MIGRATION OF VOLATILES ON THE LUNAR SURFACE
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At high latitudes on the moon, and presumably on Mercury as well, there are regions of permanent shadow that are large enough that their temperatures reach radiative equilibrium, virtually unaffected by lateral conduction of heat through the soil from surrounding sunlit areas. Watson et al. (1) and Arnold (2) have deduced, on the basis of earth-based and spaceflight photography, respectively, that about 0.5% of the lunar surface is in permanent shadow. Because some of these regions may be very cold, they probably trap condensible atmospheric volatiles. Arnold (2) suggests that polar cold traps should have accumulated a significant fraction of whatever water may have degassed from the moon or accreted on the moon as the result of comet and meteorite impacts. The probable amount of water accumulated in the cold traps is substantial, and may be a useful resource in future exploration of the moon.

An analysis of radiative equilibrium in crater-like formations (3) has shown that permanent shadow is not a sufficient condition to assure temperatures low enough to form cold traps. What is required is a surface that is permanently shielded from both incident solar radiation and infrared reradiation from sunlit surfaces. Actual cold traps are most likely to be found on equator-facing surfaces in relatively large (0.1 to 1 km.) fresh craters that are situated in permanent shadows of much larger craters. The best available estimate is that such cold traps cover only about 0.05% of the lunar surface, and that they exist mainly at latitudes above 75° (3).

The fact that the total cold trap area appears to be an order of magnitude smaller than estimated by Arnold (2) is of little consequence to his conclusion that water should have accumulated in frozen deposits in the traps. Furthermore, the significance of the existence of cold traps is not limited to the water question. Many volatiles that have low vapor pressures must have accumulated in the traps over the time that the tilt of the axis of rotation of the moon has been small, probably more than 2 aeons (2). Thus the cold traps are reservoirs of potentially useful materials. In addition, samples obtained from the traps should provide a record of the degassing history of the moon over at least the last half of its existence.

Cold traps must also act to retard the loss of escaping elements from the moon. A major component of the lunar exosphere that must be affected in this way is radiogenic argon-40, which degasses from the moon at a rate equivalent to 3-6% of its total rate of production from 40K decay in the entire moon (4). The cold traps on the lunar surface can probably retain argon for periods the order of 10 years, providing a sink for transient releases, as well as a steady supply of recycled atoms to the exosphere. The slight tilt of the lunar axis causes the adsorption of argon on a small 'winter' polar cap that dissipates near lunar equinox (3).

The Apollo 17 mass spectrometer records show the exospheric argon-40 abundance to vary with time, requiring a time dependent source that apparently consists mainly of transient releases. Initially it was thought that the logical origin of these releases was in active seismic regions, most likely deep in the semi-molten lunar interior, but a deep origin of the argon-40 is questionable due to an approximate correlation of argon releases with shallow moonquakes (4). This has prompted suggestions that the transient argon releases may be caused by seismic activity at the lunar surface, perhaps the result of rapid desorption from cold traps that have been disturbed by shallow moonquakes (3). Binder (5) has proposed that the small scarps found throughout the lunar highlands are surficial evidence of underlying thrust faults whose movement causes both the shallow moonquake seismic signals and the sudden release of radiogenic gases by mylonization and perhaps frictional melting of crustal rock along the faults.
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Whatever the origin of the argon-40, its temporal behavior on the moon must be affected by adsorption in very cold regions. This fact was ignored in early attempts to model the lunar exosphere, wherein a simple surface temperature distribution, appropriate for a smooth spherical body, was assumed. To improve the validity of lunar exosphere simulation computations, a statistical model of synodic variations of lunar surface temperature that accounts for the uneven surface of the moon, for shadowing of low places by surrounding features, for solar illumination of high sun-facing surfaces on the night side of the geometric terminator, and for heating due to infrared reradiation, has been developed.

The new lunar surface temperature model has been used in two Monte Carlo simulations of the response of the lunar exosphere to transient releases of argon-40, one for a daytime release at a latitude of 80°, and one corresponding to sudden release of the argon adsorbed on the 'winter' polar cap. Results from these calculations are shown in Figures 1 and 2. In each case the upper curve represents the time history of the fraction of the atoms that have avoided both ionization and capture in a cold trap; hence this graph is proportional to total exospheric abundance, which includes ballistic atoms and those adsorbed on temporarily cold surfaces. Each of the lower graphs is the average vertical exosbase flux at latitudes below 30° (normalized to a release of 1 mole). The noise superimposed on the flux plots is an inverse function of computation time, and of no importance.

Immediately following the release, Figure 1 indicates a rapid decrease in total abundance and a large impulsive increase in the low latitude flux for the 80° latitude source. Similar features are absent in the polar release data of Figure 2, mainly because the atoms originating at the pole are more likely to be subjected initially to temporary adsorption (i.e. for less than one lunation) on surfaces that warm only briefly during daytime. After about 15 days the low latitude flux data for the two cases become similar, and either gives a decay of about a factor of two over a period of 4 lunations, similar to the Apollo 17 mass spectrometer observation (4).

The major problem with the present argon-40 exosphere simulation data is that escape due to ionization only accounts for 1/3 of the argon loss, while cold traps apparently remove the other 2/3. The retention time for trapped argon depends on both temperature and the nature of the surface. Contaminants, such as water and other volatiles expected to have accumulated in cold traps, generally decrease activation

![Figure 1. Daytime source at latitude = 80°.](image1)

![Figure 2. Polar cap source.](image2)
energy and hence enhance argon desorption. It is expected that temperatures below 30 K are required to permanently hold argon, and that such temperatures are uncommon on the moon (3). However, a background source of recycled trapped argon is not apparent in the Apollo 17 mass spectrometer data (4), suggesting that the rate of argon release during the measurement period (1973) may have been considerably above average, masking the background. An alternative explanation is that the cold trap surfaces are pristine rock, uncontaminated by other volatiles. Then more reasonable temperatures, near 45 K, are sufficient to permanently trap argon.

That the cold traps could be devoid of condensates other than argon seems unlikely. Arnold's (2) arguments for water ice are compelling, despite the lack of evidence of water on the moon. An even stronger argument can be made for trapped Hg or perhaps HgBr₂, although the amount involved may be small.

Jovanovic and Reed (6) have reported measurements of mobilized Hg and Br released from various returned lunar samples at 400 K, which corresponds roughly to daytime lunar surface temperatures. Gradients of mobilized Hg in the upper 10 cm of core tubes from Apollo 15, 16, and 17 have been interpreted as evidence of some form of vertical diffusive equilibrium (7). Any vertical migration implies a transport interface with the exosphere, and a net outflux from the soil to supply lateral flow, which is a poleward migration to the cold traps. If there is an ongoing Hg transport process on the moon, it is necessary that either an Hg source exists, or the sum of the time constants for vertical diffusion in the soil and that for exospheric migration to cold traps be the order of the age of the regolith. Decimeter scale diffusion times for Hg or HgBr₂ in the upper regolith can be estimated conservatively to be less than a year. Preliminary results from an Hg lunar exosphere simulation show atom residence times ranging from 10² to 10⁵ years, with a median of about 10⁶ years, most of which is spent adsorbed on cold soil grains very near the surface. The migration of HgBr₂ should have similar characteristics, its decreased ballistic mobility being offset by a lower desorption activation energy as compared to Hg. Thus it appears that the mobilized mercury near the regolith surface is more likely to be a result of exospheric Hg than its source.

A deep regolith source is not indicated by the distribution of mobilized Hg below 10 cm depth in returned samples. However, it is likely that Hg is released from rocks melted by meteor impact. Mylonization and possible frictional melting caused by crustal faulting (5) may also release Hg. Thus there is every reason to expect that volatile mercury exists on the moon, and that cold trap surfaces are now coated with Hg. It is obvious that similar arguments can be made for trapping many other volatile substances. Perhaps the cold traps may prove to be a part of the explanation of the depleted abundances of sulphur and chlorine compounds on the moon relative to Mars (8).

REFERENCES