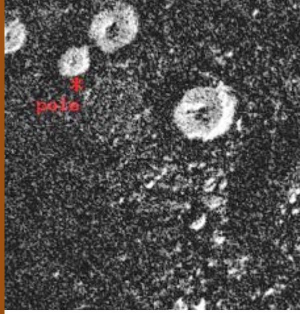

The Poles of the Moon

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The lunar poles feature a microenvironment that is almost entirely unknown to planetary science. Because of the very small tilt of the Moon's axis with respect to the Sun, craters and other depressions near the poles are permanently shaded from direct sunlight. As a consequence, these surfaces should have maintained extremely low temperatures, well under 100 K, for billions of years. There is some evidence that these surfaces act as cold traps, capturing and sequestering volatiles from the Moon and elsewhere. Most popular attention has focused on the possible presence of water ice that might be used by astronauts in the future, but the poles may offer a unique scientific resource. Possible sources for volatiles at the lunar poles range from the Sun to interstellar clouds, and if present, such volatile deposits may provide unique information about many aspects of planetary science.

Keywords: Moon, volatiles, Mercury, radar, neutrons

INTRODUCTION

It was the great geochemist Harold Urey who first called attention to peculiar conditions at the poles of the Moon. In his book *The Planets: Their Origin and Development*, Urey (1952) noted that the spin axis of the Moon was inclined only 1.5 degrees from the normal to the plane of the Moon's path around the Sun. The consequence of this geometry is that topographic depressions near the poles, which the Moon has in abundance in the form of craters, are permanently shaded from the Sun and, in the absence of an atmosphere to transport heat, should achieve very low temperatures (Fig. 1). These low-temperature surfaces ought to act as cold traps, collecting any vapors that might transiently pass through the lunar environment. The first formal scientific study of the lunar poles was published by Watson, Murray, and Brown (1961), who calculated temperatures and considered the potential retention of volatiles.

The subject lay fallow until Arnold (1979) calculated the mass of volatiles derived from a range of sources and potentially trapped at the poles and concluded that the lunar poles might constitute a water resource for future exploitation. Since then, and continuing to today, a steady trickle of theoretical studies have explored many aspects of polar science, including expected temperatures (Ingersoll et al. 1992; Salvail and Fanale 1994; Vasavada et al. 1999), volatile sources (Lucey 2000), mechanisms of transport to the poles (Butler 1997; Crider and Vondrak 2000), loss and retention mechanisms (Lanzerotti et al. 1981; Morgan and Shemansky 1991; Crider and Vondrak 2003), illumination history (Bussey et al. 2003, 2005) and in situ chemical alteration of trapped volatiles (Lucey 2000; Duxbury et al. 2001; Cocks et al. 2002).

The era solely confined to theory ended dramatically, not with the acquisition of new data from the Moon, but with observations of the planet Mercury. Like the Moon, Mercury has a very small obliquity, which should enable cold traps to form in polar craters. In 1992, radar astronomers detected features in the north polar region of Mercury that had radar reflectivity and polarization properties consistent with the presence of water ice (similar, for example, to the radar properties of the poles of Mars and the surfaces of the icy Galilean satellites of Jupiter) (Harmon and Slade 1992). Subsequent spatially resolved radar imaging showed these bright features to be circular (Butler et al. 1997), suggesting they are associated with polar craters (Fig. 2). While the radar results are not definitively diagnostic of the presence of the water molecule, the material in the polar craters of Mercury must be thick and highly transparent to radar to exhibit the anomaly; water ice is the most cosmochemically plausible material. Attention rapidly turned to the poles of the Moon, and a new era of measurement of the lunar poles from the Earth and from lunar orbit commenced, accompanied by strong scientific controversy.

CLEMENTINE

In 1994 a satellite aimed at testing technologies for the waning Strategic Defense Initiative (aka "Star Wars") was launched. This satellite, named Clementine in honor of the daughter of the gold rush prospector (ironically aptly named because the satellite was ultimately lost and gone forever due to a software error), featured optical and infrared sensors that were easily adapted to planetary-science applications, and the mission sponsors collaborated with planetary scientists to send this satellite into deep space, first to orbit the Moon to map its constituent minerals and thermal properties, then off to a near-Earth asteroid to do the same (Nozette et al. 1994).

Radar scientists participating in the mission, led by Stewart Nozette, realized that the radio transmitter of the satellite, in conjunction with Earth-based receivers, could be used in a robust attempt to detect water ice at the lunar poles with radar. The high reflectivity of radar-transparent materials such as water ice is in part due to an interference phenomenon known as the Coherent Backscatter Opposition Effect. In this mechanism, the path taken by radiation into

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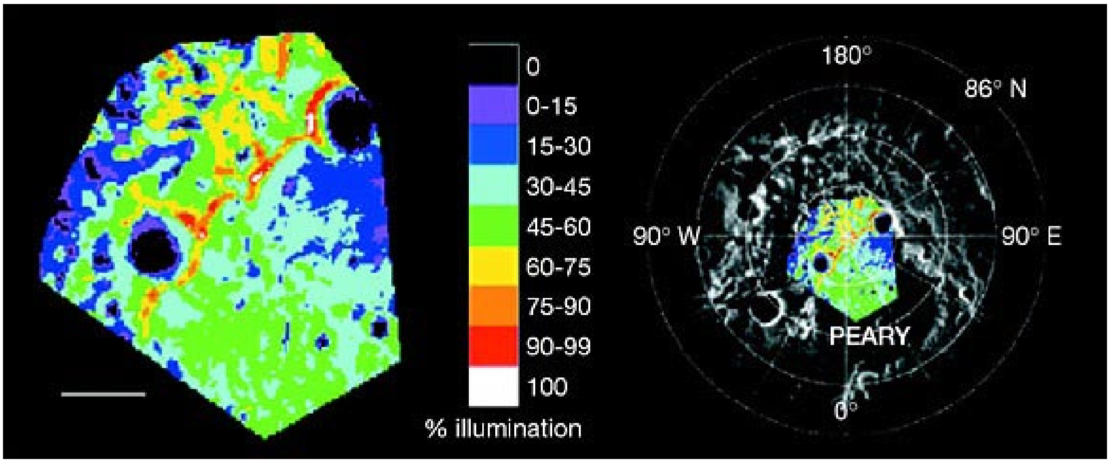

Figure 1 Percent illumination of the Moon's north pole. Patches of the interiors of impact craters are never illuminated by the Sun, and so achieve low temperatures. Scale bar is 15 km. Reprinted from Bussey et al. (2005) by permission from Macmillan Publishers Ltd [Nature] ©2005

and out of a surface has a high probability of traversing the same optical path, and so the radiation undergoes constructive interference, enhancing its magnitude. At radar wavelengths this coherent signal enhancement can be produced in highly transparent media and, to a limited degree, by roughness of the surface. In addition to the enhancement of the magnitude, the effect preferentially preserves the orientation of circular polarization of ingoing and outgoing beams. In the cases of the demonstrably icy Galilean satellites of Jupiter and the south pole of Mars, the ratio of same-sense to opposite-sense radar polarization is greater than unity, whereas for most planetary surfaces this ratio is well below one. Mercury's poles show a polarization ratio similar to that of the known icy surfaces, strongly suggesting the presence of ice (Harmon and Slade 1992). In addition to the magnitude and polarization enhancements, both of these phenomena are confined to very small phase angles (angle between the source, surface of interest, and observer—a geometry called "opposition" by astronomers because a planet under study is opposite from the Sun with respect to the observer on Earth). Together, radar magnitude, ratio of outgoing to returned polarization, and angular dependence of these properties are signatures of the Coherent Backscatter Opposition Effect. This effect, first identified at radar wavelengths in observations of the icy Galilean satellites of Jupiter, has been shown to operate at many wavelengths and accounts in part for the high visual brightness of the full Moon.

Clementine was well suited to search for the radar properties associated with radar-transparent material like ice. Typical radars transmit and receive with the same antenna, so the angle between the radar illumination of the surface and reflection from the surface is fixed at near-zero. Radar astronomers can use transmitters and receivers at different locations and with long travel times in the solar system to explore away from zero angle, but only slightly. By using Clementine as the transmitter and a radio telescope on the ground as the receiver, mission radar scientists could measure the angular dependence of sense of polarization and the magnitude of the radar return.

As Clementine traced its polar orbit about the Moon, mission engineers "painted" the polar regions with the spacecraft radio transmitter while observers at NASA Goldstone in the Mojave Desert listened with their giant radio telescope. During one orbit, where the radio beam included the lunar south pole, the Clementine radar scientists detected a weak, but statistically significant, enhancement of the polarization of the radio signal scattered at the critical zero phase angle (Fig. 3). Their results, published in *Science*, announced the detection of water ice at the poles of the Moon (Nozette et al. 1996).

LUNAR PROSPECTOR

Buoyed in part by the Clementine results, a small group of space scientists successfully proposed to a peer-reviewed NASA robotic mission program (called Discovery) to fly a powerful remote sensing experiment to lunar polar orbit (Binder 1998). That mission, called Lunar Prospector, included a water-detection experiment featuring a neutron spectrometer. Neutron detection is particularly powerful for water measurements because it is very sensitive to the presence of the hydrogen atom.

The Moon is irradiated by high-energy cosmic rays, primarily protons. When these protons strike nuclei in the surface, a range of nuclear reactions occur that boil off neutrons. Many of these neutrons can escape the surface and are detectable from lunar orbit. The energy spectrum of these neutrons is characteristic of composition. Because the hydrogen nucleus (the proton) has essentially the same mass as the neutron, the energetic neutrons produced in the lunar surface will very efficiently exchange momentum with hydrogen, so the energy spectrum of scattered

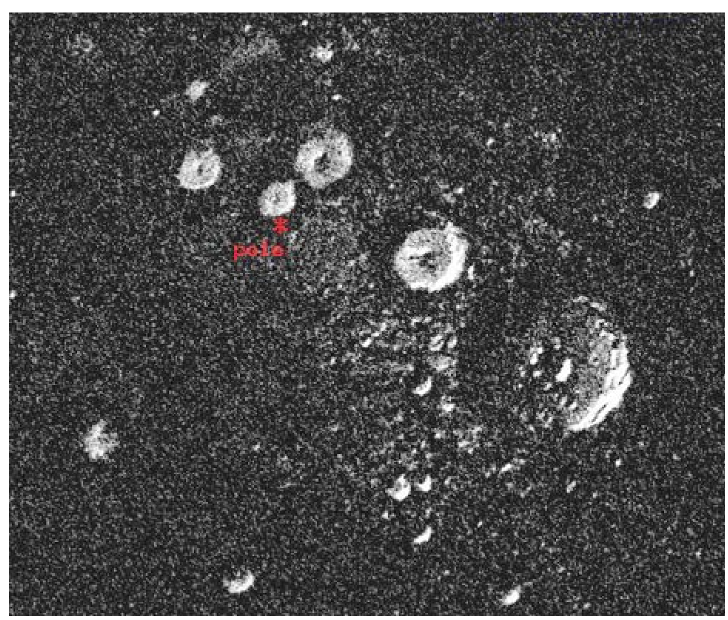

Figure 2 Radar backscatter image of the north pole of the planet Mercury. Circular features in the polar regions are large craters, and they exhibit radar-bright floors, consistent with the presence of thick material transparent to radar; water ice is the most plausible material. From Harmon et al. (2001), reprinted with permission from Elsevier

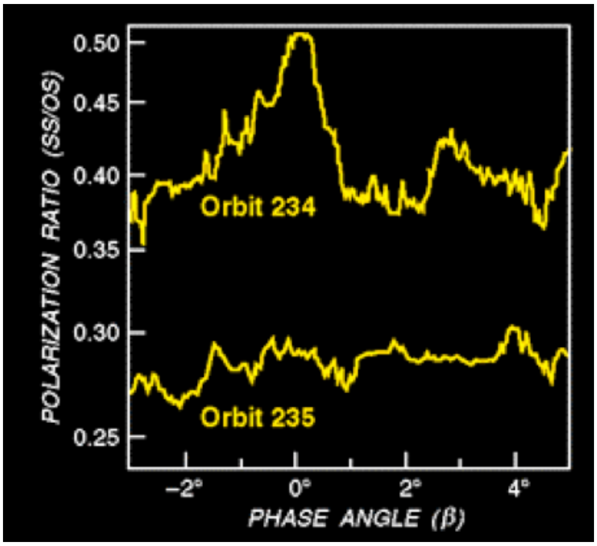

FIGURE 3 Results of the Clementine bistatic radar experiment. The upper trace shows the results from orbit 234, which included the lunar south pole; it exhibits enhancement of the ratio of same-sense to opposite-sense polarization, characteristic of the presence of a material transparent to radar. The lower trace is a control observation that did not include areas of permanent shadow. ADAPTED FROM NOZETTE ET AL. (1994)

neutrons from a portion of the Moon containing hydrogen is depleted in intermediate energies relative to the neutron energy spectrum of a dry medium.

In 1998, the Lunar Prospector satellite operated in lunar polar orbit with its neutron spectrometer sensitive to three energies corresponding to fully moderated neutrons in thermal equilibrium with the lunar surface ("thermal neutrons"); promptly scattered, energetic, unmoderated neutrons ("fast neutrons"); and the key hydrogen-sensitive, intermediate-energy neutrons ("epithermal neutrons"). After many orbits, neutron detections were averaged over longitude, and a very distinct depletion of epithermal neutron flux was found at the highest latitudes at both the north and south poles relative to the rest of the Moon (Feldman et al. 1998). Quantitative calculations suggested the presence of about 1.5 wt.% equivalent water ice, if the water were confined solely to regions thought to be in permanent shade. This was broadly consistent with the quantitative estimates derived from the Clementine radar experiment. Maps of the epithermal signal showed that hydrogen seemed confined to craters that were plausibly permanently shaded (FIG. 4).

CONTROVERSY

Radar Observations

Radar astronomers eventually turned their telescopes to the lunar polar regions and obtained results that plunged the Clementine observations into controversy. Because the inclined lunar orbit sometimes takes the Moon slightly above and below the plane of the Earth's orbit around the Sun, about 20 percent of the permanently shadowed regions can be imaged by radar (Clementine exploited this geometry to allow receivers on Earth to view the areas of permanent shade). The new radar images revealed no areas with the very high radar reflectivity seen in the Mercury images, though some radar experts point out that the lunar observations are obtained at angles a few degrees more grazing than radar observations of Mercury, complicating the comparison. Images formed of the key polarization ratio do show anomalies in portions of the polar regions viewed by Clementine in a few small areas on crater walls. Similar polarization anomalies also occur on crater walls directly exposed to sunlight, so the astronomers making the observations attribute these anomalies, within and outside of permanent shade, to the effect of roughness on the radar signal. Some members of the Clementine team disagree, and point out subtle systematic differences between the images in shadowed and illuminated crater walls. The lack of published quantitative scattering models of the radar signals hinders the debate (Weidenschilling et al. 1997).

Neutron Measurements

Like the radar results, the neutron measurements were not accepted uncritically. Theoretical work on neutron detection of water on the Moon suggested that the epithermal neutron deficit expected for water-rich material should be balanced by a thermal neutron excess—essentially a mass-balance argument. No such enhancement was reported by Feldman et al. (1998). Hodges (2002) suggested instead that the polar anomalies could be coincidental concentrations of lunar soil with atypical, but not impossible, major-element compositions with appropriate neutron-absorption cross sections. Lunar Prospector scientists had already proposed that the thermal neutron excess would be suppressed if a thin (~10 cm) layer of dessicated soil lies atop the water-bearing soil. This dessication is consistent with a range of proposed surface-ice-loss mechanisms, including sputtering, strong UV radiation scattered off interplanetary dust, and micrometeorite bombardment.

Despite this objection, the consensus in the planetary-science community is to accept the interpretation of the Lunar Prospector neutron spectrometer results as indicating much higher concentrations of hydrogen in the lunar polar regions compared with other areas of the Moon.

THE SCIENCE OF THE LUNAR POLES

While the popular literature often discusses polar water in the context of resources that may be tapped by astronauts in the future, science issues surrounding the lunar poles go well beyond the presence or absence of ice. Volatiles in the lunar environment are likely participating in a complex system of input, transport, trapping, recycling, and loss (FIG. 5). The wide-ranging theoretical studies mentioned above address this system but are largely unconstrained by measurement; however, they have interesting and potentially important implications for solar system science.

Sources

Seven sources have been suggested to provide volatiles to the poles: the Sun, Earth, Moon, comets, asteroids, interplanetary dust, and giant interstellar molecular clouds. Apollo samples (and meteorites) showed that the Sun does implant solar-wind elements into the regoliths of airless planetary surfaces. Calculations have shown that the sluggishness of diffusion of solar-wind hydrogen through soil grains at polar temperatures (as low as 40 K in some models) can account, barely, for the observed abundances of hydrogen, provided the hydrogen is distributed rather uniformly (Feldman et al. 1998). It might seem counterintuitive to cite the Sun as a volatile source for areas in permanent shadow, but the solar wind is electrically charged, and the Earth's magnetosphere bends it sufficiently to irradiate areas not in the direct line of sight. Abundances much above the observed estimated average H concentration probably cannot be explained by diffusion of hydrogen implanted by the solar wind. An interesting question that could be answered by study of polar soil is

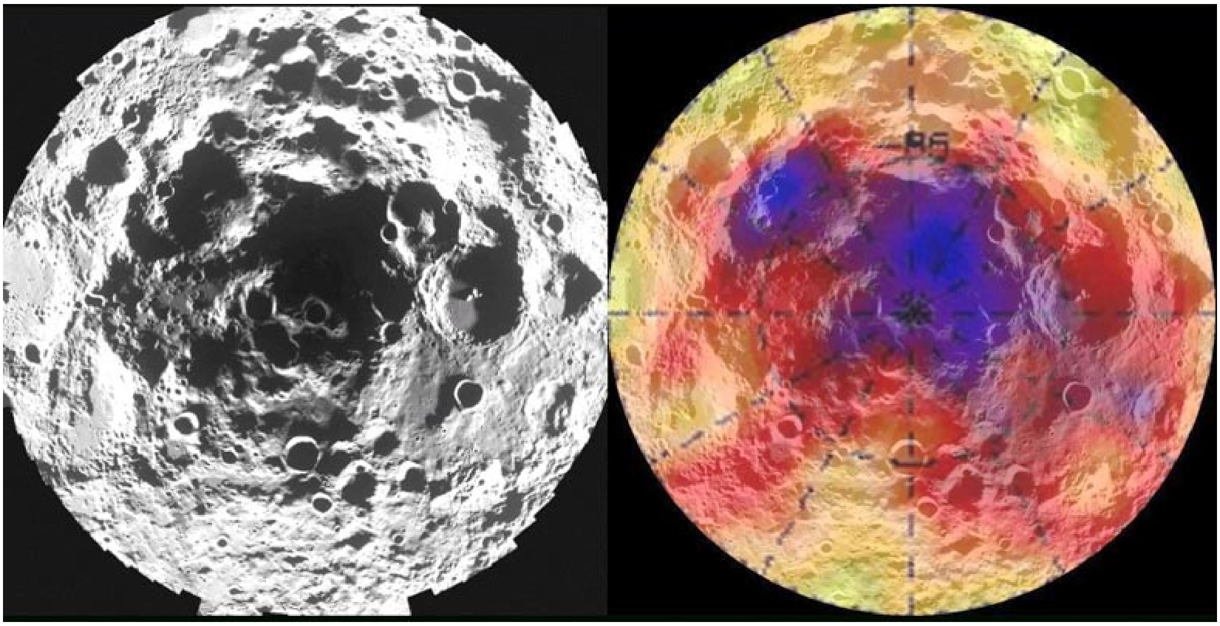

Figure 4 Results of the Lunar Prospector neutron spectrometer experiment. On the left is an image mosaic of the south pole showing regions of permanent shadow (Lunar and Planetary Institute, Houston). On the right, the water-sensitive epithermal neutron counts are shown; blue areas, corresponding to permanent shade, are deficient in epithermal neutrons, indicating the presence of an efficient moderator, most likely hydrogen.

a nagging issue regarding solar nitrogen isotopes; this issue arose during study of solar-wind gas evolved from lunar soil. When lunar soil (derived from the equator) is heated above lunar noontime temperatures, the soil degasses. At the highest temperatures, the gas evolved is assumed to be deeply implanted by energetic solar events. The nitrogen isotopes evolved are depleted in light nitrogen relative to other measures of solar composition, suggesting a still-unidentified solar nuclear process. Alternatively, it has been suggested that this isotopic anomaly is due to differential thermal diffusion of the two isotopes (Kerridge 1989). Polar soil (even in sunlight) has never experienced high temperatures (excepting brief impulses from micrometeorites), so thermal diffusion cannot have operated; therefore, a study of gas evolved at high temperature from polar soil could resolve this ambiguity.

The Earth's atmosphere introduces a variety of ions into the magnetosphere through the so-called polar fountain. During the Moon's passage through the Earth's magnetotail, the permanent shadow is irradiated by both the solar wind and terrestrial atmospheric ions. While the intrinsic merit of studying the Earth through the aperture of the lunar polar deposits has not been discussed, it should be anticipated that terrestrial volatiles are present in the polar cold traps.

The Moon itself can provide volatile material into the cold traps in two ways. Arnold's 1979 paper advocated a process previously suggested, that water could be produced from reduction of iron-bearing minerals in lunar soil by solar-wind hydrogen and could make its way to the poles. Another source is purely lunar. There is solid evidence that the Moon experienced a large, local outgassing event within the last 10 My or so, and perhaps much more recently (Schulz et al. 2006). A collapse feature called Ina in the mare deposit Lacus Felicitatis near the center of the lunar disk has optical characteristics and impact-crater densities that suggest it is extremely young. The size of this feature implies that a large quantity of some type of vapor was catastrophically emitted, and this volatile might have been cold trapped at the poles. The identity of the volatile that drove that event and the lunar explosive volcanism billions of years ago is not known, but it is assumed to be CO. Temperatures in some portions of permanent shade are likely low enough to trap even this highly volatile gas if it, or other gas, was emitted at Ina.

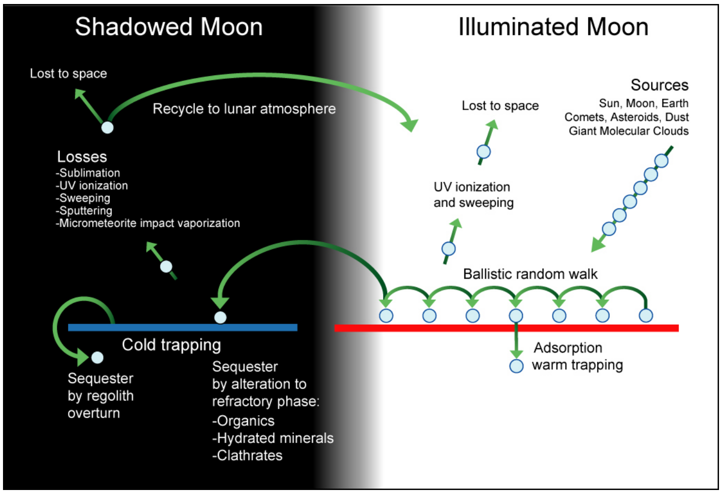

Figure 5 Schematic of the lunar volatile transport system

The origin of Earth's oceans is an area of vigorous research at present. Several lines of reasoning suggest that Earth's proximity to the young Sun likely caused it to accrete from a disk of matter circling the Sun without including water-bearing minerals or ice. Comets are frequently invoked as the source of Earth's water. However, the deuterium to hydrogen ratio of the oceans is much less than in the three comets for which D/H measurements are available (Halley, Hale-Bopp, and Hyakutake). Comets strike the Moon relatively frequently and likely introduce large quantities of water into the lunar environment. The composition of comets is only known from gas that is propelled into their comas, and strong controversy currently surrounds potential alteration of this gas as it moves from the interior of the comet to space. A polar deposit may preserve the average composition of a large sample of comets. Alternatively, asteroids may have supplied water. Both meteorites and telescopic remote sensing show that many asteroids are "wet" in the sense that they have a substantial inventory of water-bearing minerals. Asteroidal D/H shows extreme variation, but again, polar deposits may reveal an average composition. The polar deposit may help solve the "origin of oceans" problem by preserving a larger sample of cometary (or asteroidal) material than currently exists, enabling a more robust estimate of D/H for comparison with Earth's oceans.

Finally, the observed large number of giant molecular clouds in the galaxy, coupled with the known motion of the solar system through the galaxy, virtually ensures that the solar system has passed through several of these objects in the last few billion years (Talbot and Newman 1977) Some of these clouds are so dense that they can affect the solar heat budget of the Earth during such a passage and, by extension, will deposit dust and possibly even icy grains into the lunar environment. Spectroscopic measurements of giant molecular clouds show they contain abundant organics with extreme deuterium to hydrogen ratios, which may imprint onto the isotopic signature of lunar polar deposits.

Poles as a Natural Laboratory

The conditions of the lunar poles are analogous to conditions in the outer solar system beyond Neptune and to some regions of interstellar space: silicate surfaces are present, they are cold, some of them may be coated with a range of volatiles, and these grains are bombarded with ultraviolet and cosmic radiation. Laboratory experiments simulating these conditions for understanding the evolution of comets and interstellar dust reveal a range of chemical processes that give rise to the production of organics. At the lunar poles, these processes could be observed in situ, with the added benefit of geologically lengthy exposures not possible in the laboratory. Lucey (2000) proposed that organic synthesis occurs at the lunar poles using trapped volatiles as a feedstock, with reactions prompted by radiation exposure forming reactive radicals. Natural temperature cycling in portions of the poles can enable chemical reactions to proceed episodically. In addition to organic synthesis, Duxbury et al. (2001) suggested that the formation of clathrates can promote retention of more volatile species, such as methane and carbon dioxide, that are otherwise difficult to retain against sublimation. Monolayers of ice should eventually form hydrated minerals from reactions with dry silicates (Cocks et al. 2002), and hydrated minerals can form in temporary hydrothermal systems in hot ejecta blankets from meteorite impacts into any icy polar target (Newsom and Graup 1984).

Lunar Atmosphere

The lunar atmosphere is technically known as a surface-bounded exosphere (as opposed to an atmosphere-bounded exosphere), one of several in the solar system, including those of Mercury; the Jupiter satellites Europa, Ganymede, and Callisto; and the Saturn satellite Enceladus (Stern 1999). In these extremely tenuous atmospheres, collisions with the surface are much more likely than collisions between particles. Surface experiments during Apollo missions showed strong diurnal compositional and pressure variations of the lunar atmosphere, but other than this, the dynamics of the atmosphere are unknown. The ballistic nature of the lunar atmosphere ensures eventual interaction of this atmosphere with the polar cold traps, so the poles must be an important sink in a dynamic lunar-atmosphere system (Fig. 5). The fact that an atmosphere is present shows that the poles do not condense the entire atmosphere, so equilibrium between cold trapping and escape must be in play at the poles. In fact, the flux and identity of gases flowing in and out of the lunar cold traps may hold the key to the lifetime of volatiles in these cold traps and to understanding the major differences between the lunar poles and the poles of Mercury.

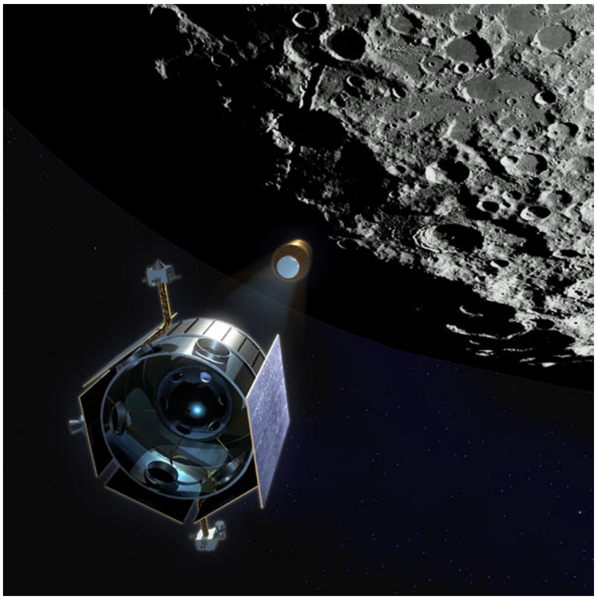

Figure 6 Artist's conception of the LCROSS remote sensing spacecraft following the spent rocket booster towards the lunar south pole. Image from NASA

SYNTHESIS

Our understanding of the lunar poles is similar to our understanding of the Moon itself at the dawn of the space age, with more possibilities than current data can support. However, considering Mercury and the Moon together, the consensus is that these polar microenvironments trap volatile material, as the Mercury radar and lunar neutron spectrometer results strongly suggest. The difference between these bodies may indicate that the poles are recharged episodically, perhaps by large comet impacts, and that losses appear to outweigh continuous sources (such as the steady impact of small water-bearing meteorites). Beyond this tentative conclusion, hypothesis and informed speculation take over. It will require new data to make progress.

THE FUTURE

The first question to be addressed experimentally concerns the nature of any volatiles that may be present. While it appears likely that enhanced concentrations of hydrogen are present, and possibly correlated with permanent shadow, none of the potential sources for lunar polar hydrogen supply hydrogen alone. It is almost certain that the detected polar hydrogen is only the "tip of the iceberg" of a complex volatile deposit, though not necessarily a deposit with high concentrations.

Direct measurement of polar ice will be attempted in 2009. An innovative experiment conducted by the NASA Ames Research Center called LCROSS (Lunar Crater Observation and Sensing Satellite) will crash the spent Earth-orbit departure booster stage of a scheduled NASA lunar orbiter (the Lunar Reconnaissance Orbiter, LRO) into an area of permanent shade (Fig. 6). The impact is intended to loft ice-laden soil into sunlight, and modeling suggests that as much as 200 tons of lunar soil may thus be propelled. The impacting mass will be followed by a remote sensing spacecraft that will search the soil hurled into sunlight for spectroscopic evidence of water, as will telescopes on Earth.

The trailing spacecraft will then also crash into the surface of the Moon and will loft soil from this second location, providing another source for spectroscopic inspection by Earth-based telescopes.

In addition to LCROSS, several well-instrumented satellites will explore the poles indirectly with remote sensing. Two satellites now in lunar polar orbit were sent by the nations of Japan and China (Kaguya and Chang'e-1). India placed Chandrayaan-1 into orbit in 2008, and the United States will follow with LRO in 2009. The exploration of the poles is a major objective of the LRO (which will share the launch with LCROSS and provide the booster stage for the impact experiment).

These missions will determine in detail the temperature, temperature variation, and topography of the regions of permanent shade and will determine if surface frosts are present. Chandrayaan-1 and LRO will carry imaging radars provided by US teams that include the scientists who carried out the Clementine observations; the aim is to search for scattering properties consistent with shallow buried ice, and the instrument will survey the 80 percent of permanent shade not examined by Earth-based radar. New, higher-resolution neutron data will be collected for the immediate vicinity of the lunar poles. A neutron spectrometer is also on the instrument complement of the Mercury orbiter mission MESSENGER, which will determine in 2011 if the polar deposits on Mecury exhibit neutron anomalies indicating water ice.

Even if LCROSS results show the presence of water ice, neither LCROSS nor the remote sensing measurements planned can answer in detail the most basic questions: What is the full complement of phases that host the detected hydrogen and what are their relative abundances? Can the sources of the volatiles be inferred from their chemical and isotopic compositions? What role do the poles play in the lunar-atmosphere system? Such questions will require, at the minimum, measurements conducted on the surface of the Moon, and some of them will require samples to be returned to the Earth.

Nevertheless, the next two to three years will be exciting to monitor. Interested readers should watch for results of measurements of polar temperatures, conceivably as low as 25 K; possible reports of surface frosts or radar anomalies that may reveal shallow buried ice; results from deep radar tomography of the poles that could reveal subsurface layering; and reports of high concentrations of hydrogen. These measurements continue the exploration of one of the most extreme, least understood environments in the solar system, the lunar poles.

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