The Arid Regolith of the Moon

R. R. Hodges1 and W. M. Farrell2

1Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, USA, 2Space Science Institute, Boulder, CO, USA

Abstract  In the original hypothesis of ice in lunar polar cold traps, it was presumed that meteoritic water acquired by the lunar surface would be concentrated in cold traps by exospheric lateral transport. That supposition is proven to be false by the absence of evidence of exospheric water in data obtained by the neutral mass spectrometer on the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft. The upper limit for exospheric water at the lunar surface, $\sim 3$ molecules cm$^{-3}$, is deficient by several orders of magnitude in accounting for transport of the present influx of meteoritic water to cold traps. The proffered process for removal of meteoritic water from the lunar regolith is solar wind sputter. This LADEE result does not rule out the possibly of past impulsive exospheric events like cometary impacts but does place a rigid constraint on the modern day water cycling.

Plain Language Summary  Whether vast deposits of water ice have accumulated in lunar polar cold traps may hinge on an unproven hypothesis that water acquired from meteor impacts and possibly other sources is moved to polar cold traps by the dynamic transport process of the lunar exosphere (a rarefied, collisionless atmosphere). Movement of exospheric molecules over the lunar surface is a two-dimensional random walk process in which the steps are random segments of ballistic trajectories that begin with thermal desorption from soil grains and end with adsorption at distances measured in hundreds of kilometers. Obviously, trajectories that end in cold traps must create ice deposits. However, the upper bound for exospheric water derived here from data collected in 2013–2014 by the neutral mass spectrometer on the Lunar Atmosphere and Dust Environment Explorer spacecraft, about three molecules/cc, pales in comparison to the concentration of $\sim 15,000$ molecules/cc needed to sequester the meteoritic water influx. The only pragmatic conclusion is that the hypothesis for water ice accumulation at the poles due to exospheric transport is false. This conclusion forces the question of the fate of water that accretes on the lunar surface.

1. Introduction

Optimism about resource level abundances of water sequestered near the lunar poles stems mainly from a reasonable hypothesis of Watson et al. (1961) and a more focused discussion by Arnold (1979) about how water acquired from external and internal sources could have been concentrated in polar cold traps by exospheric transport processes. A simplistic description of the lunar exosphere is a collisionless atmosphere where molecules travel randomly from point to point on the surface via ballistic trajectories that are segments of Kepler orbits. Upon impacting the regolith surface of the Moon, exospheric molecules tend to do a three-dimensional random walk among soil grains, each encounter involving adsorption followed by thermally controlled desorption and thermal departure either to another grain or back into the exosphere. If photolysis and surface chemistry could be neglected it would be inevitable that the exospheric lifetimes of water molecules would end in cold traps and create ice.

However, the elephant in the room is argon-40 sorption, an issue that has been known and, like Krylov’s Inquisitive Man, ignored for decades. The diurnal variation of inert gases at the lunar surface was predicted by Hodges and Johnson (1968) to approximate the classic $T^{-5/2}$ law of exospheric equilibrium. For the Moon, that translates to a night to day ratio of about 30:1. That expectation was shattered in the data from the first hour of operation of the Apollo 17 neutral mass spectrometer (NMS, Hodges et al., 1973): argon-40 mimics the behavior envisioned by Hodges and Johnson for water vapor, that is, depletion at night due to condensation and a sunrise bulge as the surface warms.

The activation energy for desorption required to remove argon from the nighttime lunar exosphere is about 25 kJ/mole (Hodges, 1980, 1991, 2002). This level can only occur on pristine, water-free surfaces (Bernatowicz &
Podosek, 1991). While the Apollo 17 data relate only to low latitudes, the identification of a seasonal oscillation of argon-40 in the presently quiescent lunar atmosphere (Hodges & Mahaffy, 2016) extends the pristine soil requirement into parts of lunar polar regions that are not permanently shadowed.

In practical terms, surfaces of soil grains over nearly all of the lunar surface, including polar regions, are limited to significantly less than one monolayer of water. Implicit in this assertion is that without adsorbed water, experimental studies involving rehydration of returned soil samples are not relevant to the global water issue.

This report begins with the derivation of an upper bound for lunar exospheric water based on data collected at low latitudes by the NMS on the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft. The discussion progresses to an explanation of why water, assimilated continuously and globally, is not moved to cold traps by exospheric lateral transport as proposed by Watson et al. (1961) and Arnold (1979). Subsequent discussion centers on global processes for removal of incoming water fast enough to avoid creating a detectable exospheric signature while avoiding the sub-monolayer limit imposed by argon sorption observations.

2. The Upper Limit for Exospheric Water

The data that form the basis for this discussion were acquired by the NMS on the LADEE spacecraft (Mahaffy et al., 2014). These measurements are contaminated by artifact water and methane created in a getter by gases evolving from the hot filament of the ion source (Hodges, 2016). Ironically, the getter was installed in the mass analyzer for vacuum maintenance, facilitating the inclusion of a mass spectrum in pre-flight and post-launch verifications of the operational status of the NMS. The extraction of an exospheric component of methane from the compromised data is explained in Hodges (2016), and an obvious correlation of water and the artifact component of methane is discussed in Hodges (2018).

Among the neutral mass spectra acquired by LADEE there are 394 orbits, spread over 140 days, wherein the mode of operation provided repetitious, paired monitoring of water and methane beginning around local noon, traversing the sunrise terminator, and ending around local midnight. Salient facts about this data set include that the orbit was retrograde with periapsis near the sunrise terminator to sample the highest concentrations of minor species in the classic sunrise bulge of exospheric gases (Hodges & Johnson, 1968). Spacecraft battery capacity restricted operation of the NMS to 1/2 of an orbit each time it was powered. Resource sharing further limited usage of the NMS to a few orbits per day. Owing to the inability of the mass analyzer to separate the 16 amu mass defects of methane and atomic oxygen, the unencumbered CH$_3$ fragment of methane at 15 amu is used here as a proxy for methane. The unit of measure is counts per integration period (247 ms) after applying the standard adjustment for thermo-molecular pressure difference (Mahaffy et al., 2014).

Paired measurements of H$_2$O and CH$_3$ from each of the 394 orbits that meet modal criteria have been averaged in one hour local time (LT) zones, condensing the data to one point per orbit per LT hour (about 4.6 min of instrument time). These points are presented in Figure 1 as color-coded scatter plots. The format is H$_2$O versus CH$_3$, with abscissas shifted by $\sqrt{10}$ in successive time zones. The order of plotting data points is randomized to keep late orbits from overwhelming early ones and obscuring color trends. LT boundaries are annotated at the top of each LT collection of data points and the corresponding scale factor of abscissas is at the bottom. Owing to the retrograde orbit of the spacecraft, LT decreases from left to right as operating time of the instrument increases. Trend lines are intended only to guide the eye.

In panel A of Figure 1 there are two identical sets of LT zone scatter plots of raw data points. The upper row is color-coded in days measured from 1 January 2014; color-coding in the lower row is according to spacecraft altitude. What immediately meets the eye is the stratifications of colors in the upper row, and the lack thereof in the lower row. If water and methane were both atmospheric constituents, the altitude identification colors in the lower row would progress upwards barometrically from blue to red. On the other hand, the well-defined rainbow patterns in the upper row of scatter plots are consistent with an instrumental process that created artifact water and methane with steadily decreasing efficiency over the duration of the mission (Hodges, 2018).

Inasmuch as methane is (and by inference, water must be) depleted in lunar nighttime due to adsorption on cold soil grains, neither natural water nor methane could have contributed to the measurements in the 00–05 LT zones (which are combined in the scatter plots). In other words, this set of data points is entirely instrumental artifact.
Figure 1.
It follows that the nature of the instrumental process that created these artifacts can be derived from the 00–05 data collection. The rainbow effect, the general power-law trend of the data, and a less obvious, but important, difference in the trends of red and blue dots, suggest that the artifact generating process can be approximated empirically by

$$[H_2O] = \eta_{\text{orbit}} G(t) F([CH_3])^P$$  \hspace{1cm} (1)

where $G(t)$ is a LT-dependent scale factor, and the coefficient $\eta$ accounts for orbit-to-orbit variations in the feedstock of the instrumental process that creates CH$_4$ and H$_2$O. The function $F$ is

$$F(X) = e^{\alpha X^{1+\beta D}}$$  \hspace{1cm} (2)

where $D$ is fractional time in days measured from the start of year 2014, the first term is the correction for the rainbow effect while the second term corrects for a systematic perturbation of the power law of the process. Coefficients derived from a least squares error fit of Equation 1 to the 00–05 hr data collection are: $\alpha = 0.01177$, $\beta = -0.001559$, and $P = 2.446$.

In Panel B of Figure 1 the scale of abscissas is transformed from raw data counts to the temporal function $F([CH_3]_{\text{raw}})$. The validity of the transformation function $F$ is supported by the way that almost two thousand nighttime data points cling to the 00–05 LT regression line. In daytime the scatter of the dots is probably owed to variations of rates of filament out-gassing of the feedstock components of the artifact-generating processes, rates that are influenced by randomness in previous periods of annealing of the filament surface each time power was removed at the end of about an hour of NMS operation (Hodges, 2018).

In daytime hours of Panel B the methane correction of abscissas tends to align dots parallel to regression lines at high altitude levels but curve downward at the low end. This is caused by the barometric distribution of natural exospheric methane. In Panel C, the diurnal methane simulation of Hodges (2016), scaled to a global supply rate of $4 \times 10^{23}$ molecules per second and converted to detector counts, has been subtracted from the raw data before application of the abscissa transformation. The resulting conformance of all residual daytime data with trend lines and the absence of a barometric decay with altitude is ample proof that water in LADEE data is artifact.

Figure 2 shows the results of converting detector counts for H$_2$O to exospheric concentrations as described in Mahaffy et al. (2014), and then extrapolating them barometrically to the lunar geoid to identify the lowest concentration in each LT group. Each point represents the converted average of 65–91 H$_2$O measurements in one orbit; the vertical error bars give standard deviations. These data points are absolute upper bounds for water concentration at the geoid. However, it is apparent in Figure 1 that if the exospheric contribution near noon were 50% at lowest altitudes, the nature of the distribution of dots would be noticeably different. In other words, Figure 2 exaggerates the upper limit for exospheric water by at least a factor of two. However, it is apparent in Figure 1 that if atmospheric water approached one of these limits, the artifact contribution for both water and methane would approach zero, and the low altitude data in scatter plots of panel C of Figure 1 (i.e., red points) would resemble a hockey stick. A subjective, but reasonable, assumption is that Figure 2 exaggerates the upper limit for exospheric water by at least a factor of two.

Figure 1. Scatter plots of lunar atmosphere and dust environment explorer (LADEE) mass spectrometer measurements of water versus the methane proxy CH$_4$ from a set of 394 orbits wherein NMS power-on occurred within ±7.5°of longitude from the sub-solar meridian and ended near nadir (the orbit is retrograde). The unit is detector counts per 237 ms. Coordinates of each data point represent the time averages of 13–80 paired measurements in a 1 hr local time (LT) interval. Trend lines are included to guide the eye; LT is at the top of each trend line and abscissa scale offset is at the bottom. Panel A: Raw data color coded according to time in days from 1 January 2014 (top), and according to spacecraft altitude (bottom). Panel B: Raw dated re-plotted with the abscissa transformed by Equation 2. Panel C: CH$_4$ corrected for exospheric methane and transformed by Equation 2.
3. Discussion

There are some important but obscure points to keep in mind throughout this discussion. In the reports of Epstein and Taylor (1971, 1972, 1973, 1974, 1975) on the pyrolysis of soil samples from all Apollo sites shortly after their collection, a common thread is that prior to reaching 600°C (approximately solidus for silicates) all of the water extracted from fresh samples had the isotopic characteristics of terrestrial water that was acquired during or after sample collection. Trapped, deuterium-depleted solar wind hydrogen emerged at higher temperatures (Epstein & Taylor, 1974). This pattern was inherent in surface samples as well as all three sections of the Apollo 15 deep core (Epstein & Taylor, 1975). (Note that these observations are unlikely to be reproducible because of disintegration of the sample collection (Cooper et al., 2015)).

The absence of indigenous water in returned surface soil samples implies that, in addition to being exosphere-averse, water molecules deposited on the surface do not migrate downward. In addition, the absence of primordial lunar water in Apollo 15 deep core samples implies that water does not percolate upward from the lunar interior. These observations are consistent with the argon adsorption data collected by the Apollo 17 and LADEE mass spectrometers (see above) that preclude the formation of a monolayer of sorbed water on grain surfaces, even in polar regions that are not cold traps. An additional complication is that water adsorbed on pristine soil grains is so tightly bound that laboratory bakeout temperatures approaching silicate solidus are inadequate to satisfy the argon cleanliness requirement (Bernatowicz & Podosek, 1991; Cadenhead & Stetter, 1974).

In Arnold (1979) the candidate sources of water in polar cold traps include the reduction of Fe+++ by solar wind, chondritic meteorites, volcanic activity, and comet impact. The solar wind origin of lunar water has been effectively dismissed (Basu, 2005). There is photographic evidence of recent basaltic volcanism (Bradon et al., 2014), but it is not clear that water is involved. On the other hand, it is possible that one or more comets have impacted the moon and deposited significant amounts water in polar cold traps (Stewart et al., 2011). However, the only certain source of water on the moon is meteorites, and the only route to polar traps is exospheric transport.

Inasmuch as exospheric lateral flow is analogous to two-dimensional diffusion (Hodges, 1972), the meridional gradient of the effective lateral diffusion coefficient offsets the natural tendency of exospheric molecules to congregate in cold places (Hodges & Johnson, 1968). As a result, there should be little meridional variation in the concentration of water molecules in daytime.

If the exosphere were Maxwellian and orography were non-existent, the flux of water molecules striking the lunar surface would be $n \sqrt{kT/2\pi m}$, where $n$ is the molecular concentration at the surface, $m$ is molecular mass, and $T$ is the average surface temperature (about 150 K near the poles). Based on the LADEE limit of three molecules cm$^{-3}$, and assuming that cold traps cover 5% of the surface area at latitudes above 80°, the present estimate of the maximum downward exospheric water flux into cold traps is 8.600 g/A.

Borin et al. (2017) estimate that 3.66 x 10^{9} g of meteoritic material impact the Moon each year. While water and hydrous phyllosilicates tend to be concentrated in carbonaceous chondrites, there is no consensus regarding the meteoritic abundance of H$_2$O and/or OH. For demonstration purposes, that fraction will be assumed to be 30% of the carbonaceous chondrite mass flux. Assuming that carbonaceous chondrites account for 4.6% of the meteoritic infall (Bischoff & Geiger, 1995), the rate of water acquisition by the Moon should amount to $\sim$5 x 10^{7} g/A. In other words, the upper bound for exospheric transport of meteoritic water to the poles amounts to less than 0.02% of the estimated meteoritic water influx. The sheer magnitude of this discrepancy begs the question: What could happen to 5 x 10^{7} g of meteorite water accreted by the Moon each year?

Meteorites impact the Moon at speeds capable of vaporizing themselves and surrounding lunar material. Vapor temperatures that are great enough to cause significant escape (i.e., greater than 5,000 K) are unlikely. Instead, the heat of vaporization limits vapor temperature, the mean speed of gaseous molecules increases with adiabatic expansion, the vapor becomes collisionless, and water is ballistically dispersed over an area of hemispheric dimensions, with each molecule following an independent, planetary scale, Keplerian trajectory. The result is a constant “rain” of water molecules over the entire lunar surface. Owing to the pristine nature of soil grains required for argon adsorption, the impacting molecular rain becomes tightly bound by unidentified processes of adsorption and/or possibly absorption, creating the phenomenon that commonly drives laboratory bakeout temperatures above 600°C and irreversibly alters soil grain surface physics (Cadenhead & Stetter, 1974).
Reconciliation of the meteoritic water influx and the essentially water-free exosphere requires a presumption of escape and/or dissociation that leaves no residue of OH. A plausible scenario suggested by Housley (1977) is that cleansing of regolith grain surfaces and forced escape of extra-lunar contaminants occurs naturally as a result of solar wind bombardment. The nominal solar wind flux is ∼3 × 10^8 cm^-2 s^-1. At low latitudes, diurnal averaging reduces the influx to ∼10^8 cm^-2 s^-1 on the far side; solar wind blockage during the periodic passage of the Moon through the geomagnetic tail decreases the flux an additional 20% on the near side.

The semiannual oscillation of argon-40 detected by LADEE (Hodges, 2018; Hodges & Mahaffy, 2016) is a polar phenomenon that requires pristine soil grain surfaces at polar latitudes. With increasing latitude the geometric influx of solar wind on the surface tends to decay as the cosine of latitude. Some assurance that the solar wind cleanses polar regolith can be found in the comparable abundances of trapped solar wind ^4He, ^20Ne, and ^36Ar in Apollo 16 soils collected from permanent shadow near House Rock and those in soils collected from exposed regolith nearby (Eberhardt et al., 1976). Assuming that this effect translates to solar wind access to exposed grains at polar latitudes (i.e., latitudes greater than 80°), and accounting for geomagnetic tail passage, the minimum diurnally averaged solar wind flux is probably around 1.4 × 10^7 cm^-2 s^-1.

In steady state, the fraction of occupied adsorption sites, δ, is

\[ \delta = \frac{\Phi_W}{\Phi_W + \eta \Phi_{SW}} \]  

(3)

Where \( \Phi_W \) is the influx of meteoritic water, \( \Phi_{SW} \) is the average solar wind proton flux, and \( \eta \) is the efficiency of solar wind erosion. There is a paucity of experimental information on the probability that an adsorbed water molecule would be ejected if its adsorption site were to be hit by a solar wind ion. A related bit of information is that the yield for 1 keV protons on ice is about 60% (Bar-Nun et al., 1985). Another is that solar wind sputter simulations of lunar soils by Wurz et al. (2007) give sputter yields of 4%–7% for oxygen and lesser amounts for other elements. Wurz et al. also found that “practically all” species are ejected with super-escape speeds. It is not clear how this extrapolates to sorbed water, but \( \eta \) must lie somewhere between the sputter yields for ice and rock.

Assuming that \( \eta \approx 30\% \), the maximum rate of water removal by solar wind scouring is

\[ \Phi_{W,\text{max}} = 1.4 \times 10^7 \frac{\delta}{1-\delta} \text{ cm}^{-2} \text{ s}^{-1}. \]  

(4)

Evidence of adsorption site competition for argon-40 (Hodges, 2018) suggests that, in the current epoch, \( \delta \) could be as great as 50%. That would allow solar wind scouring of water from polar soil grains at a rate that is equivalent to nine times the total mass influx of carbonaceous chondrites. Despite the heuristic nature and large uncertainties of this analysis, it is obvious that the solar wind is more than capable of removing meteoritic water from the lunar surface fast enough in polar regions to preserve the semiannual oscillation of argon-40.

4. Conclusions

The key experimental finding of this report is that the LADEE mass spectrometer data show no evidence of exospheric water on the Moon. More important, the upper bound for exospheric water falls short by several orders of magnitude of allowing the exosphere to be the conduit for transferring the meteoritic water influx to polar cold traps. This conclusion eliminates meteoritic water from the possible sources of polar ice deposits, but appears to leave open the possibility of trapped cometary water.

Data Availability Statement

The actual data set used in this investigation was assembled by the first author during the Lunar Atmosphere and Dust Environment Explorer mission. It is identical to the raw data set that is publicly available at the Planetary Data System (https://pds-atmospheres.nmsu.edu/PDS/data/PDS4/LADEE/).
Acknowledgments
This work was in part supported by the NASA Solar System Exploration Research Virtual Institute. It is a pleasure to acknowledge the thoughtful efforts of the reviewers.

References
Arnold, J. R. (1979). Ice in the lunar polar regions. Journal of Geophysical Research, 84(B10), 5659–5668. https://doi.org/10.1029/jb084i10p05659
Bar-Nun, A., Herman, G., Rappaport, M. L., & Meekers, Y. (1985). Sputtering of water ice at 30–140 k by 0.5–6.0 keV h+ and Ne+ ions. In D. Reidel (Eds.), In Icer in the solar system (p. 287–299).
Basu, A. (2005). Nanophase Fe2+ in lunar soils. Journal of Earth System Science, 114(3), 375–380. https://doi.org/10.1007/bf02702956
Bernatowicz, T. J., & Podosek, F. A. (1991). Argon adsorption and the lunar atmosphere. Proceedings of the Lunar and Planetary Science Conference, 21, 306–313.
Bischoff, A., & Geiger, T. (1995). Meteorites from the Sahara: Find locations, shock classification, degree of weathering and pairing. Meteoritics (ISSN 0026-1141), 30(1), 113–122. https://doi.org/10.1111/j.1945-5100.1995.tb01219.x
Borin, P., Cremosile, G., Marrari, F., & Lucchetti, A. (2017). Asteroidal and cometary dust flux in the inner solar system. Astronomy and Astrophysics, 605, A94. https://doi.org/10.1051/0004-6361/201730617
Brad, S. E., Stopar, J. D., Robinson, M. S., Lawrence, S. J., van der Bogert, C. H., & Hiesinger, H. (2014). Evidence for basaltic volcanism on the moon within the past 100 million years. Nature Geoscience, 7(11), 787–791. https://doi.org/10.1038/NGEO2252
Cadenhead, D. A., & Stetter, J. R. (1974). The interaction of water vapor with a lunar soil, a compacted soil, and a cinder-like rock fragment. Proc. Lunar Sci. Conf, 5th, 2301–2316.
Cooper, B. L., Thaisen, K., Chang, B. C., Lee, T. S., & McKay, D. S. (2015). Disintegration of apollo lunar soil. Nature Geoscience, 8(9), 657–658. https://doi.org/10.1038/ngeo2527
Eberhardt, P., Eugster, O., Geiss, J., Grögler, N., Guggisberg, S., & Mörgeli, M. (1976). Noble gasses in the Apollo 16 special soils from the east-west split and the permanently shadowed area. Proceedings of Lunar Science Conference, 7th, 563–585.
Epstein, S., & Taylor, H. P. (1971). O16/O18, Si28/Si29, D/H, and C13/C12 ratios in lunar samples. Proceedings of Lunar Science Conference, 2th, 1421–1441.
Epstein, S., & Taylor, H. P. (1972). O16/O18, Si28/Si29, C13/C12 and D/H studies of Apollo 14 and 15 samples. Proceedings of Lunar Science Conference, 3th, 1429–1454.
Epstein, S., & Taylor, H. P. (1973). The isotopic composition and concentration of water, hydrogen, and carbon in some Apollo 15 and 16 soils and in the Apollo 17 orange soil. Proceedings of Lunar Science Conference, 4th, 1559–1575.
Epstein, S., & Taylor, H. P. (1974). D/H and O16/O18 ratios in the rusty breccia 66095 and the origin of lunar water. Proceedings of Lunar Science Conference, 5th, 1839–1854.
Epstein, S., & Taylor, H. P. (1975). Investigation of the carbon, hydrogen, oxygen, and silicon isotope concentration relationships on the grain surfaces of a variety of lunar soils and in some Apollo 15 and 16 core samples. Proceedings of Lunar Science Conference, 6th, 1771–1798.
Hodges, R. R. (1972). Applicability of a diffusion model to lateral transport in the terrestrial and lunar exospheres. Planetary and Space Science, 20(1), 103–115. https://doi.org/10.1016/0032-0633(72)90145-6
Hodges, R. R. (1980). Lunar cold traps and their influence on argon-40. Proceedings of Lunar Science Conference, 11th, 2463–2477.
Hodges, R. R. (1991). Exospheric transport restrictions on water ice in lunar polar traps. Geophysical Research Letters, 18(11), 2113–2116. https://doi.org/10.1029/91gl02533
Hodges, R. R. (2002). Ice in lunar polar regions revisited. Journal of Geophysical Research, 107(E2), 5011. https://doi.org/10.1029/2000JE001450
Hodges, R. R. (2016). Methane in the lunar exosphere: Implications for solar wind carbon escape. Geophysical Research Letters, 43(13), 6742–6748. https://doi.org/10.1002/2016GL068994
Hodges, R. R. (2018). Semiannual oscillation of the lunar exosphere: Implications for water and polar ice. Geophysical Research Letters, 45(15), 7409–7416. https://doi.org/10.1029/2018GL077745
Hodges, R. R., Hoffman. J. H., & Johnson, F. S. (1973). Composition and dynamics of the lunar atmosphere. Proceedings of Lunar Science Conference, 4th, 2855–2864.
Hodges, R. R., & Johnson, F. S. (1968). Lateral transport in planetary exospheres. Journal of Geophysical Research, 73(23), 7307–7317. https://doi.org/10.1029/ja073i023p07307
Hodges, R. R., & Mahaffy, P. R. (2016). Synchronous and semiannual oscillations of argon-40 in the lunar exosphere. Geophysical Research Letters, 43(1), 22–27. https://doi.org/10.1002/2015GL067293
Housley, R. M. (1977). Solar wind and micrometeorite effects in the lunar regolith. Philosophical Transactions of the Royal Society of London, A, 285, 363–367. https://doi.org/10.1098/rsta.1977.0075
Mahaffy, P., Hodges, R. R., Benna, M., King, T., Arevey, R., Barciniaik, M., et al. (2014). The neutral mass spectrometer on the lunar atmosphere and dust environment explorer mission. Space Science Reviews, 185(1–4), 27–61. https://doi.org/10.1007/s11214-014-0043-9
Steward, B. D., Pierazzo, E., Goldstein, D. B., Varghese, P. L., & Trauton, L. M. (2011). Simulations of a comet impact on the moon and associated ice deposition in cold traps. Icarus, 215, 1–16. https://doi.org/10.1016/j.icarus.2011.03.014
Watson, K., Murray, B. C., & Brown, H. (1961). The behavior of volatiles on the lunar surface. Journal of Geophysical Research, 66(9), 3033–3045. https://doi.org/10.1029/jc066i09p03033
Wurz, P., Rohner, U., Whiby, J. A., Kolb, C., Lammer, H., Dobnikar, P., & Martín-Fernández, J. (2007). The lunar exosphere: The sputtering contribution. Icarus, 191(2), 486–496. https://doi.org/10.1016/j.icarus.2007.04.034