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Lunar Polar Ice and the Obliquity History of the Moon

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Abstract

Water ice is currently stable from sublimation loss in shadowed environments near the lunar poles. However, most current temperature environments are generally too cold to allow efficient diffusive migration into the subsurface by that would protect water from non-sublimation loss. This has not always the case. Higher past lunar obliquities caused currently shadowed polar regions to have warmer thermal environments. These past environments may have been both cold enough to be able to capture surface ice, but warm enough to drive it into the subsurface.

1. Lunar Orbit History

Roughly halfway through its outward migration (due to tidal interaction with the Earth) the Moon was tilted (currently 1.54^{o}) up to 83^{o} with respect to the ecliptic. During this time, all polar craters would fully illuminated at some point in the year and have been far too warm to preserve water ice [1].

This extreme change in insolation is a result of a spin-orbit configuration, within which the Moon currently resides, known as a Cassini state. A Cassini state results from dissipation within the satellite and drives the spin axis of the satellite to precess at the same angular rate as its orbit. As spin precession is controlled by the satellite moments of inertia and orbit precession by its semimajor axis, the satellite is driven into an obliquity that will cause the spin and orbit angular precession rates to synchronize [2].

According to our model**,** when the lunar semimajor axis measured roughly 30 Earth radii (RE, currently 60.2) it transitioned between two stable Cassini states, reaching very high obliquities (~77^{o}) [1,3]. Since that time (roughly 2.5-3.5 Bya) the obliquity has slowly decrease (to the current 6.7^{o}), causing each currently shadowed crater to go through a period of partial illumination.

In addition to the variation of obliquity, the inclination and precession of the lunar orbit also varied [14]. This caused dramatic variation in the illumination environment of the early Moon. Recent reanalysis [1] of these orbital models combines these orbital parameters to create a history of the axial tilt (maximum yearly sun angle) as seen in Figure 1.

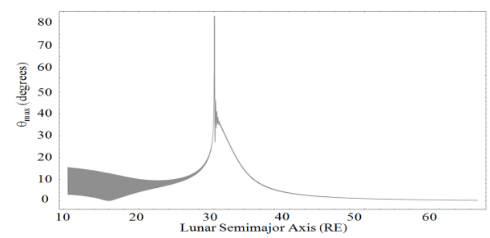

Figure 1: Axial tilt (with respect to the ecliptic) history of the Moon. The large increase at approximately 30 RE semimajor axis is a result of a transition between two Cassini States. The current tilt is roughly 1.54^{o}.

2. Thermal Model

Next, we examine the thermal environments resulting from the slow orbital evolution since the Cassini State transition. Past work [1] modeled the effects of this evolution at a single location (Shackleton crater, 89.7°S, 111°E). Temperatures in this prototypical crater were found to exceed 380K during the peak of the transition, likely erasing any ice existing in the subsurface before this time. Temperatures were not found to cool enough to allow ice deposition (<150K) until roughly 35RE (Figure 2). After about 45RE, temperatures dropped below 90K, too cold to allow ice to be mobile in the subsurface.

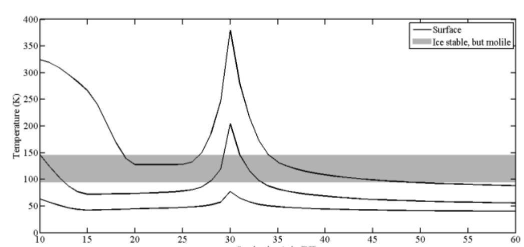

Figure 2: Thermal history of an example lunar polar crater (Shackleton crater, 89.7°S, 111°E). The grey bar marks rough limits of temperatures where ice would be stable on the surface, but mobile enough to diffuse downward before being lost.

With new topographic thermal models produced in association with the Diviner Lunar Radiometer [6], we can examine how changing insolation impacted temperatures at specific locations near the lunar poles. These models artificially illuminate topography (either from the Kaguya LALT or LRO LOLA), then allow for exchange and reradiation of visible and infrared radiation between surfaces. These models have been shown to accurately reproduce current surface temperatures and can be extracted to depth based on past subsurface temperature measurements [7]. Figure 3 (A and B) illustrate mean annual temperatures at the current and past 12^o tilt.

3. Ice Stability and Deposition

Stability of ice on near the lunar poles has long been suggested to control ice retention on the Moon [6, 15,16]. However, mobility of ice is also important, as lack of current surface ice deposits in polar craters imply that some mechanism of burial is required to preserve ice before it is lost to surface processes. When in the right temperature range, ice may be stable in the near subsurface, but mobile enough to be driven downward by diffusion along thermal gradients at a faster rate than it is lost.

When a given environment was in this "icetrap" temperature regime, generally between 90 and 150K (depending on supply rates and temperature amplitudes), ice had a better chance to be preserved by burial via thermal diffusion processes than any time before or since. Once a shaded environment cools below roughly 90K, thermal diffusion processes can be considered negligible and only burial by impact gardening [4, 5] has been proposed as a viable mode of ice preservation.

Given an assumed supply and loss rate, one can then model how specific locations would have gained or lost subsurface ice by vapor diffusion [8,9]. Such modeling has proven to accurately reproduce ground ice distribution on Mars [10] and differs here only in that past supply rate of water molecules to the surface is unknown.

4. Summary and Conclusions

Figure 3 (C and D) illustrate the regions and relative ice deposited in the top meter of regolith with a simple ice diffusion/loss model [8]. This early modeling highlights that, as suggested by the models of a single location, ice deposition near the lunar poles is not very efficient in the extremely cold current lunar thermal environment compared to the distant past. It also illustrates that geographic location of ice deposition can vary dramatically with obliquity. By varying ice supply and loss rates, we can begin to identify if past thermal environments could have produced the ice distribution measured on the Moon today [12,13].

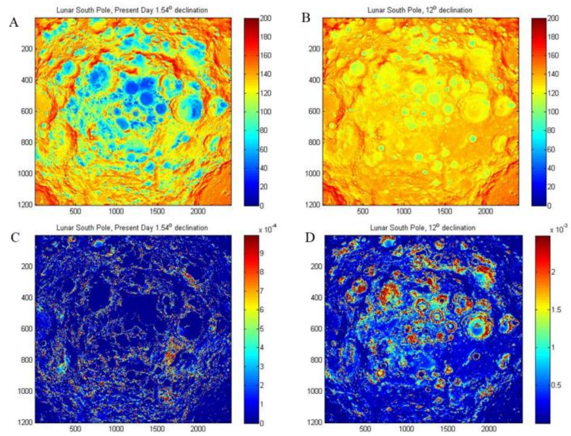

Figure 3: (A) Mean annual temperature in the current (1.54^o tilt) lunar south polar region (stretched 0-200K), (B) Mean annual temperatures at 12^o tilt, (C) Modeled ice mass (kg m^{-2} yr^{-1}) gained at 1.54^o assuming simple model [8], (D) Modeled ice mass (kg m^{-2} yr^{-1}) gained at 12^o.

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