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Tidal Friction in the Earth-Moon System [and Discussion]

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Tidal friction in the Earth–Moon system

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Modern computers enable us to obtain realistic values for the present tidal torque between the Moon and the oceans; those values agree with the observations. In principle, computations for distant geological epochs are possible as well and have been performed. However, the very complex eigenperiod spectrum of the oceans today precludes a continuous reconstruction of the tidal torque for an essential part of the Earth's history. Hence the original state of the Earth–Moon system is still uncertain. We emphasize the importance of results for intermediate timescales.

> *Die Wahrheit finden wollen ist Verdienst, wenn man auch auf dem Wege irrt.*
> G. Ch. Lichtenberg, F.R.S. (1742–1799)

1. The principle

Rotation is a special manifestation of organized angular momentum. The angular momentum of the Earth–Moon system is not an arbitrary quantity but fits well with the mass–angular momentum correlation of other planets (Brosche 1963). What does not fit is the preponderance of the *orbital* angular momentum of the satellite as compared with the *rotational* angular momentum of the central planet. Hence a process which carries angular momentum from the Earth into the lunar orbit is also of interest with respect to the more general question of the uniformity of our planetary system.

The first empirical evidence for such a transfer was noted qualitatively by Halley in 1695 and quantitatively by Dunthorne in 1749: an apparent change in the mean motion of the Moon. The theory started without knowledge of the empirical findings: in 1754 Kant proposed a decelerating effect of the oceanic tides on the rotation of the Earth. This was actually one half of a qualitative theory, namely the 'actio' of the Moon on the Earth. The other part, the 'reactio' on the Moon, and thus for the first time a complete – although qualitative – theory, was provided in 1848 by Robert Mayer, more famous for his discovery of the principle of energy conservation. According to him, the two slightly retarded tidal bulges caused by the Moon produce a net torque which transfers angular momentum from the Earth's rotation into the lunar orbit. In a pessimistically exaggerated view, this is still our level of understanding. The main reason lies in the fact (which has become more and more clear) that *oceanic* tides play the dominant role in the interaction (Zschau 1978), while the tides of the solid Earth only modify the first to some extent; oceanic tides are of great geometrical and physical complexity. As a result, all the different schematic quantitative theories developed by Darwin and his successors (which are based on some kind of a solid tide picture) cannot provide the most essential information: the strength of the interaction and its dependence on the time.

2. HISTORICAL TIMES

The compilations of ancient eclipse data, of lunar occultations embedded in a Mercury timescale, and recently of lunar laser ranging data have led to consistent values for the tidal torque

$$L = 5 \times 10^{16}\ \mathrm{N\ m}$$

(positive on the Moon, retarding on the Earth) which corresponds to an extension of the lunar orbit of about $\dot{r} = +4$ cm per year and a decrease of the rotational energy of the Earth of -4×10^{12} W (for a brief review see Brosche & Sündermann 1984). This power amounts to about 20% of the radioactive heat production of the Earth.

The advent of large electronic computers has made it possible to treat the hydrodynamical equations for the tides in a sufficiently narrow mesh to obtain a realistic value for the average torque between the Moon and the waters of the oceans. In short, modern models of the present oceanic tides, especially of the most important M_2-tide, are able to represent the above mentioned torque to within 10% or 20%, which seems quite satisfactory since such accuracy is comparable both with the empirical and the theoretical uncertainty.

However, both sides should be developed further because (1) only a more precise agreement gives full justification to the application of our models at times when there were no measurements, (2) a full understanding of *all steps* of the interaction is desirable, and (3) *instantaneous* consequences of the models may soon come into a measurable range. While we shall treat the first topic in the next section, we should note with regard to the second the still unsettled question of where and how the tidal dissipation takes place: for a fixed eccentricity of the lunar orbit, only a fraction (*ca.* 1 day per month $\approx \frac{1}{30}$) of the rotational energy lost by the Earth enters into the lunar orbit. Hence the overwhelming majority is dissipated. The values of phenomenological dissipation coefficients in the hydrodynamical equations can be adjusted accordingly, but this does not give a physically sound answer. And with respect to the third topic, we may mention that obviously not even all the *qualitative* aspects have been clarified. Recently we were able to show (Baader *et al.* 1983) that contrary to a previous assumption, the main instantaneous influence of the M_2-tide does not act via the changing moments of inertia on the Earth's rotation, but instead via the changing velocities of the water. The total range of the effect for the M_2-tide – 0.05 ms in U.T. – may be larger for fortnightly tides and hence soon touch the steadily improving limits of very long baseline interferometry measurements.

3. GEOLOGICAL TIMES

The main incentive of research in our field has been and still is the 'ultimate' fate of the Earth–Moon system when we trace its evolution: in other words whether there was – and if so, when – a narrow state of the system such that the Moon was within the Roche limit of the Earth. This is, of course, crucial for all theories of the evolution of the Earth–Moon system. As a rule, schematic backwards integrations (with two bulges, etc. resembling solid Earth tides) reach a narrow state in too short a time into the past, in contradiction with the lack of any geological evidence. Hydrodynamical calculations offer a more realistic approach but they require the sea-floor topography for the epoch under consideration. Owing to continental drift, this topography changes continuously. Apart from the lack of precise ocean depth data, we have fair maps of the Earth's surface for the last few 100 Ma (Ziegler *et al.* 1982). Moreover, Piper (1982) extended the palaeogeographic reconstructions up to 2.8×10^9 years! He found a single continent for a long time interval but with varying positions with respect to the Earth's axis.

On the basis of this information – including the limits of the shelf areas – we computed models for the M_2-tide at several geological epochs (Brosche & Sündermann 1984), the oldest being the Middle Ordivician 450 Ma ago. The main result is a variation of the average tidal torque by a factor of two, large enough possibly to solve the timescale problem mentioned above, but far from sufficient to show that the torque was indeed on the low side for most of the time. This is so not only because our oldest time is just 10% of the total age of the Earth, but also because the large time intervals between our consecutive models do not permit any interpolation. The reason for this is not a new effect but has become increasingly evident during recent years: it is the very complex eigenperiod spectrum of the oceans. While the schematic backwards integrations implicitly assume that the oceans are very far from any resonance state, they are in fact just within a rich manifold of eigenvalues (Sündermann 1982). That becomes obvious as soon as hydrodynamics is introduced into an otherwise schematic picture: Webb (1982*a*, *b*) determined the tidal torque for a hemispherical ocean with different latitudes of the centre. When the torque changed the Earth's rotation and the lunar orbit accordingly, the torque (a function of time) went through a large number of peaks. Only by averaging over all latitudes was it possible to smooth out the variations. Such statistical averaging is probably not in accordance with the real palaeogeographic variations.

Consequently, Webb (1982*b*) adopted Piper's (1982) southern position of the single continent and obtained curve (e) in his figure 2, to be compared with curve (c) for statistically-averaged continent position: while the first does not reach a narrow state within the age of the Earth, the second does it marginally. Hansen (1982) thinks that he found another *via regia* to overcome the complexity of the oceans. He argues that the oceans are only now near to a state of resonance but were not so in the distant past; furthermore he assumes that the influence of changing continent configurations is averaging out as compared with the influence of the changing parameters of the Earth–Moon system. He therefore performs backwards integrations using the *present* topography. Also in his scenario, the system does not become narrow within the time available. Although I agree with this result, it does not seem to be the final proof. The change of the oceanic eigenperiods due to continental drift occurs much faster than the change of the forcing periods due to tidal friction. Therefore, at least in the short run, the first process determines the rapid changes in the torque (nevertheless, the second process may be decisive for the average). As an illustrative example (see figure 1), we studied the effect of the present continental drift idealized by a pure east–west shift of the two Americas (Brosche & Hövel 1982). Our extremal shifts correspond to about 20 Ma in the past and 10 Ma in the future. We obtain a certain resonance curve of the torque with a flat minimum *ca.* 13 Ma ago and a rather sharp maximum in *ca.* 6 Ma. The ratio of the torques at the extrema is nearly 1:2. Our present value is somewhat above the average. From the timescale of the variation we can conclude that, in general, the time step between consecutive models needs to be not larger than a few (preferably one) million years. This is a very strong demand. On the other hand, such a considerable variation within around 20 Ma means that the tidal torque is not a tedious function of time of which only the final result is of scientific importance. Instead, this function has a rich spectrum of its own interest; its geophysical implications have still to be explored. For example since the magnetic field of the Earth and its rotation are related,

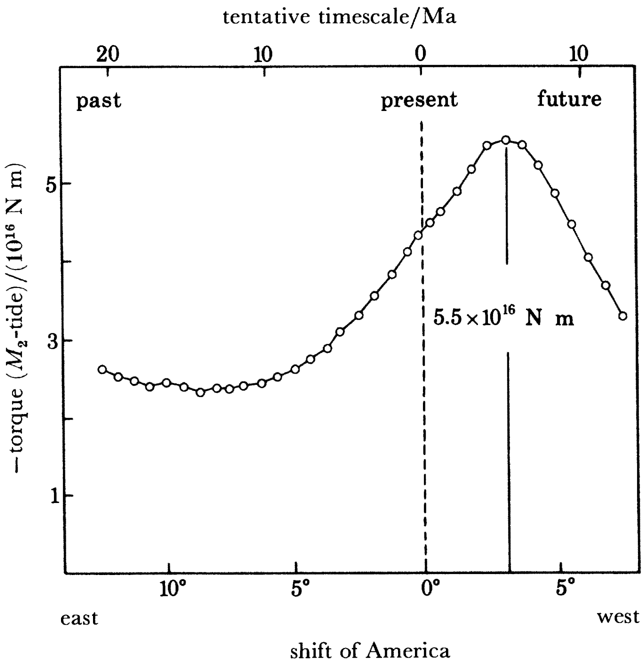

FIGURE 1. The tidal torque of the Moon (M_2-tide only) acting on the Earth in dependence on the position of the American continents.

the torque variations may be connected with the reversals of the field (Brosche 1981). Also the palaeooceanography of the different epochs is certainly of great interest. Therefore research in this field should not be done with eyes fixed on the 'end' of the journey only (that is, the origin of the Earth–Moon system), but should be done equally for the journey itself.

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Discussion

M. M. Woolfson, F.R.S. (*Department of Physics, University of York, Heslington, York, U.K.*). While I appreciate the uncertainties in the models, is Professor Brosche able to postulate anything about the origin of the Earth–Moon system?

P. Brosche. From the results on palaeotides, it seems more probable that the Moon was not in a ‘narrow’ state, especially if there were no oceans during the first aeons. But this depends on the rheology of the early Earth.