COULD LUNAR POLAR ICE BE A 'FOUNTAIN' SOURCE FOR THE DAYSIDE WATER VENEER?

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Introduction: We discuss the possibility that the lunar polar regions are a source of a lunar 'rain' which provides a light coating (veneer) of water at mid-latitudes.

Chandrayaan-1's Moon Mineralogy Mapper (M^3) instrument observed a surficial water veneer on the Moon (via the 3 micron IR absorption feature) that progressively intensified from ~70° latitude to extreme poleward locations in both the northern and southern hemispheres. A number of ideas have been put forth to
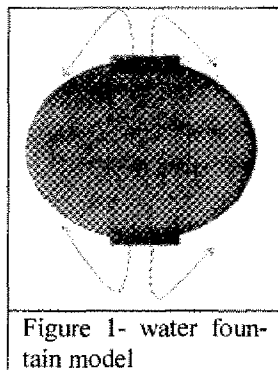

Figure 1- water fountain model

account for the surficial water, including manufacturing of water via the solar wind [1-3]. Recent LCROSS and LRO findings [4-6] suggest that regions northward of 85° latitude contain large amounts of water ice (~5-10% by weight), and these regions are close enough to the surface to be modified by the harsh space environment that includes micro-meteoroid impacts and some level of solar wind attrition.

Given the proximity of the known polar ice source to the locations of the mid-latitude veneer, an obvious question is whether space environment erosion (impact vaporization, sputtering, etc.) in icy regions within 5° of the pole can be a source for the thin veneer at lower latitudes (~70-85°) . We examine the hypothesis that the icy poles are a water fountain source that ejects water molecules over an extended latitude range (Fig 1). We will consider herein a set of known surface processes and make preliminary estimates on their viability as the fountain energy driver.

The Water Veneer. This veneer is defined as the exposed thin-layered dayside water/OH detected by Chandrayaan-1, CASSINI, and EPOXI. The CASSINI VIMS lunar water/OH observations [2] suggest that this veneer is present in an extended region at mid-latitudes at near-surface abundances of 10-1000 ppm (consistent with an observed ~3% absorption in the 3 micron IR feature). If we assume that the dayside region between 70-85° latitude about each pole possesses a water content at this 10-1000 ppm abundance, then the total number of near-surface molecules comprising one hemisphere is N ~ 10^{27} to 10^{29}. In this model we assume that the water molecules are loosely bound and dynamic, such that they reside only temporarily on the warm dayside surface, migrating back toward the cooler high latitudes via ballistic hopping trajectories. From an equatorial starting position, Crider and Vondrak [7] demonstrated that the primary loss process for ~ 96% of such migrating surficial water molecules is photo-dissociation. Only 4% of the water molecules successfully return to the cold polar trap region (Figure 2). We can thus estimate that this water veneer has to replenish itself on a time scale of τ ~ 10^5 seconds due to their photo-dissociation destruction.

However, photo-dissociation of water creates OH which also has an IR absorption feature that is part of the large absorption signature near 3 microns. Hence, the replenishment time, τ, for consideration is not that of water, but of its dissociative product OH liberally and randomly mixed with the water at mid-latitudes.
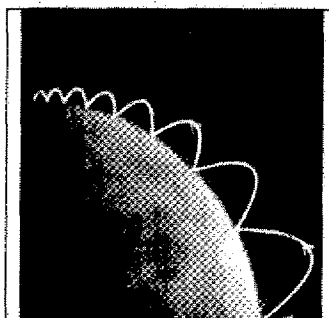

Figure 2- Water molecule ejected from ice block (red) and then migrating toward pole

Following dissociation, the OH will be immediately adsorbed to the surface at mid-latitudes and will remain bound (desorption temperature of over 400K [8]). The OH molecule will reside until it is sputtered from the surface. For a solar wind fluence of F ~2 $10^{12}/m^2$-s and sputter interaction area of ~ 25Å^2, the local residency time for the OH is $(25 \text{ Å}^2 F)^{-1}$ ~ 2 x 10^6 seconds. Due to the $1/E^2$ sputtered energy distribution [9], the impulsive event creates random OH surface migration and/or escape. Hence, an upper limit for the OH loss time is estimated to be a few sputter-induced hops or τ ~ 10^7 s. This surface temperature independent migration also allows a more-equatorial migration of OH as compared to thermally-migrating water.

In steady state, the rate of water from an external (polar) source, S, required for dynamic replenishment for H_2O and dissociated OH is S ~ N/τ ~ 10^{20} to 10^{22} H_2Os/sec. Are there processes that can eject polar water-ice to lower latitudes at the required rate?

Polar Ice Block. Based on the LCROSS, Lunar Prospector Neutron Spectrometer, and the evolving LRO/LEND observations, it appears that a near-surface polar icy regolith layer is present (neutron suppressed regions - NSRs) that encompasses close to the entire $5°$ cap about both poles [10]. For the calculations herein we assume that the area of the polar ice forms a cap of $A_s \sim 10^{11}$ m^2 about each pole. Comparison of fast and epithermal neutron levels suggest the presence of a water-free/dry top layer over buried icy regolith; this layer being possibly of 10's of centimeters in thickness [10].

As we demonstrate, the burial depth of the icy-regolith layer is a key factor in determining which process is acting and the associated source emission levels.

Solar Wind Ion Sputtering, and Electron & Photon Stimulated Desorption from Polar Ice. We examined each of these processes as an energization and releasing source for polar icy regolith. All three processes require water molecules very close to the surface, since the associated radiation penetrates small distances ($< 10^{-5}$ cm [9]) into the material. As such, these processes are view more pessimistically especially when considering activation of a buried icy-regolith layer.

Assuming a near surface icy layer, the source value of sputtering is estimated to have an upper bound of $S_{sputtering} \sim 10^{22}$ H_2Os/sec. This upper bound estimate assumes solar wind ions have full entry into polar craters, etc. For ESD from solar wind electrons and PSD from Solar UV [9,11, 12], we find source values at S_{esd} of $\sim 10^{20}$ H_2Os/sec and S_{psd} of at least $5\ 10^{20}$ H_2Os/sec, respectively. Again, these source values are applicable only for exposed icy-regolith.

Impact Vaporization. This process is attractive for two reasons: 1) the ice does not have to be directly exposed since the impact can penetrate below a cover layer. 2) An impact release at 4000K will create a water scale height of ~800 km, a lateral single hop distance of ~400 km, and an initial water velocity of ~2 km/sec. (i.e., capable of coating surfaces at lower latitudes).

The micro-meteoroid impact vapor flux is found to be 10^{-15} kg/m^2-s [13] and for an icy polar regolith with 5%wt water provides an outward flux of $\Phi \sim 10^9$ H_2Os/m^2-s. Integrated over the polar source area, $S_{impact} \sim \Phi A_s \sim 10^{20}$ H_2Os/s.

However, if the water is buried beneath a dry layer, more massive impactors are required for excavation. If we consider meteoroids of 1 g or greater that excavate > 6 cm into the regolith [14], then the resulting vapor flux from this contribution is 1-10% of Φ (Fig 12 of [13]), making $S_{impact} \sim 10^{18}$ to 10^{19} H_2Os/s (assuming a depth-integrated 5% wt of water).

Conclusions: Preliminary calculations suggest that impact vaporization of the polar icy regolith could indeed provide a fountain-like source of water molecules to lower latitudes. Can this source account for the mid-latitude water/OH levels reported previously [1-3]? For 5-10% icy regolith layer buried many centimeters under a dry regolith in the polar cap, the amount of the impact-ejected water is relatively low, requiring an additional source to explain the reported veneer levels (or a longer OH residency time than that assumed). However, if the polar icy regolith layer lies relatively close to the surface, enough water may be released from the polar cap region ($>85°$) to account for a large part or all of the mid-latitude veneer.

We will review other aspects of the model and provide some observational-oriented predictions that will help to either verify or nullify the water fountain hypothesis. Remote sensing of exospheric OH using the LADEE UVS should provide hypothesis support/nullification: the lack of any dissociated water products like OH in the exosphere would make this idea less attractive. However, if LADEE detects exospheric OH with progressively increasing concentrations with increasing latitude, then this would provide some level of added support to the hypothesis.

References: [1] Pieters, C.M, et al., Science, 326, 568, 2009.[2] Clark, R. N., Science, 326, 562, 2009; [3] Sunshine, J. M. et al., Science, 326, 565, 2009. [4] Colaprete, A. et al., Science, 330, 463, 2010. [5] Schultz, P. H., Science,330, 468, 2010. [6] Mitrofanov, I. G., Science, 330, 483, 2010. [7] Crider, D. H. and R. R. Vondrak, J. Geophys. Res., 105, 26773, 2000. [8] Hibbits, C. A. et al., Icarus, submitted, 2010.[9] Johnson, R. E., Energetic charged particle interactions with atmosphere and surface, Springer-Verlag, 1990. [10] Feldman, W. C., Science, 281, 1496, 1998. [11] McGrath, M. A., et al., Nature, 323, 694, 1986. [12] Thrower J. D. et al., J. Vac. SCi. Technol., A 28, 799, 2010. [13] Cintell, M. J., J. Geophys. Res., 97, 947, 1992. [14] Gault, D. E., The Moon, 6, 32, 1973.