PAST EXTENT OF LUNAR PERMANENTLY SHADOWED AREAS. Norbert Schörghofer[1] and Raluca Rufu[2], [1]Planetary Science Institute, Tucson, AZ (resident in Honolulu, HI) (norbert@psi.edu), [2]Planetary Science Directorate, Southwest Research Institute, Boulder, CO; Sagan Fellow.

The current lunar obliquity is small ($\epsilon = 6.7°$) thus allowing for perennially shadowed regions (PSRs) at the poles, where, due to low temperature, ices can accumulate. The lunar axis experienced a major reorientation when the Moon transitioned from Cassini state 1 to 2 [1]. The Cassini state transition occurred at $\sim$ 34 Earth-radii [1] (about 4.1 Gyr ago [3]), and the axis tilt may have briefly reached 77° before it was damped to small values [1]. Such high obliquities must have resulted in the loss of all ice deposits. PSRs appeared and then grew after this transition and are often younger than their host craters [2]. The time evolution of the Moon-Earth distance was long a conundrum, but recently Farhat et al. [3] found a consistent solution that agrees with geological proxies for the history of the Earth-Moon system. This breakthrough enables us to calculate the lunar obliquity and the extent of PSRs as a function of time.

In this work we consider the lunar evolution after the Casini state transition. We assume the lunar spin axis follows the stable Cassini state 2 [eqn. (1) in 1] and use values for the Earth's obliquity and distance as provided by Farhat et al. [3]. The orbital inclination of the Moon was obtained using a tidal model for planetary tides [4], and agrees with previous results [5]. We combined these quantities to obtain the maximum solar declination θ (currently 1.5°) as a function of time, where θ is the difference between the lunar obliquity and its orbital inclination.

Figure 1 shows the lunar obliquity ϵ and the declination θ over the past 3.5 Gyr. The declination θ had twice the current value about 2.1 Gyr ago. We note that the history of the lunar obliquity involves some uncertainty due to stochastic impacts, however, true polar wander due to impacts is estimated to be less than 2° over the last 3.8 Gyr [6].

We use Raytracing to determine the extent of PSRs based on a LOLA shape model at 240 m/pixel resolution (LRO-L-LOLA-4-GDR-V1.0). The Python-based programs at *https://github.com/sampotter/python-flux* interface with a wrapper for the Embree ray-tracer *https://github.com/sampotter/python-embree*. We assume a circular orbit at 1 AU and calculate shadows for 360 azimuths over a solar day at solstice. To account for the size of the solar disk, 1/4° was added to the declination. The present-day PSR area agrees with previous results [7]. Figure 2 shows the resulting PSR maps for three solar declinations.

We find that PSR formed relatively early in Shackleton, de Gerlache, and Idel'son L, among others, whereas most of the PSR areas in Amundsen and Sverdrup are relatively recent. In the north polar region, PSRs emerged early in Hermite A, Whipple, and Sylvester N, but are recent in Roshdevstvensky and Nansen F.

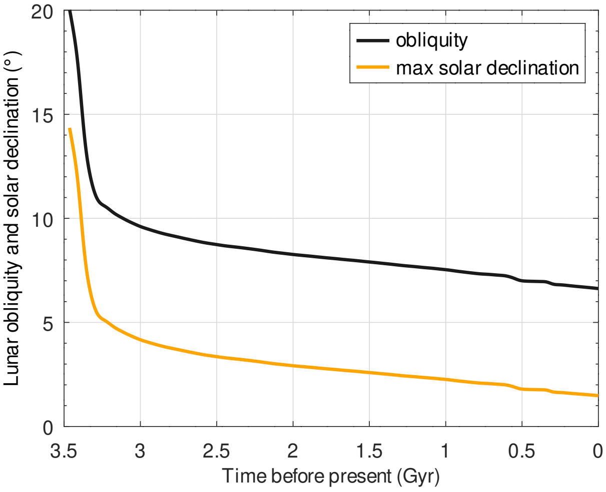

Figure 1: Time dependence of the lunar obliquity and maximum solar declination.

Figure 3 shows the PSR area in each polar region as a function of time. The PSR area is here measured poleward of 80°. Many PSRs are found farther equatorward, but are often not cold traps because of terrain irradiance. The PSRs poleward of 80° are more representative of cold traps than the global PSR area would be. The cumulative PSR area was half as large 2.1 Gyr ago in each hemisphere. It reached a quarter of its current size $\sim$3.1 Gyr ago (assuming all craters already existed at that time). The PSR area becomes negligible beyond 3.4 Gyr ago. The cold trap area is expected to have decreased more quickly, because of increased terrain irradiance.

Small PSRs reside on the floors of some deep craters for solar declinations well above 6°. However, craters with a large depth-to-diameter ratio are subject to a large terrain irradiance contribution [8] and therefore less likely to act as cold traps. Shackleton Crater, at the south pole, may host a very old cold trap, as was already described by [9], who modeled cold trap temperatures for various values of θ using an older shape model.

Large ($\gtrsim$50 km) craters have model ages of about 4 Gyr [10] and therefore are older than the PSRs they host. Most sources of lunar water predate the present-day cold traps, and estimates for the expected amount of ice in cold traps have to be revised downward dramatically. Delivery of comets and carbonaceous asteroids peaked early. Volcanic outgassing may have lasted 4–2

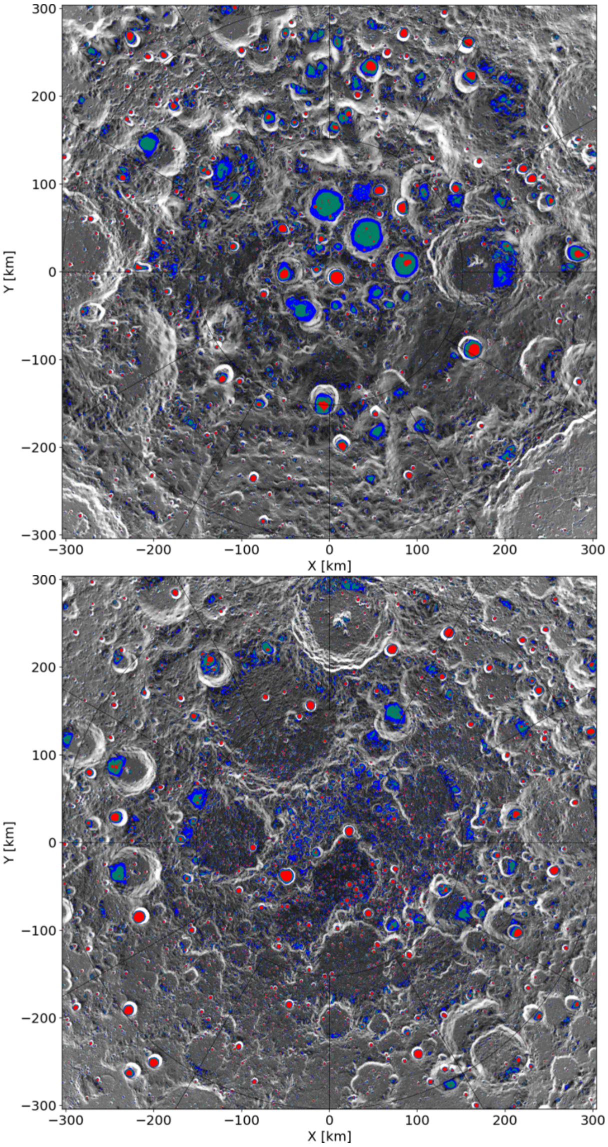

Figure 2: Extent of PSRs for maximum solar declinations of 1.5° (blue; current), 3° (green; 2.1 Gyr ago), and 6° (red; 3.3 Gyr ago) in polar stereographic projection at the South (top) and North (bottom) pole. The background grayscale map is maximum direct solar irradiance for the present-day.

Gyr ago, and late stage outgassing overlapped with early PSRs. Solar-wind generated water may be a relatively important component of the water ice still preserved.

References

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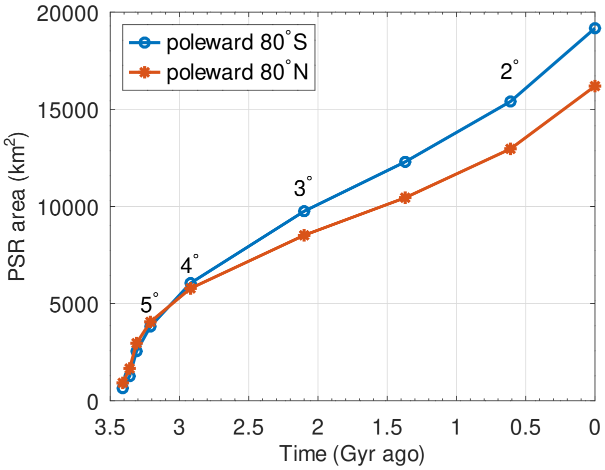

Figure 3: PSR area as a function of time assuming present-day topography. The numbers above the data points indicate the maximum solar declination θ.

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