TIDAL HEATING OF THE MOON: A REAPPRAISAL. Joseph A. Burns (Cornell University, Ithaca, NY 14853) and Peter H. Schultz (Lunar Science Institute, Houston, TX 77058).

Tidal stresses--or, more correctly, their variation with time--deposit heat in any non-perfect material during its flexing back and forth. Tidal stresses in today's Moon, and therefore its tidal heating, are quite small but in the past, when the Moon had not yet orbitally evolved far from the Earth, they were significantly larger. Attention has been drawn for nearly two decades to this heating as a possibly important lunar thermal source, following its original mention (1). Moreover, tidal despinning--merely another variant of an oscillating tidal stress--has been considered as perhaps appreciable in the early thermal budgets of the Moon, the Galilean satellites (cf.2) and Mercury (3). However in these cases, a simple calculation (3) of the rotational energy density shows that despinning accounts for no more than about a 100°K temperature rise. In this paper we wish to reappraise the usual tidal heating taking into account new tidal stress calculations by Peale and Cassen (4).

The original detailed calculations of tidal heating were done improperly by Kopal (5) and nearly correctly in a fundamental paper by Kaula (6,7). The latter work has now been improved by Peale and Cassen (4), who have corrected a few mistakes in it, given it a sounder physical basis and extended it by considering both a homogeneous and a non-homogeneous (two-layer) Moon. They rely on expressions (8) for the displacement of an incompressible homogeneous sphere subjected to a harmonic body force; then they compute the tidal energy dissipation in the Moon when driven by either eccentricity (libration) or inclination (obliquity) terms.

Interest in such tidal heating has been heightened by contentions that mare basalts may be produced in this manner (9) and that the entire Moon may have been melted (10), at least if it had an unusual orbit. In addition, Schultz, Burns and Greeley (11) point out that mare flooding may in part be activated by the large tidal variations that occur during passage of the Moon through the region between about 30 and 45R. At that time, the Moon lay near a resonance at 34.2R such that Cassini's laws require the obliquity to be high, reaching a maximum of 77° but throughout being larger than at least about 15° (12). These authors (11) further suggest that features may be found on the maria to identify such a high tide phase; however, tidally unrelated processes such as devolatization may make certain identifications problematic. Kaula and Yoder (13) have qualitatively included such an obliquity history in a tidal heating calculation but continue to find the time-integrated thermal input due to tidal heating to be insignificant in comparison to radiogenic sources. Peale and Cassen's (4) refinement does not affect this conclusion unless special circumstances prevailed.

We argue here that these conclusions may have been too quickly reached and point out several ways in which tidal heating may become appreciable: (i) new choices of the anelasticity factors for the Earth and Moon; (ii) inhomogeneities in lunar properties; and iii) runaway heating. The first of these is the best argued. The total heat deposited is proportional to $Q_{\oplus}/Q_{☾}$, where the numerator comes from the lunar orbital evolution time scale and the denominator determines the efficiency of energy deposition in a single flex

of the Moon. Figure 1 shows possible evolution tracks for the Moon's orbital semimajor axis assuming a circular orbit and the simplest tidal evolution. The present orbital evolution rate corresponds to $Q_{\oplus}$ =13 according to classical measurements, but more recent observations suggest that $Q_{\oplus}$=7 may be more nearly correct (14). Thus, if the Moon is taken to have originated near the Earth 4.5 x 10^9 years ago, $Q_{\oplus}$ must have been much higher in the past. Taking the simplest view (that throughout history there have been only two Qs-today's and one other), we see that $Q_{\oplus}$ in the past may have been ten times the current value, implying that the high obliquity region (stippled) was traversed relatively slowly, starting several times 10^8 years following origin. Furthermore, recent lunar laser ranging of the phase lag in the libration even suggests that the global Q of the Moon may be as low as 10 (15), in contrast to previous local seismic measurements. These two factors could raise the deposited heat due to tides by as much as one hundred times the conservative estimate of (4), although even then tidal heating is not the primary heat source once the Moon moves beyond 50R . Furthermore, as previously noted (4,9,13), radial and/or lateral inhomogeneities heighten strains and stresses and thus can make energy deposition locally more efficient. A thermal runaway scenario has been investigated (4) in which the melting of a thin-shelled Moon is triggered by tidal heating, thereby making the shell thinner yet so that heating is even more effective. High temperatures increase energy absorption as well because they are known to drastically lower Q (16,17). The latter effect may permit a thermal runaway, in which increased temperatures make energy deposition yet more effective, further increasing T, ...and, when coupled with the previous mechanism, may make tidal heating particularly important in enlarging and opening magma chambers. Thus although special circurstances may be necessary to allow tidal heating to be important, these circumstances may indeed have occurred. Therefore, tidal heating must continue to be kept in mind as a possibly important process of the global and especially the local history.

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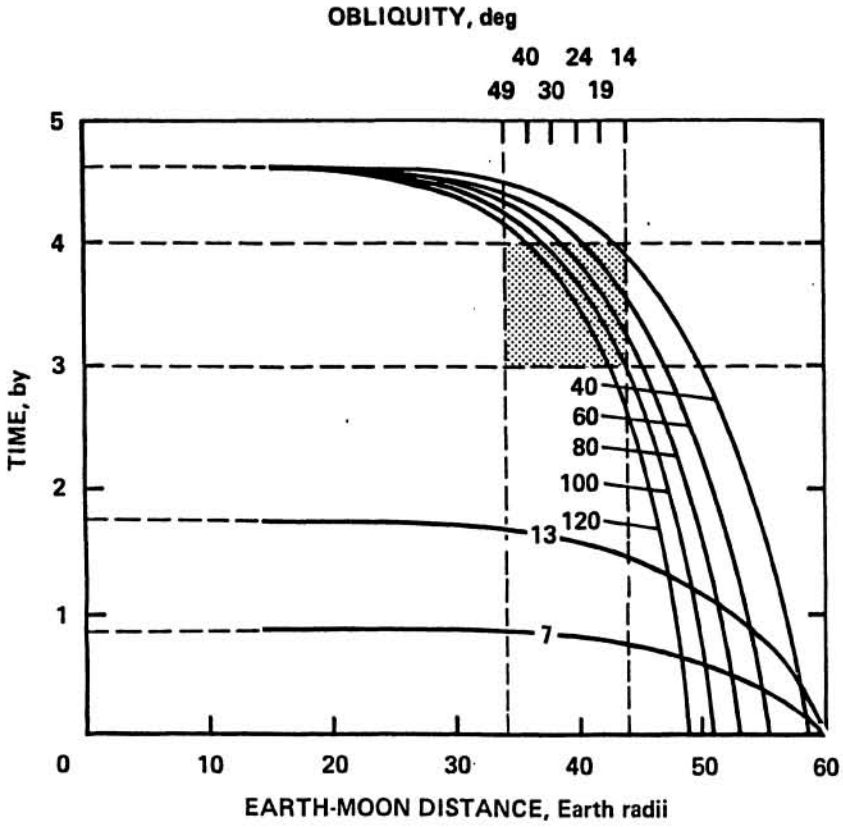

Figure 1. Orbital evolution tracks of the Moon for different values of the Earth's tidal Q. Present values of $Q_{\oplus}$ between 7 and 13 evolves the Moon's position close to the Earth between about 0.9 to 1.8 by ago. If the Moon evolved from a position near the Earth at the time of its formation (4.6 by ago), then a change to higher values of Q is necessary, and the Moon would have passed through high obliquity states during the time of mare flooding indicated by the stippled area. Obliquities shown correspond only to the final stable Cassini state 2. Prior to this time (inside 34.2R) the obliquity was for a short time as high as 77° but more generally less than 26° (12).