HISTORY OF THE SOLAR SYSTEM ACCORDING TO LUNAR COLD TRAPS.

D. H. Crider[1] and T. J. Stubbs[2], [1]Catholic University of America, 106 Driftwood Dr., Gibsonville, NC 27249 (crider@cua.edu), [2]University of Maryland Baltimore County and NASA Goddard Space Flight Center, Greenbelt, MD 20771 (timothy.j.stubbs.1@gsfc.nasa.gov).

Summary of Science Topic: The stratigraphy of the Moon acts as a recorder for the conditions in the neighborhood of Earth throughout most of the history of the Solar System, and certainly much longer than any known recording plate on the Earth. Permanently shadowed regions (PSR) on the Moon act as a cold trap for volatiles, including those steadily delivered from the lunar exosphere and those deposited after cometary impacts. One source of the lunar exosphere is the solar wind. Thus, the stratigraphy in lunar regions of permanent shadow act as a recording plate for the history of volatiles in the inner solar system and the history of comet impacts on the Moon. Core samples in the permanently shadowed regions would provide this information.

Value of Science Topic: Understanding the origin of the volatiles in the cold traps will help understand the inventory there, which is important if astronauts should use this resource. In addition, understanding the migration process of particles in the lunar exosphere is important for upcoming operations on the Moon, which will drastically increase the mass of the lunar atmosphere. Finally, understanding the polar deposits of the Moon will provide some basis for interpreting ground-based and orbital data for analogous regions in permanent shadow on Mercury. Cross-disciplinary impacts: *Origin of volatiles; history of solar system; characterization of volatile concentrations*.

Description of Science Topic: There are regions near the poles of the Moon that are permanently shaded from the Sun's light and are extremely cold ($T<100$ K)[1]. If any water ice exists on the Moon, then this is the only place where it would be stable over geologic timescales[2]. Lunar Prospector has observed a neutron signature associated with the regions in permanent shadow that is best explained by an enhancement in the hydrogen concentration, which could be in the form of water ice[3]. The actual contents, their distribution with depth, their source, and there accessibility for in situ resource utilization (ISRU) all require further study. However, this objective focuses on how the contents of the cold traps act as a record of the history of the solar system in the neighborhood of Earth.

There are two potential sources of water on the Moon: (1) episodic cometary impacts; and (2) steady production from chemical interactions between solar wind protons and oxygen in the lunar regolith. Water from these sources can migrate through the lunar exosphere to the cold traps. This water can accumulate and get mixed in with the regolith over geologic timescales. By taking core samples within the regions of permanent shadow, one can study the inventory of volatiles on the Moon for as long as that region has been shaded from sunlight, which is typically about 2-3 Gyr. There is no other record currently known to extend as far back in time.

After a cometary impact, there would be a relatively pure water ice deposit in the cold traps, which would reveal information about the composition of the comet. The varying contents and total number of ice layers will be indicative of the size distribution and impact frequency of comets on the Moon.

Since the Moon has neither a significant atmosphere nor a global magnetic field, the solar wind flow is able to impinge directly on the lunar surface. Most of the incident hydrogen is lost from the Moon in steady state; however, the interaction can produce water by two mechanisms. Firstly, micrometeoroid impacts melt local material, which permits the release of the implanted protons and oxygen from the regolith as H_2O[4]. Secondly, the bombardment of oxides in the lunar regolith by keV solar wind protons can produce H_2O by chemical sputtering[5]. This water vapor can hop on ballistic trajectories around the Moon before being lost by photodissociation or photoionization[6]. A small fraction of the water (~4%)[7] is able to reach the cold trap of the permanently shadowed regions before being lost from the Moon.

Once water is emplaced in the PSR, impact gardening and exposure effects modify both the absolute abundance of water ice and its depth distribution[8]. Modeling of these processes is necessary to interpret the history held in the stratigraphy of the PSRs[9].

Methodology and Implementation: The NASA Apollo missions have returned many lunar drill cores, obtained manually by astronauts on the Moon (see Fig. 1). Earth-based laboratory analyses of Apollo drill cores provided insight into topics such as regolith processes on the Moon [10] and solar wind history[11]. However, drilling into the permanently shadowed regions involves a different drilling environment--extremely low temperature and the significant power constraints (e.g., limited access to solar power).

Drill cores would be taken to depths of 5-10m from regions of permanent shadow. Initial analyses can be

Photo Credit: Pete Conrad for NASA.
Figure 1. Apollo 12 astronaut Alan Bean obtaining a lunar core sample. Apollo drill cores were very useful in providing information about impact gardening and surface exposure effects on the Moon.

done using down-hole instrumentation on robotic missions. Analysis can be conducted while drilling to get temperature (thermocouples), and surrounding volatile composition (mass, neutron, and gamma-ray spectrometers). Honeybee Robotics has built the Mars Deep Drill for automated drilling into frozen, planetary environments (see Fig. 2).

Later, with a lunar base near the rim of a permanently shadowed crater, astronauts can perform laboratory analysis of drill cores. Lunar cold trap drill cores may be obtained robotically and brought to the astronauts in the lunar base. For preservation of the volatiles, the cores can tolerate temperatures of ~170K for <1 hr[12] while they are transported from the PSR to the base. They should be maintained at as low a temperature as possible for transport, storage, and analysis. In-lab analysis would look at strata, the form of water ice on regolith grains, solar wind implanted element concentrations, variations of concentration with depth, and isotopic composition.

Photo Credit: Kiel Davis for Honeybee Robotics.
Figure 2. Mars Deep Drill Bit & Core Sample. This system is being developed for automated drilling and coring in frozen, planetary environments by Honeybee Robotics.

Benefit of Astronaut Involvement: Because of the cold temperatures needed for maintenance of the cores, astronaut analysis at a Moon-base might be the best option for analysis of the cores.

Rationale of Timing wrt Lunar Exploration: Understanding atmosphere-surface interactions, the migration process, and the contents of PSRs will help plan for human activities. Robotic down-hole analysis should be accomplished in the early robotic phase. In-lab analysis should await lab facilities on the Moon, but should be done in the early human phase.

Early Robotic Phase (<2018)	Down-hole instrumentation.
Early Human Phase (2018-2025)	On-Moon analysis of cores
Beyond (>2025)	

Future Wider Benefits: Understanding the source of the volatiles in the cold traps will help understand the inventory there, which is important for ISRU applications. Understanding the migration process of particles in the lunar exosphere is important for upcoming operations on the Moon, since proposed activities will drastically increase the mass of the lunar atmosphere[13]. Therefore, it would be extremely valuable to study the lunar atmosphere before these long-term modifications occur.

References: [1] Vasavada A. R. et al. (1999) *Icarus 141,* 179-193. [2] Watson K. et al. (1961) *JGR* 66, 3033-3045. [3] Feldman W. C. et al. (1998) *Sci.281*, 1496-1500. [4] DesMarais D. J. et al.. (1974) *LSC V,* 1811-1822. [5] Roth J. et al. (1979) *IPP Report 9/16*. [6] Butler B. J. (1997) *JGR 102,* 19283-19292. [7] Crider D. H. and Vondrak R. R. (2000) *JGR 105*, 26773-26782. [8] Crider D. H. and Vondrak R. R. (2003) *JGR 108*, 5079. [9] Arnold J. R. (1975) *LPSC VI,* 2375–22395. [10] Morris R. V. et al. (1979) *LPSC X,* 1141-1157. [11] Epstein S. and Taylor H. P. (1975) *LSC VI,* 1771-1798. [12] Andreas E. L.. (2007) *Icarus 186,* 24-30. [13] Vondrak R. R. (1988) *2nd Conf. On Lunar Bases,* 246-247.