the seasonal cycle. As discussed by Scrutton (1978) and Lambeck (1980), this strategy works well for the biologically advanced bivalves and corals of more recent times. It works less well for recent stromatolites, and strangely if at all when applied to the Precambrian.

Most of the published data are due to Panella (1975). Two additional data are taken from Mohr (1975) and Vanyo and Awramik (1982). All are shown in Figs. 5 and 6. The most easily interpreted are two years of 446 and 448 days c. 2 Ga ago (Panella, 1975). These have been obtained using 'maximum counts', meaning that the largest number of laminae counted per annual variation is taken to most closely reflect the real number of laminae. Smaller counts are explained by degradation of the sample. However, maximum counts consistently overestimate the number of counts by ~ 4–7% when applied to Phanerozoic samples (including a stromatolite dating to ~ 510 Ma bp), which in the case of days per month gives impossible results (cf. Lambeck, 1980). A similar adjustment applied to 447 counts per annum reduces the number of days per year to ~ 425 (or 20.6 h per day) c. 2 Ga bp.

Also interpreted as days per year is an imprecisely determined periodicity of ~ 410 laminae c. ~ 850 Ma bp (Vanyo and Awramik, 1982). This sample differs from the others in that the longer periodicity is a side-to-side motion, explained by the authors according to the premise that the colony tracked the seasonal motion of the sun (modern examples of this behavior are reported (Awramik and Vanyo, 1986). Although their estimate is not inconsistent with a resonant ~ 21 h day, it is much too recent and far too imprecise to differentiate between the two models.

The other three samples show the bimodal distributions expected from fortnightly and monthly tidal periodicities. They are otherwise puzzling and inconsistent. Mohr (1975) obtains a mean period of ~ 26 ± 4 days per month from the Biwabik formation c. 2 Ga bp. Using con-

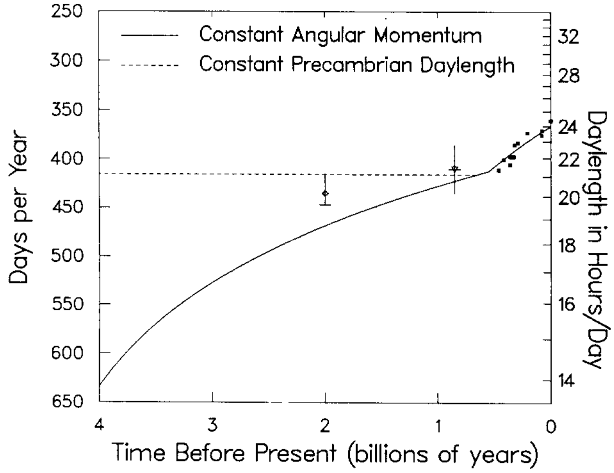

Fig. 5. Comparison of Precambrian stromatolitic data with the number of days per year calculated according to the assumptions of constant Earth-Moon system angular momentum (solid line) and constant resonant 21 h day (dashed line). The triangle is from Vanyo and Awramik (1982) and the diamond from Panella (1975) - see text for details. Also shown are mean-count data from the Phanerozoic (after Scrutton, 1978).

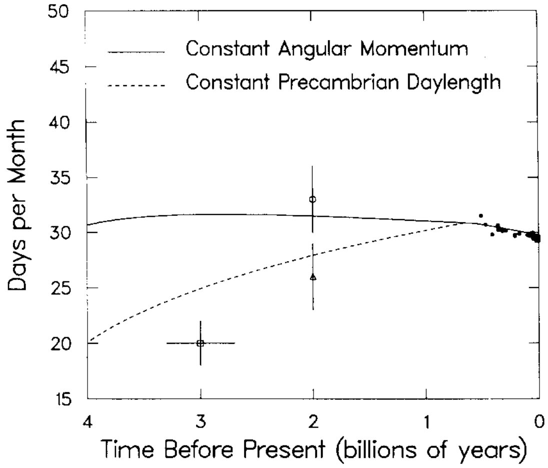

Fig. 6. Comparison of Precambrian stromatolitic data with the number of days per month calculated according to the assumptions of constant Earth-Moon system angular momentum (solid line) and constant resonant 21 h day (dashed line). The triangle is from Mohr (1975); the circle and the square are from Panella (1975) - see text for details. Also shown are mean-count data from the Phanerozoic (after Scrutton, 1978).

temporaneous samples from the nearby Gunflint formation, Panella (1975) obtains a maximum count of ~ 39 days per month. However, comparing histograms of Mohr's and Panella's data, as Lambeck (1980) does, indicates that the difference between the two datasets is not nearly so great. Indeed, the mean of Panella's data appears to be ~ 33 ± 3 days per month. Both means are plotted in Fig. 6. The error bars refer only to the scatter in the data. They say nothing about systematic errors that may arise from the observer's methodology or eyesight, or to perverse behavior by the stromatolites themselves. It can be seen that they neatly bracket the range of 'acceptable' months.

The third and oldest month is also the most puzzling in the context of tidal evolution. Panella (1975) reports a bimodal distribution with rather sharp periodicities of ~ 10 and ~ 20 counts (not maximum counts, in this case) for a sample from the Bulawayan Group of Zimbabwe. These cannot be understood within the confines of traditional tidal theory as days per fortnight or days per month. On the other hand, the quality of the data appears to be pretty good, if it can be judged by the low scatter in the histogram. If the sample were old enough, it would be possible to explain these data in terms of a resonant daylength sustained over most of the Precambrian (Fig. 6). According to Windley (1977), the Bulawayan is somewhere between 2.7 and 3.5 Ga old, but probably closer to 2.7. In this context, it is interesting to note that the atmosphere c. 3 Ga bp may have been quite rich in CO_2 - J.F.Kasting (personal communication, 1986) estimates ~ 0.1–1 bar of CO_2. Such an atmosphere would have a reduced scale height and therefore a longer resonant day. As a specific example, equal N_2 and CO_2 abundances coupled with a reasonable lunar distance of 48 $R_\oplus$ implies ~ 21 days per month, provided of course that the daylength was regulated all the time by the hypothetical metastable resonance.

As implied above, these data should not be taken too seriously. To the extent that Precambrian stromatolitic data can be believed, they do tend to support the hypothesis of a ~ 21 h day better than they support conservation of Earth–Moon system angular momentum.

Impact of a sustained resonance on the orbital elements of the Earth–Moon system

To assess the impact of a stabilized resonance on the orbital elements of the Earth–Moon system, we need to integrate the time-averaged tidal torques retaining obliquity. It is convenient to refer tidal torques to the plane of the ecliptic, following the notation used by Goldreich (1966) in his lucid review of these matters. It can be shown that the nonvanishing torques on the resonant component of the atmospheric tide may be expressed as

$$T'_{\oplus 2} = \frac{3\pi G M_\odot R_\oplus^4}{4a_\odot^3}\,\frac{\delta p(0)}{g}(1.000 + 0.854\cos^2\gamma)\sin\gamma\sin(2\Delta\phi) \qquad (4)$$

$$T'_{\oplus 3} = \frac{3\pi G M_\odot R_\oplus^4}{4a_\odot^3}\,\frac{\delta p(0)}{g}(1.146 + 0.854\cos^2\gamma)\cos\gamma\sin(2\Delta\phi) \qquad (5)$$

where γ is the obliquity; $T'_{\oplus 3}$ is the average torque around the ecliptic axis; and $T'_{\oplus 2}$ is the average torque around the axis in the ecliptic plane perpendicular to the line of nodes. The rate of change in the rotation angular momentum $H_\oplus$ of Earth in this notation is

$$\frac{dH_\oplus}{dt} = T_{\oplus 2}\sin\epsilon + T'_{\oplus 2}\sin\gamma + T_{\oplus 3}\sin\epsilon + T'_{\oplus 3}\sin\gamma \qquad (6)$$

In a stable resonance this must vanish. Equations 4–6 may therefore be solved for the product $\delta p \sin(s\Delta\phi)$ required to balance the lunar torques. The lunar orbit may then be integrated backwards in time following Goldreich's prescription.

The results of the exercise with and without an imposed 21.3 h day are compared in Fig. 7. Aside from the assumed impact on the length of day, the only orbital parameter that would be visibly affected is the total angular momentum of the Earth–Moon system, which conceivably could have increased as much as 10–20% over the life of the solar system, if the resonance had lasted so long (the additional angular momentum being extracted from Earth's orbit). The resonance would have no direct impact on the timescale problem, because the evolution of the semimajor axis of the lunar orbit is unchanged by solar tides, and hence is affected by a resonant daylength only insofar as oceanic tidal dissipation is affected.

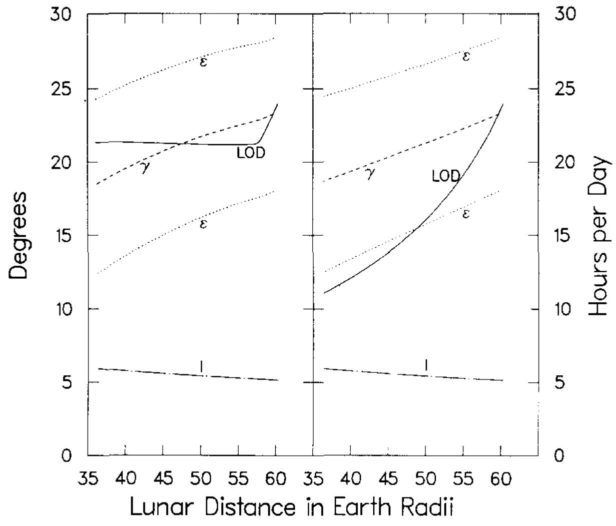

Fig. 7. Integration of the lunar orbit with and without a sustained resonant day. Length of day (LOD), obliquity (γ) of Earth's equator to the ecliptic, inclination (I) of the lunar orbit to the ecliptic, and the limits to the precessing inclination (ϵ) of the lunar orbit to Earth's equator are shown.

Summary

We have observed that the solar semidiurnal atmospheric thermal tide would have been resonant with free oscillations of the atmosphere when the day was ~21 h long. Paleontological evidence implies that the resonance took place about 600 Ma ago, coinciding with the end of the Precambrian and the beginning of the Phanerozoic. Near resonance, tidal amplitudes may well have grown large enough to have influenced the weather, especially in the tropics. This potential to seriously perturb the tropical climate is of particular interest in the late Precambrian, since widespread episodes of apparently tropical glaciation have been reported at that time. Possibly related is the apparent preservation of the sunspot cycle and the lunar nodal tide in the 680 Ma old Elatina formation implying enormous amplification of very small changes in climatic forcing, such as might be provided by a nearly resonant atmospheric tide.

The solar torque on the resonant tide could have been as large or larger than lunar torques on oceanic tides. Since the solar torque on the thermal tide can accelerate Earth's rotation, a balance between lunar deceleration and solar acceleration dynamically regulating daylength could have resulted. In principle this balance could have been maintained indefinitely, perhaps for most of the Precambrian, provided that changes in the atmosphere's temperature and composition did not take place too quickly for tidal evolution to keep pace. Escape from the resonance could have followed a relatively abrupt global warming, such as that occurring at the transition from the Precambrian to the Cambrian, or it may simply have resulted from the onset of anomalously high oceanic tidal dissipation in the Cambrian. A less appealing alternative mechanism could have been provided by a postulated rise in ozone at that time.

Finally, we have considered some of the consequences of an imposed 21 h day on the evolution of the orbital elements of the Earth–Moon system, and, where possible, have compared these consequences with the few available data.

Acknowledgments

The authors thank H. Heuben, R. Zurek, and G. Thomas for helpful discussions and J. Kasting for suggesting the use of moist adiabats and supplying the code to calculate them. This research was supported in part by NASA under Grant NAGW-176.

References

Awramik, S. and Vanyo, J., 1986. Heliotropism in modern stromatolites. Science, 231: 1279-1281.

Berkner, L.V. and Marshall, L.L., 1965. On the origin and rise of oxygen concentration in the Earth's atmosphere. J. Atmos. Sci., 22: 225-261.

Chapman, S. and Lindzen, R.S. 1970. Atmospheric Tides. Gordon and Breach, New York, 190 pp.

Craig, R.A., 1965. The Upper Atmosphere. Academic Press, New York, 509 pp.

Crowley, T.J., 1983. The geological record of climatic change. Rev. Geophys. Space Sci., 21: 828-877.

Dobrovolskis, A. and Ingersoll, A., 1980. Atmospheric tides and the rotation of Venus. Icarus, 41: 1-17.

Frakes, L.A., 1979. Climates Throughout Geologic Time. Elsevier, Amsterdam, 300 pp.

Forbes, J.M. and Garrett, H.B., 1978. Theoretical studies of atmospheric tides. Rev. Geophys. Space Sci., 17: 1951-1981.

Gold, T. and Soter, S., 1969. Atmospheric tides and the resonant rotation of Venus. Icarus, 11: 356-366.

Goldreich, P., 1966. History of the lunar orbit. Rev. Geophys., 4: 411-439.

Hamilton, K., 1981. Latent heat release as a possible mechanism for atmospheric tides. Mon. Weather Rev., 109: 3-17.

Hansen, K.S., 1982. Secular effects of oceanic tidal dissipation on the moon's orbit and the Earth's rotation. Rev. Geophys. Space Sci., 20: 457-480.

Holmberg, E.R.R., 1952. A suggested explanation of the present value of rotation of the Earth. Mon. Not. R. Astron. Soc. Geophys. Supp., 6: 325-330.

Kasting, J.F., Pollack, J.B. and Ackerman, T.P., 1984. Response of Earth's atmosphere to increases in solar flux and implications for loss of water from Venus. Icarus, 57: 335-355.

Kasting, J.F., Holland, H.D. and Pinto, J., 1985. Oxidant abundances in rainwater and the evolution of atmospheric oxygen. J. Geophys. Res., 90: 10 497-10 510.

Kato, S., 1980. Dynamics of the Upper Atmosphere. Center for Academic Publications, Tokyo, 473 pp.

Kelvin, L., 1882. On the thermodynamical acceleration of the Earth's rotation. Proc. R. Soc. Edinburgh, 11: 396-405.

Krohn, J. and Sündermann, J., 1982. Paleotides before the Permian. In: P. Brosche and J. Sündermann (Editors), Tidal Friction and the Earth's Rotation. Springer-Verlag, New York, pp. 190-209.

Lamb, H., 1932. Hydrodynamics. Dover, New York, 738 pp.

Lambeck, K., 1980. The Earth's Variable Rotation. Cambridge University Press, Cambridge, 500 pp.

Lindzen, R.S., 1978. Effect of daily variations in cumulonimbus activity on the atmospheric semidiurnal tide. Mon. Weather Rev., 106: 526-533.

Lindzen, R.S. and Blake, D., 1972. Lamb waves in the presence of realistic distributions of temperature and dissipation. J. Geophys. Res., 77: 2166-2176.

Lindzen, R.S. and Chapman, S., 1971. Atmospheric Tides. Space Sci. Rev., 10: 3-180.

Mohr, R.E., 1975. Measured periodicities of the Biwabik stromatolites and their geophysical significance. In: G.D. Rosenberg and S.K. Runcorn (Editors), Growth Rhythms and the History of the Earth's Rotation. Wiley, New York, pp. 43-55.

Morss, D.A. and Kuhn, W.R., 1978. Paleoatmospheric temperature structure. Icarus, 33: 40-49.

Panella, G., 1975. Paleontological clocks and the history of the Earth's rotation. In: G.D. Rosenberg and S.K. Runcorn (Editors), Growth Rhythms and the History of the Earth's Rotation. Wiley, New York, pp. 253-284.

Scrutton, C.T., 1978. Periodic growth features in fossil organisms and the length of the day and month. In: P. Brosche and J. Sündermann (Editors), Tidal Friction and the Earth's Rotation. Springer-Verlag, New York, pp. 154-196.

Siebert, M., 1961. Atmospheric tides. Adv. Geophys., 7: 105-187.

Sündermann, J. and Brosche, P., 1978. The numerical computation of tidal friction for present and ancient oceans. In: P. Brosche and J. Sündermann (Editors), Tidal Friction and the Earth's Rotation. Springer-Verlag, New York, pp. 165-174.

Trendall, A.F., 1973. Varve cycles in the Weeli-Wolli Formation of the Precambrian Hamersley Group. Econ. Geol., 68: 1089-1097.

U.S. Standard Atmosphere Supplements, 1966.

Vanyo, J.P. and Awramik, S.M., 1982. Length of day and obliquity of the ecliptic 850 Ma ago: preliminary results of a stromatolitic growth model. Geophys. Res. Lett., 9: 1125-1128.

Walker, J.C.G., Klein, C., Schidlowski, M. Schopf, J.W., Stevenson, D.J. and Walter, M.R., 1983. Environmental evolution of the Archean-early Proterozoic Earth. In: J.W. Schopf (Editor), Earth's Earliest Biosphere: Its Origin and Evolution. Princeton University Press, Princeton, NJ, pp. 260-290.

Walker, J.C.G. and Zahnle, K., 1986. The lunar nodal tide and the distance to the moon during the Precambrian Era. Nature, 320: 600-602.

Webb, D.J., 1983. On the reduction in tidal dissipation produced by increases in the Earth's rotation rate. In: P. Brosche and J. Sündermann (Editors), Tidal Friction and the Earth's Rotation II. Springer-Verlag, New York, pp. 210-221.

Williams, G.E. and Sonett, C.P., 1985. Solar signature in sedimentary cycles from the Late Precambrian Elatina Formation, Australia. Nature, 318: 523-527.

Windley, B.F., 1977. The Evolving Continents. Wiley, New York, 385 pp.

Zahnle, K. and Walker, J.C.G., 1987. Climate oscillations during the Precambrian Era. Climatic Change, in press.