THE SCIENCE OF THE LUNAR POLES. P.G. Lucey[1] and G.J. Taylor[1], [1]Hawaii Institute of Geophysics and Planetology, University of Hawaii at Manoa, 1680 East-West Road, Honolulu HI 96822, lucey@higp.hawaii.edu

Introduction: The rocks and soils returned by the Apollo missions to the Moon have enabled planetary scientists to understand the evolution of our neighbor better than any other extraterrestrial object. But far from the lunar equator where the lunar samples are derived, the lunar poles conceal a place as different scientifically from the Moon's equator as the surface of Pluto. Indeed, the surface of Pluto is in some ways a better analog to the lunar poles than any more tropical portions of the Moon. The lunar poles, and those of Mercury, comprise a microenvironment with conditions that are unlike any found inside the orbit of Neptune.

The Moon and the planet Mercury share an very small tilt of their rotation axis relative to the plane of their orbits. Near the poles this geometry allows declivities, of which the Moon and Mercury have an ample supply in the form of impact craters, to be permanently shaded from the Sun; there are lunar and mercurian polar surfaces that have not seen direct sunlight for billions of years. The natural consequence of this permanent night is that these surfaces achieve extremely low temperatures. Without an atmosphere to propagate heat, shaded polar surface temperatures are dominated by heat flow from the planets' interiors, by small amounts of light reflected off nearby topographic highs, and by the background of space. While surface temperatures have not been directly measured, thermal models show maximum surface temperatures of 40 kelvins will be common, and 25 kelvins will be possible[1].

Recognizing this special condition, Watson Murray and Brown [2] suggested that these polar surfaces could act as cold traps, allowing any volatile species that transiently migrate through the lunar environment to accumulate at the poles. Theoretical studies of the poles have occurred regularly since 1979 when Jim Arnold revived interest in these polar regions [3]. The era of pure theory came to a close with two space missions that conducted experiments aimed at direct detection of lunar volatiles. The 1994 Clementine polar orbiting lunar satellite conducted a bistatic radar experiment that used the spacecraft transmitter and a terrestrial receiver to examine the angular dependence of radar reflectivity of portions of the poles. That experiment showed that the polar crater Shackleton exhibited anomalous scattering consistent with a coherent backscatter mechanism that can be caused by the presence of thick ice [4]. In 1998 the Lunar Prospector spacecraft carried a neutron spectrometer with an aim to detect the presence of hydrogen at the poles. This experiment showed that both poles exhibit a deficient of epithermal neutrons consistent with efficient moderation of neutrons by hydrogen, with an indication of some variation in H abundance with depth [5]. Despite controversies surrounding both experiments, their positive results have largely confirmed the original suggestions that the lunar poles cold-trap volatiles, and have initiated a new era of interest in the lunar poles. Lest Mercury be forgotten, radar imaging of Mercury using powerful terrestrial radio telescopes revealed that large polar craters show very high radar reflectivities, and that all polar craters modeled as having low temperatures reveal this radar behavior that is consistent with thick ice [6]. While the radar does not reveal the composition of this scatterer, the consensus is that this material is water ice filling mercurian cold traps. Similar imaging of the lunar poles does not show a similar high radar reflectivity[7]. Geometrically the poles of the two small planets are similar, but for unknown reasons they differ greatly in detail.

Polar Science: The lunar poles are usually discussed in the context of resources, where the near-continuous sunlight and potential source of water in the form of ice makes a polar site attractive to engineers. But scientific aspects of the poles makes them a compelling object of study beyond resource issues. While we know very little at present, the poles are undoubtedly a dynamic volatile system, with inputs from a variety of sources, a range of processes that can operate on and alter trapped volatiles while resident in the cold traps, and several loss mechanisms that can rob the poles of volatiles. These mass fluxes are conveyed through and constitute part of the lunar atmosphere that links the lunar surface to the rest of the solar system. However, there are almost no measurements that constrain these possibilities.

Sources: Potential sources of polar volatiles include the Moon itself, the Sun, the Earth, asteroids, comets, IDPs and giant molecular clouds [8]. Identifying material at the poles from any of these sources would provide new insights into the bodies that provide the volatile. In fact, the plausible diversity of sources may even diminish the value of the deposit as dcconvolving a complex deposit may require a priori assumptions about the sources.

The most widely assumed volatile source is comets. A comet contains large amount of ice and a cometary impact anywhere on the Moon should place very large amounts of water into a transient lunar atmosphere [9]. This vapor will eventually find the poles and be trapped[2,3]. Probably the most fundamental question to be asked is the deuterium-hydrogen ratio of this cometary material. Comets are a favored source of water for Earth's oceans, but D/H ratio of the ocean is three times lower than the D/H ratio of the three of four comets for which it has been measured (Halley, Hale-Bopp, and Hyakutake, with LINEAR being the exception). Cometary material trapped at the lunar poles may represent many comets.

The Sun is also a favored source of polar volatiles via the solar wind [10]. The LP detection is on the edge of allowing the entire signal to be derived by H diffusing through silicate grains, so it is possible that solar wind H accounts for the entire signal. Polar lunar soil is priceless for studying the Sun. A solar source of H would be unmistakable as deuterium is consumed by nuclear reactions in the Sun, so the solar D/H ratio is zero. Equatorial soil, when heated to high temperatures, releases trapped solar wind nitrogen that has an anomalous and inexplicable ratio of $^{15}N/^{14}N$ [11]. This may indicate an unrecognized solar nuclear process, but it is also conceivable that this ratio has been imposed by thermal diffusion of light N relative to heavy N owing to high (400k) equatorial temperatures. Polar soil has never experienced high temperatures and so would allow immediate resolution of this problem.

Wet asteroids are also potential sources for lunar polar volatiles. As with a comet, an impact of hydrated asteroids, thought to be common based on hydrated water bands detected using earth-based telescopes, would place large amounts of released water into the lunar environment to be trapped at the poles.

Hydrated IDPs could also be a significant source of water to the Moon with the complication that IDPs should efficiently taken up solar wind H with its extremely low D/H ratio.

The Moon itself is a potential source of both water and other volatiles. Lunar soil is highly reduced by a process called space weathering where micrometeorite impact and sputtering cause reduction of lunar ferrous iron to native iron. It has been proposed that solar wind H may take up the excess oxygen and form water that could be transported to the polar cold traps [2]. The Moon also emits volatiles. Radon is produced by decay of naturally radioactive elements and has been detected at restricted locations on the Moon. This radon could cold trap at the poles. The nature of the volatile that causes the vesicularity of lunar basalts is unknown, but assumed to be CO. A geologically recent (<100 Mya) feature on the Moon (Ina) has been suggested to be a gas release and collapse feature [12] (it certainly is young and not obvously related to cratering) and this gas—perhaps CO--may be trapped at the poles.

The Earth too can provide volatiles as the Moon sweeps through the magnetotail and trapped terrestrial ions illuminate the polar regions, trapping in a similar way to the solar wind. Presumably large meteorite impacts, even into the atmosphere, will loft some material into the lunar vicintity as well. The Moon may preserve (highly altered) samples of the ancient terrestrial atmosphere.

Finally, the solar system occasionally passes through giant molecular clouds that push the heliopause within one AU [13]. The lunar poles could conceivably trap interstellar volatiles trapped in dust particles during these these events.

Processes: Regolith turnoever may tend to preserve at least some volatiles [14]. Once in the cold traps, volatiles can be processed rather than lost. The presence of clathrates [15], minerals containing boundwater [16] and organics [Lucey, 17] have all be suggested as a way the Moon can sequester volatiles in more refractory phases.

Losses from the cold traps includes sublimation, sputtering, erosion due to Lyman alpha UV radiation and meteorite impact [2, 14,18,19] . Models suggest these loss mechanisms are effective, especially (or only in some cases) for surface frosts.

The Future As is typical in planetary science, a mix of orbital remote sensing, in situ measurements, and sample return are needed to understand the polar environment, as well as a contemporaneous modeling effort. The fleet of lunar remote sensing spacecraft presently in orbit and en route will make most of the useful measurements possible from orbit. If all are successful, we will have a detailed temperature and topographic map of the poles and improved constraints on the H abundance in the immediate polar vicinity. These missions are also equipped for possible detection of isolated patches of thick ice or surface frosts in permanent shadow, and for detection of organic or hydrated material if ejected from shadow into sunlit areas.

The remote sensing provides vital guidance for further study, but greater leaps will require in situ analysis. Landed experiments can directly measure the chemical and isotopic compositions of the polar soil volatiles and the magnitude, directions and compositions of volatile fluxes in and out of the cold traps. Roving experiments can constrain and characterize the spatial variability of volatiles and their character.

Finally, if the lunar polar deposits are rich enough scientifically, cryogenic sample return may be warranted, to utilize the power of terrestrial laboratories in their analysis, for example, to measure isotope ratios on individual grains.

Conclusions: At the present time lunar polar science barely exists, but the possibilities suggest detailed study of the poles may yield a wealth of new information about the Moon, Mercury, the Sun and other planetary objects as well as improve the understanding of planetary exospheres. The conditions at the poles are certainly unusual for the inner solar system, but they are analogous to outer solar system, even interstellar, conditions, so the poles may provide a convenient natural laboratory to study conditions otherwise inaccessible.

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