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Coupled Thermal-Orbital Evolution of the Early Moon

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The shape of the Moon is not in hydrostatic equilibrium with its current orbit or any other low-eccentricity past orbit. Garrick-Bethell et al. (2006) proposed that the shape of the Moon could be explained if the lunar shape was frozen in at one of two high-eccentricity orbits. We focus on the solution of a synchronous orbit with semimajor axis of 22.9 Earth radii and an eccentricity of 0.49. Two questions remain about this explanation of the Moon's unusual shape: 1) can the Moon plausibly pass through such a high-eccentricity phase and still end up in today's orbit, and 2) will the shape freeze in during this phase? We address both of these questions.

We find that a high-eccentricity phase of the lunar orbit is possible. A coupled thermal-orbital model of the early lunar evolution enables a peak in eccentricity that can be easily tuned to pass through the shape solution. A key and novel feature of our model is the feedback between the thickness of the solidifying magma ocean's plagioclase lid and the amount of tidal heating. Our model consists of a plagioclase lid overlying a magma ocean overlying a solid mantle. The lid is tidally heated and heat is transported by conduction and melt migration. We find that, for certain parameters, an initially small eccentricity will grow. As the eccentricity grows and tidal heating increases, the lid becomes warm and more dissipative. This causes the eccentricity to decrease sharply. The resulting peak in eccentricity could explain the lunar shape, if the shape could be retained from this epoch when tidal heating is near a maximum.

A simple energetics argument can be used to assess whether the shape can freeze in at the eccentricity required. When the lunar orbital eccentricity drops from the shape solution value to the very low value necessary for the evolution to be consistent with today's orbit, the Moon will either deform or not. If it deforms to the new hydrostatic shape, elastic energy will be stored via the resultant stresses in the lithosphere. If the Moon does not deform, gravitational energy will be stored as a result of the non-hydrostatic shape. Since the Moon will assume the lower-energy configuration, a simple comparison of these two energies will reveal the fate of the lunar shape. We find that the hypothetical stored gravitational energy exceeds the elastic energy and conclude that the Moon will deform. Therefore, even if the Moon had a high-eccentricity phase in its past, the shape cannot be preserved from this epoch.