
The dissipation of mechanical strain energy associated with the tidal flexing of the moon as it librates and follows its eccentric orbit is frequently mentioned as a possibly important means of heating the lunar interior. Although it is generally recognized that such dissipation is not important at the present time, this may not have always been the case, since the Moon was much closer to the Earth in the past. Recently several investigators have proposed that tidal heating could have provided heat for producing mare lavas (Wones and Shaw, 1975; Schultz et al., 1976), complete melting of the moon (Turcotte et al., 1977) or that tidal stresses could have triggered basin flooding (Schultz et al., 1976). Kaula and Yoder (1976) discuss several ways in which tidal heating might contribute to lunar thermal history, but conclude that such contributions are unlikely from order of magnitude calculations; they in fact anticipate some of our conclusions. The purpose of this paper is to define as precisely as possible within the bounds of the uncertainties the conditions under which tidal heating could have been an important factor in the evolution of the moon. The tidal dissipation is determined as a function of position in a homogeneous, incompressible moon and as a function of the Earth-Moon separation. The lunar obliquity as a function of Earth-Moon separation was assumed to be that corresponding to the stable equilibrium Cassini states (Ward, 1975), and results are given for two values of eccentricity £=0.0 and £=0.055, which are maintained throughout the orbital evolution.

Figures 1 and 2 illustrate the distribution of the tidal dissipation throughout an incompressible, homogeneous moon with Q=100, for the cases where the tidal variations are caused by a non zero obliquity or a non zero eccentricity respectively. Dissipation is maximal at the center. Fig. 3 shows the total dissipation and the dissipation at the center as a function of the Earth-Moon separation again with a lunar Q=100. In order to compare the tidal dissipation with heating by nuclear decay (Reynolds et al., 1972), a simplified orbital evolution is assumed, where the moon regresses from a semimajor axis a=3a_E (a_E = Earth radius) to its present location in 4.6 x 10^9 years with a constant dissipation factor Q for the earth. The increase in dissipation at a/a_E ~ 34 results from large values of the obliquity when the moon transfers from Cassini state 1 to state 2 (Ward, 1975). Although tidal heating exceeds the radiogenic heating when the moon is sufficiently close to the earth, its total contribution to lunar thermal history is negligible in the above model. The cumulative energy deposition is shown in Fig. 4.
with $Q = 100$ for the simplified orbital evolution, and it is seen that the high dissipation rate for the small Earth-Moon separation is not effective in heating the moon since the Moon is pushed away from the Earth too rapidly. For this model of orbital evolution and lunar properties an average temperature increase not exceeding $40^\circ K$ would result over a $4.6 \times 10^9$ year history. Hence, for this model tidal friction has been a negligible contributor to lunar thermal history.

Kaula and Yoder (1976) discuss the possible existence of two orbital resonances between the Sun and Moon and Jupiter and Moon as a means of keeping the Moon close to the Earth while increasing the orbital eccentricity. The increased eccentricity could easily lead to melting the moon in these resonances, but for distinct reasons, each is likely not to have occurred.

Figure 5 shows the tidal dissipation as a function of Earth-Moon separation which would have occurred in a solid lunar mantle over a molten core. The local dissipation in this two layer model exceeds that for the homogeneous Moon by a factor of 5 if the core radius $r_c$ is $0.5 a_e$ ($a_e$ = lunar radius) and a factor of 100 if $r_c = 0.95 a_e$. If the Moon remained within about $45 a_e$ for more than $10^8$ years with $r_c \geq 0.5 a_e$ the above heating rates are sufficient to cause a runaway melting of the outer portion of the moon. However, the interior of the Moon would have had to have been melted by some other energy source prior to such a runaway.

As circumstances must be very special for significant heating by tidal friction, we conclude that lunar thermal history was essentially controlled by radiogenic sources and initial accretional heating. Whereas a previously molten interior or a more exotic orbital history involving large eccentricities (Turcotte et al., 1977) would drastically increase the importance of the tides, we see no compelling reasons for assuming either state of affairs ever existed. Details of the calculations and further discussion of assumptions, uncertainties and conclusions are given by Peale and Cassen (1977).

**FIGURE CAPTIONS**

Fig. 1. Distribution of tidal energy dissipation in the moon when inclination terms are dominant. Contours are labeled in ergs cm$^{-3}$ sec$^{-1}$.

Fig. 2. Distribution of tidal energy dissipation in the moon when eccentricity terms are dominant. Contours are labeled in ergs cm$^{-3}$ sec$^{-1}$.

Fig. 3. Central and total tidal dissipation as a function of lunar orbit semimajor axis. $Q=100$ is assumed.

Fig. 4. Cumulative energy deposition by tidal dissipation and nuclear sources as a function of time.

Fig. 5. Dissipation in the solid mantle at the core-mantle interface for $A = 0^\circ$. 

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CONT. OF TIDAL DISS. TO LUNAR THERMAL HISTORY

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References

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