SPACE WEATHERING EFFECTS ON LUNAR COLD TRAPS.

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Introduction: The lunar surface is constantly bombarded by solar wind particles and meteoroids. Because the Moon lacks a substantial atmosphere, interplanetary dust particles and other impactors are not stopped before they reach the surface. They impact, melt, process, and redistribute the regolith [1]. In addition, the Moon lacks a magnetic field that would protect the surface from interacting with the solar wind. Charged particles interact with the surface and induce sputtering, radiation damage, and chemical reactions depending on the incident particle's energy [2].

We investigate the effects of these space weathering processes on a deposit of volatiles in a lunar cold trap. There are regions of the Moon at the poles that are permanently in the Sun's shadow. Heat transfer models of the regolith in these regions show that the temperature remains well below 110 K in these areas [3]. Because they are cold enough to retain volatile species, the permanently shaded areas are called cold traps [4]. Margot et al. [5] estimate the total surface area in permanent shadow at the lunar poles by radar topography studies. They find that 5100 km^2 are in permanent shadow near the south pole while 2650 km^2 are in permanent shadow near the north pole.

Although no water ice has been detected in the cold traps through spectroscopy or radar techniques, the presence of hydrogen has been deduced from Lunar Prospector Neutron Spectrometer (LPNS) measurements [6; 7]. The LPNS measures a decrease in neutron flux in the epithermal energies that could correspond to approximately 7.5×10^{11} kg of water in the topmost meter of regolith at the poles. A larger signature is observed near the southern pole than the northern pole, in agreement with the Margot estimates of areas in permanent shadow.

Possible sources for hydrogen in the cold traps include the solar wind, the magnetosphere, comets, and interstellar sources [8]. We estimate the amount of hydrogen that is released and migrates to the polar cold traps by space weathering processes. Then we conduct a detailed simulation of the balance of source and loss processes at the cold traps. Finally, we discuss the implications the modeling results have for the expected stratigraphy of the cold traps.

Vaporization of implanted hydrogen: As the solar wind protons encounter the lunar surface, they implant themselves a few hundred Å into the regolith [9]. Materials returned by the Apollo missions show that the amount of hydrogen in a soil is related to the exposure age of the soil [10; 11]. The hydrogen content increases with soil maturity, but seems to reach a plateau with very mature soils. This indicates that equatorial soils saturate with hydrogen at around 50-75 ppm. Because the solar wind continues to bombard exposed soils, a steady state must be achieved in which hydrogen is released from a mature soil at the same rate as it is added by the solar wind. We have calculated the branching ratios for physical and chemical sputtering, diffusion, and backscattering of solar wind protons [12] based on laboratory experiments [13; 14].

However, micrometeoroids are also able to remove implanted hydrogen from the regolith. This is implied from the study of lunar agglutinates, which are formed as the results of micrometeoroid impacts [15]. The impact melts local material which encases intact soil grains as it cools into glass. The agglutinatic glass is enriched with single domain metallic iron content and has a paucity of solar wind elements compared to the encased grains [10]. Therefore, the assumption is that solar wind implanted hydrogen combines with local oxygen in the impact melt to form water vapor. The local oxygen is most easily released from FeO and Fe_2O_3, leaving metallic iron as a result [16]. One can estimate the amount of water released by micrometeoroid bombardment by studying the single domain Fe^0 content of the lunar regolith and assuming that all the metallic iron formed from the reaction:

$$2H + FeO \quad Fe^0 + H_2O.$$

This provides the amount of water vapor released by micrometeoroid bombardment.

The water released by micrometeoroid bombardment has a chance of migrating to the lunar cold traps and sticking there. We use our Monte Carlo model [12; 17, see also 8; 18] to simulate the delivery efficiency of the released water vapor to the poles. We release the water vapor with a thermal velocity distribution and allow the particle to hop around the lunar surface until it is lost to photodissociation, achieves escape velocity, or arrives at the cold traps. On each hop, the particle thermalizes to the local surface temperature and is reemitted with an appropriate energy. Due to the relatively heavy mass of water, only a small fraction escapes the lunar gravity. Most of the water is photodissociated. However, a small fraction of the water reaches the polar cold traps. Over the history of the Moon, the small delivery rate to the cold traps results in a large deposit if the cold traps are able to effectively retain the water. So we next consider the stability of the deposits by simulating the balance of source and loss terms at the cold traps.

Source and loss comparison: There are several mechanisms acting at the cold traps that can alter the inventory of volatiles there. The mechanisms we investigate here are sputtering, impact, and UV radiation from extrasolar sources. Although the regions are in the permanent shadow of the Sun, there is a small flux of radiation incident on the regions from interstellar sources. Subliming material from the incident flux may be lost from the inventory. A thin layer of covering material is enough to protect volatiles from UV sources. UV fluxes on cold traps are a loss term for volatile retention. In contrast, sputtering and impacts are two processes that can serve both as constructive and destructive forces at the cold traps.

Charged particles from the solar wind and from the magnetosheath have limited access to the permanently shaded regions. Sputtering ejects material from the target material while the incident particle is embedded into the target. However, sputtering yields for 1 keV protons on oxides are rarely greater than 1 [9]. In fact, for lunar type soils, sputtering yields are around 0.015 atoms/ion [19]. This suggests particle sputtering is a net source of hydrogen at the poles.

Impact processes can either protect or remove deposits of volatiles depending on the location of the impact. If the impact occurs in the cold traps, it vaporizes local material. These volatiles may then leave the cold trap area. However, an impact outside of the cold trap area may produce an ejecta blanket that buries deposited material. Because many loss processes affect only the top layer of the soil, a layer of ejecta over a deposit protects the deposit from loss.

We model the competing processes occurring in the cold traps to determine the retention efficiency of the cold traps. We include space weathering processes on several time and spatial scales to simulate the constant rain of micrometeoroids as well as sporadic larger impactors. Borg et al. has performed a Monte Carlo simulation of surface exposure ages of soil grains [20]. This simulation includes the exposure age as well as the probability of loss from vaporization during a period of surface exposure. In addition, freshly deposited volatiles are given by the fluxes calculated in [12]. The source terms of volatiles into the cold traps are considered to be a continuous process, like from solar wind bombardment or micrometeoroid release. However, a cometary impactor, which would also be a viable source of volatiles, would be episodic in nature. This type of source is not considered here, but will be in future simulations.

Expected stratigraphy: The constant modification of the lunar regolith from space weathering churns the lunar soil. As a result, continuous strata are not expected to be found if one were to take core samples in a cold trap. Space weathering processes act on several scale lengths in an essentially non-unique way. However, we show how the hydrogen content would vary with depth following certain events.

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