
Present solid-body tides on the moon induced by the earth trigger only meager seismic energy (1). However, the tide-raising force was once much greater since the continuous transfer of angular momentum from the earth's rotation to the moon's orbital motion requires that the moon was much closer to the earth in the past. Theoretical models suggest that this period of earth-moon tidal interaction could generate appreciable heating of the lunar interior (2,3) and produce mare basalt magmas (4,5). We consider here the possible surface effects from such an interaction, specifically the effects of periodic tides similar to, but much larger than, present tides on the earth.

The tidal decay time for the lunar spin rate can be shown to be at least an order-of-magnitude shorter than the characteristic time for orbital evolution (6,7,8). As a result, the moon arrived in a synchronous state with one side always facing the earth early in its orbital history: such a state alone would not produce periodic surface tides for a circular orbit. However, tilt of the lunar spin axis relative to the orbit normal (lunar obliquity) would introduce librational tides that would migrate north-south during a lunation. Ward (7) has recently shown that the lunar obliquity was once as great as 77° when the moon was at approximately 34R_e (earth radii). Assuming that the moon's orbit evolved smoothly and that the early terrestrial dissipation function (Q) was appreciably higher (Q=60 or 100), we can calculate from the well-known relation for orbital decay (9) that this distance corresponds to ages of 0.2by to 0.3by (billion years) after formation. The high obliquity state was unstable and, within 10^5 years, a new state was attained with an obliquity nearly 50°, which thereafter decreased gradually. Approximately 0.6by-0.9by after formation, the moon's distance had increased to 40R_e while the obliquity decreased to 25°. These ages generally correspond to the early epochs of mare flooding.

Superposed on this rotation and obliquity may have been large but short-term perturbations induced by the impacts which formed the large lunar basins (10). An oblique impact such as the Imbrium impact may have unlocked the moon's synchronous rotation and temporarily changed the axis of the least moment of inertia. Consequently, significant librations in latitude and longitude probably occurred approximately 4by before the present. During this time, the tidal bulge traced an entirely new path across the lunar surface with large tidal displacements. The perturbation on the dynamical model by Ward (7), however, would have been short-lived (on the order of 10^3 years at 35R_e) and the orientation returned to near the pre-impact configuration.

The maximum tidal difference (Δh) experienced each lunation at the latitude (+ or -) equal to the value of the obliquity can be estimated by modifying the classical equilibrium formula (11) for a mare "ocean" of constant, great depth over the entire moon (this relation also holds approximately elsewhere):

\[ \Delta h = \frac{H}{(1 - \frac{6}{5} \frac{\rho}{\rho_0})} \sin^2 \theta \]
where \( H = R(E/M)(R/r)^3 \); \( R \) = radius of the moon; \( r \) = earth-moon distance; \( E \) = mass of the earth; \( M \) = mass of the moon; \( \rho \) = density of the fluid mare basalt; \( \rho_o \) = mean density of the moon; and \( \theta \) = lunar obliquity. Solid body tidal amplitudes would be less by \( 10^{-1} \) to \( 10^{-2} \).

As the obliquity decreased, the maximum tidal difference lessened owing to the smaller excursions of the tidal bulge from the lunar equator. If the depth (thickness) of the molten mare unit is included (11), it can be shown that a 100m-deep flow over the entire moon would respond essentially the same as a much thicker unit. This is in contrast to a 2km-deep ocean on the earth that exhibits smaller tidal variation than does a much deeper ocean -- a result reflecting the slow lunar rotation rate (10° hours) relative to the terrestrial rate (10 hours).

Table I summarizes the approximate timing and estimated tide heights from equation (1); the results suggest that the emplacement history of the maria should have been affected significantly. Even greater variations could be expected during the perturbations induced by the formation of the large impact basins. Because present fortnightly tides may trigger volcanic eruptions on earth (12,13), the much greater tide-raising forces in the past on the moon also may have played an important role in the eruptive rates and mare distribution. Based on the preceding outline of the dynamical history, the following geologic history is proposed.

1. The earliest stages of mare flooding were initiated prior to the Imbrium impact when the axis of the least moment of inertia was near 30°E. Large librational tides triggered mare-flooding eruptions that remain as the eastern maria from Mare Humboldtianum to Mare Australe. Remnants of this early period include the elevated benches and plateaus surrounding Nectaris and the large departures of the elevation of Mare Tranquilitatis (+1km - +2km) from the tidally induced ellipsoid that fits most later maria as noted by Sjogren and Wollenhaupt(14). Nectarian Plains materials (15) also may be related to this early epoch of volcanism.

2. The Imbrium impact, and later the Orientale impact, induced large migrations of the tidal bulge in longitude and latitude but quickly damped the axis of the least moment to a new location near 30°W. Volcanism continued within the older basins for 0.3by and is exposed as the old mare plains of the eastern hemisphere. The large librational tides extended north to the Imbrium basin and south to the Nubium basin and continually triggered massive eruptions of basalt. This eruptive history is consistent with the interpretation that the Imbrian-age maria represent large eruptive rates producing relatively featureless flood basalts (16). The short tidal period (10^2 years) relative to the cooling rate (10^4 years) of thick flows aided in both leveling the mare plains and encroachment of small inlets on the mare borders. Large terraces in northern Mare Imbrium, mare platforms, and certain wrinkle ridges are interpreted as...
surface expressions of these large lunar tides (17).

3. The tidal variation gradually decreased with lessened latitudinal migration resulting in less voluminous eruptions primarily along a north-south axis coinciding with Oceanus Procellarum. This stage may be represented by the plains-basalt morphology typical of the Eratosthenian maria (16). The response of the thinner (<100m) flows of sufficient areal extent to the tides resulted in the formation of small collapse depressions, ghost rings expressing buried relief, and smaller aprons and terraces surrounding pre-flow topography. Other possible relicts of this orientation include the coincidence of the loci of the present periodic moonquakes with the axis of the last lunar extrusions (4) and the high level of western Oceanus Procellarum relative to the best-fit ellipsoid of other maria (14).

The dynamical models suggest that large lunar tides and mare flooding may be nearly contemporary and that such tides may have an important effect on the emplacement history of the maria. Conversely, future geologic studies could provide constraints on the details of the orbital evolution of the moon.


TABLE I
(ages for Q = 100 and 60)

<table>
<thead>
<tr>
<th>Earth-moon distance (earth radii)</th>
<th>34.2</th>
<th>38</th>
<th>40</th>
<th>42</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (by before present)</td>
<td>4.3-4.4</td>
<td>3.9-4.2</td>
<td>3.7-4.0</td>
<td>3.4-3.6</td>
</tr>
<tr>
<td>Obliquity</td>
<td>77°</td>
<td>30°</td>
<td>25°</td>
<td>15°</td>
</tr>
<tr>
<td>Tidal variation (m)</td>
<td>160</td>
<td>90</td>
<td>60</td>
<td>20</td>
</tr>
</tbody>
</table>