SPATIO-TEMPORAL EVOLUTION OF LUNAR POLAR COLD TRAPS.

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Introduction: Temperature is the dominant control of ice stability on the Moon. In order to examine the spatial, temporal, and quantitative variability of lunar ice, in this study we develop components of a comprehensive thermal-diffusion model of ice migration and stability, which evolves as a function of changes in the lunar orbit.

The lunar surface thermal environment varies dramatically with latitude, from roughly 400 K at the equator, to as low as ~20 K in shadowed polar regions [1]. As the sublimation of water ice is exponentially dependent on temperature, this causes an even larger variation in ice stability.

Additionally, the lunar thermal environment is a dynamic system, having changed dramatically over the past several billion years. In this work, we model orbital interactions of the Moon with the Earth and Sun that caused large changes in lunar polar illumination. The most dramatic event in this orbital evolution was a high obliquity spin-orbit transition (Cassini State transition), during which surface temperatures of currently shadowed regions would have exceeded 390 K. Therefore, all pre-existing ice would have been driven off, and all extant lunar ice should have been deposited after this event.

This orbit history model is combined with a preliminary thermal-diffusion model, which will allow for examination of spatial and quantitative prediction of subsurface ice. This model shows that retention of supplied ice is highly temperature dependent, favoring efficient migration of ice into the subsurface between roughly 95 and 145 K, depending on local temperature amplitudes. Below about 95 K, water ice will be essentially immobile, subject only to redistribution by non-thermal processes- meaning that supplied ice will be difficult to retain unless quickly buried. Above roughly 145 K water molecules are so mobile that they quickly escape the subsurface. This causes a favored period in the evolution of the lunar orbit for ice deposition at a given location. Therefore, variations in the spatial distribution of polar volatiles may mark a specific period of enhanced supply, most likely in the form of cometary impacts.

Lunar Orbitial Evolution: The spin axis of the Moon is currently tilted by approximately 1.54^{o} with respect to the ecliptic. Dynamical calculations [2, 3] show that this angle should have increased to nearly 83^{o} when the lunar semimajor axis was approximately half of its current value. This large tilt is due to a period of very high obliquity that occurred when the Moon transitioned between two damped spin pole states. In these special damped spin states, called Cassini states, the spin pole and orbit pole precess with the same period. As the spin and orbit poles generally precess at different angular rates, equal periods is achieved by adjusting the the length of the spin pole path (done by changing the obliquity) so as to match the orbit precession period [4]. This equilibriation is a natural result of dissipation within the satellite.

According to this theory, when the lunar semimajor axis was roughly 30 Earth radii (currently 60.2) it transitioned between two stable Cassini states, reaching very high obliquities (~77^{o}) [2,3]. Since that time (roughly 2.5-3.5 Bya) the obliquity has slowly decreased (to the current 6.7^{o}), causing each currently shadowed crater to go through a period of partial illumination.

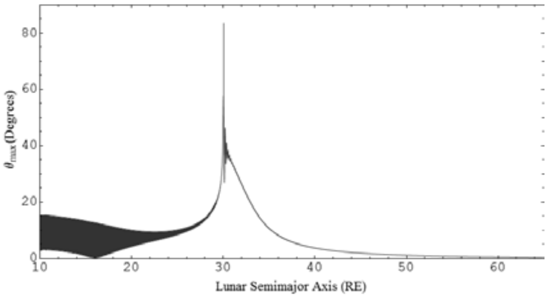

Figure 1: Evolution of the tilt of the Moon with respect to the ecliptic as a function of lunar semimajor axis.

Long-term evolution of lunar cold trap temperatures: We have examined how surface temperatures of the lunar polar regions have chaned during lunar orbital evolution. We use a full, 3D, ray-tracing model developed for the Diviner Lunar Radiometer [5], coupled with lunar topography (from LRO LOLA and Kayguya LAT). We can model current lunar temperatures, comparing them to Diviner data. We are then able to input models of past insolation to examine how surface temperatures of the lunar polar regions have changed as a function of the evolution on the lunar orbit. These models show that the standard "cold traps", generally defined as an area where maximum temperatures remain below 100 K [6], did not exist until the Moon's semimajor axis grew to roughly 35 Earth radii. [7]

Figure 2 illustrates mean annual temperatures (scaled 50-200 K) in the Lunar south polar region up to ~80 S at 1.54^{o}, 4^{o}, 8^{o}, and 12^{o} "declination" (tilt with repect to the ecliptic). Most traditional cold traps [6] did not exist before the Moon reached ~8^{o} declination. This means is that ice in such areas became thermally immobile in these coldtrap locations after ~8^{o} (when their temperatures fell below roughly 90 K). At this point ice would cease to concentrate by thermal migration. Below ~90 K, burial may occur, but will be dominated by impact gardening [8, 9].

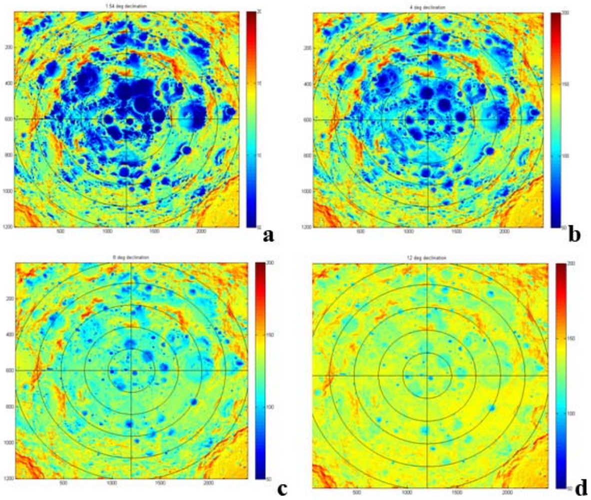

Figure 2: Mean annual temperatures (scaled 50-200 K) in the Lunar south polar region up to ~80 S at (a) 1.54^{o}, (b) 4^{o}, (c) 8^{o}, and (d) 12^{o} "declination" (tilt with respect to the ecliptic).

However, this does not necessarily mean that the Moon could not have collected and concentrated any subsurface ice in slightly warmer periods before this time. At earlier, higher declinations, many areas existed where ice might be stable for part of the year, but mobile enough to migrate into the subsurface. These areas, classified more appropriately as "ice traps" will occur when mean temperatures range between roughly 95 and 145 K [10, 3]. Ice collected in one of these areas may then be permanently retained as a location evolves from ice trap to cold trap.

The mean temperature at which migration into the subsurface is most efficient depends on temperature amplitude and the rate at which water molecules are supplied to the surface. Therefore, for a given supply, any given location will be most efficient at collecting subsurface ice during a specific period in its history. Figure 3 illustrates such a modeled temperature history for Shackleton crater (89.7°S, 111°E), with the grey bar marking temperatures between 90 and 145 K [3].

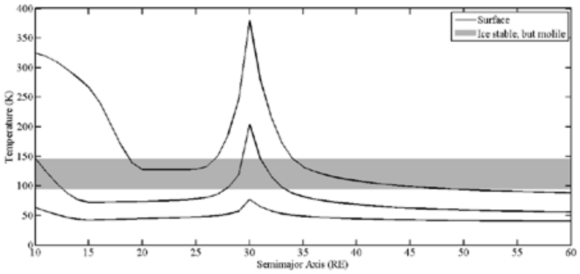

Figure 3: Maximum, mean and minimum temperature history of an example lunar polar crater (Shackleton crater, 89.7°S, 111°E). The grey bar marks rough limits of temperatures where ice would be stable on the surface, but mobile enough to diffuse downward before being lost.

Here we show new models and map the spatial distribution of ice that would have been likely to collect in the distant lunar past. We will also examine if these models shed light on the origin of neutron depleted regions measured by the Lunar Prospector Neutron Spectrometer [11, 12] and LRO LEND [13]. As these data sets show geographically distributed neutron enhancement, they may point to an enhanced delivery of ice at particular point in lunar history. This is a distinct alternative to enhancement by direct, localized cometary impact. If so, the location and abundance of such deposites could shed light on the recent delivery rate of ice to the Moon.

References

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