HISTORY OF THE LUNAR POLAR CRYOSPHERE . M.A. Siegler[1], B.G. Bills[2] , D.A. Paige[1] , [1]UCLA Earth and Space Sciences, Los Angeles, CA 90095 *(siegler@ucla.edu)* [2] Jet Propulsion Laboratory, Pasadena, CA 91109

Introduction: Since the discovery of ice in cold, permanently shadowed polar craters on Mercury[1], debate has reopened over the presence of ice in similar environments on the Moon. Though the Moon has similar shadowed craters currently, this has not always been the case. Here we examine a 4.5 billion year history of insolation in the lunar polar environment and the resulting surface and subsurface temperatures. We present thermal calculations for lunar polar subsurface locations to depths of 1 km in order to examine relative stability of water ice over lunar orbital history.

The lunar orbit and equator planes both precess in response to torques from the Earth and Sun. The lunar spin axis responds to the changing orbit as determined by its Cassini state. Cassini states are configurations in which the obliquity is adjusted so that the spin pole precesses about the orbit pole in the same period as the orbit pole precesses about the invariable (ecliptic) pole. Such a state is the expected outcome of tidal dissipation within the Moon.

Tidal dissipation within the Earth drives the lunar orbit outward, which in turn influences the rates of orbit and equator plane precession. The Moon's original, low obliquity Cassini state ceased to exist at about half its current semimajor axis. Thereafter, the lunar spin pole reoriented into a new, higher obliquity Cassini state which then evolved into the current low obliquity. During the transition, there was a brief period of even higher obliquity values (up to 77^o). The duration of this transition is not well constrained, as it depends on the dissipation rate within the Moon at that time, but was likely of order 10^4-10^5 years [2,3].

We model the subsurface thermal response to surface radiative forcing for a calculated lunar spin pole history. We examine cases within and surrounding an idealized, currently shadowed, near polar crater that received direct illumination in earlier orbital epochs. We show depths at which temperatures may have been low enough for ice to remain, if it were present, and comment on its mobility.

Orbital History: Two slowly varying angles, inclination and obliquity, control the subsolar latitude on the Moon. The inclination is the angular separation between the Moon's orbit plane and the ecliptic. The obliquity is the angular separation between the Moon's spin pole and orbit pole.

Inclination variations are a direct response to torques from the Sun (which makes the orbit plane precess about the ecliptic) and the oblate figure of the Earth (which makes the orbit plane precess about the Earth's equatorial plane). When the Moon was near to the Earth, the oblate figure torque dominated. As the lunar semimajor axis grew solar torques dominated the Moon's motion, resulting in a nearly constant inclination [4,5,6].

Obliquity variations result from the fact that the spin pole precesses about the instantaneous orbit pole and damps towards it. For a fixed orbit pole, this would lead to zero obliquity. However, since the orbit pole is precessing, the damped spin pole maintains a constant, but non-zero, separation from the orbit pole. The damped obliquity state, known as a Cassini state, depends upon the lunar moments of inertia and the ratios of the spin and orbit precession rates.

There are either 2 or 4 such states, depending upon the precession rate ratio. The Moon is assumed to have initially occupied the lowest obliquity state of 4 possible states (state 1). As the semimajor axis grew, the orbit and spin precession rates both varied and the obliquity grew until states 1 and state 4 merged and then ceased to exist. The actual Earth-Moon distance at which this transition occurred depends on the past lunar moments of inertia. As the current lunar shape itself is far from hydrostatic, reasonable shape evolution models result in transitions between a semimajor axis of roughly 30 to 36 Earth radii. After the transition, the Moon has occupied Cassini state 2.

Surface Radiative History: The early inclination variations resulted in the subsolar latitude changing dramatically over each precession period (18.6 years today, 80 years at its longest). This caused early precession period length "seasons" on top of the yearly seasons. As the semimajor axis grew and precessional variations lessened, so did these seasonal effects. Like seasons on Earth, variations are much more extreme near the poles, causing 6 months of night for high latitudes. The radius of the polar circle is equal to the inclination plus obliquity.

The Cassini state transition caused a one time excursion of the subsolar latitude to angles up to 70 degrees. This caused high latitude areas to receive high angle radiation for 6 months followed by 6 months of night.

Near-polar craters will shadow sections of their interiors when the angle to the top of the sunward wall is greater than the elevation angle of the sun. The fractional direct illumination of a simple bowl-shaped crater and the resulting scattered visible and reradiated infrared radiation were determined as formulated by Ingersoll et al [7]. In this model scattering is isotropic and all craters are sections of a sphere resulting in equal radiation to all shadowed areas. Non-isotropc scattering and actual crater geometries will cause variation and will be handled in detail in future work by this group. Given these assumptions, the resulting model can be used to determine surface illumination conditions for any crater at any latitude for any time in Moon's history.

Surface Temperature History: Surface temperatures were calculated numerically with a 1-D layered thermal model similar to that described in Vasavada et al [8]. Incident radiation was balanced with outgoing infrared radiation, geothermal heat, and conduction of heat into the subsurface.

Resulting variation within a near polar crater can be seen to vary dramatically over the history of the lunar orbit. For example, the center of our modeled Shackelton Crater saw maximum temperatures from around 350K during the Cassini transition to minimum temperatures averaging about 50K for periods of permanent shadow.

Subsurface Temperature History: Monthly and yearly thermal forcings do not penetrate deeply into the subsurface. Apollo measurements show yearly surface temperature swings dying off to a constant yearly average temperature within the top two meters. At the equator, this average temperature is around 240K, but decreases near the poles and drops dramatically in a shadowed crater.

Precession cycle thermal waves will travel deeper before reaching the seasonal average. Craters that spend part of a precessional cycle in shadow and part in sunlight will have very large temperature variation on the precessional time scale strongly effecting temperature to order 10m depth.

Even deeper thermal waves depend only on the percessional timescale average temperatures. The average temperature at any given semimajor axis was calculated then scaled to time based on a presumed lunar recession rate. This rate is very uncertain as extrapolations from the current recession rate lead to an unreasonable semimajor axis of zero about 1.5 Bya. The model presented here assumes that the lunar semimajor axis was zero 4.5 Bya and that the dissipation within the Earth+ocean system has varied linearly. This model does not fall far from estimates from tidal sedimentary deposits which may be used as a constraint.

The time scaled, precessionally-averaged temperatures were Fourier transformed then propagated downward at each frequency. A simple model for conductivity with depth was extrapolated from Apollo surface measurements of density increase with depth. The model assumed fragmented regolith with increasing density to depth. At each frequency, the Fourier transformed wave was propagated through a thin, single thermal conductivity layer, then passed to lower layers by matching boundary conditions.

Impact on the search for ice: Many mechanisms have been proposed for the delivery of ice to near polar craters from cometary materials to solar wind implantation [9]. Ice sitting at the surface is relatively stable below 110K as sublimation rates fall below 10^{-9} m/yr. However, ice will only be driven thermally downward if subsurface temperatures are colder than those at the surface [10]. Thermal gradients create a saturation vapor pressure gradient which drives molecules to move. Molecules are more mobile at higher temperatures, so warm seasons will cause a net subsurface deposition of ice, while cold seasons will move ice upwards, but very slowly.

Our model hints that the current lunar cold traps, colder on the surface than the subsurface (due to geothermal heat), are especially poor retaining newly trapped surface ice. Water molecules reaching shadowed craters will likely remain at or very near the surface and be subject to micrometeorite gardening, sublimation and other possible mechanisms for removal. Assuming this is also the case for Mercury, it may be that near surface ice there is very ancient and originated from a larger subsurface reservoir.

Our modeled early lunar history, when large inclination variations drove higher amplitude precessional period waves, would have been a comparably ideal time for capturing and burying volatiles. Shadowed seasons might capture abundant ice delivered to the surface by heavy bombardment era comets or lunar volcanism, while illuminated seasons drove it downward.

The question then is how deep might early ice driven and did temperatures in the subsurface get warm enough during the Cassini transition to desiccate the Moon to depth? Early calculations show maximum temperatures during the transition may be low enough, but commentary on the survival of ice requires a more detailed diffusion modeling of ice loss rates. As of now, it seems a reasonable claim that early cold trap ice could have been driven to depths on the order of 10m, survived the Cassini state transition, and is presently migrating very slowly towards the surface. The lunar cold traps may be filling with ice, but more likely from below, rather than from above.

References: [1] Slade M. et al (1992) *Science, 258*, 635-640. [2] Ward W. (1975), 189, 377-379. [3] Siegler M. et al (2007) AGU abstract, [4] Goldreich P. (1966), Rev. Geophys. 4, 411-439. [5] Touma J., Wisdom J. (1994), Astron. J. 108, 1943-1961. [6] Atobe K., Ida S.(2007), Icarus 188, 1-17 [7] Ingersoll A. et al (1992), Icarus 100, 40-47. [8]Vasavada A. et al (1999) Icarus 141, 179-193. [9] Arnold J. (1979), JGR 84, 5659-5668. [10] Schorghofer N., Taylor G. J. (2007) JGR 112, doi 10.1029/2006JE002779.