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LUNAR ARGON CYCLE MODELING

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Introduction

The isotope of ^{40}Ar was first detected by the Apollo 17 surface-based mass spectrometer LACE, along with Ne and He [1]. Its measured atmospheric density at the surface of ~10^4 atoms cm^{-3} is similar to that of He and makes them the most abundant gases in the lunar exosphere. Contrary to helium, argon is a truly native element in the lunar environment, resulting from the decay of ^{40}K within the lunar crust. Besides its importance for sounding the lunar interior, argon's behavior as a condensable gas might resemble that of other volatiles (e.g. water vapor) that can be stored in Permanently Shaded Regions (PSR) of the Moon for >1 billion years. The study of reflectance from these shadowed regions is the main objective of the LAMP instrument onboard the LRO spacecraft [2] and a detailed model of argon transport at the lunar surface has thus been developed.

Argon observations

The Apollo data, obtained during 9 lunations in 1973, showed a diurnal pattern typical of a condensable gas at the cold nightside surface temperature (figure 1). The decreasing trend from the sunset to the sunrise is consistent with increasing adsorption of argon at the cold lunar surface. The peaks at sunrise and sunset represent lateral migration of argon from the subsolar point to the nightside, due to the $T^{-5/2}$ dependence for a non-condensable gas at the hot dayside surface temperature [3]. The green line is the maximum density profile during one lunar night. The red line is the minimum density profile during one lunar night, recorded nearly 4 months later. There appears to be a variation of ^{40}Ar density, with maximum to minimum abundance ratio of ~3. This requires a presently active mechanism for transient venting of gas from deep within the Moon [4].

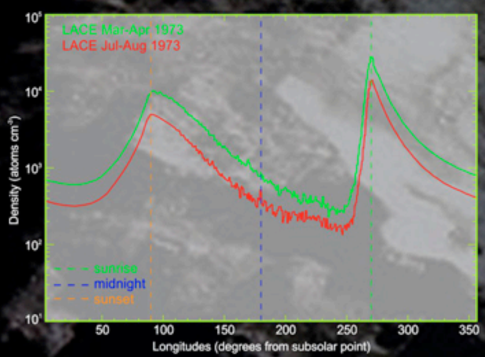

Figure 1: LACE measurements of lunar argon. Green: March – April 1973; red: July – August 1973

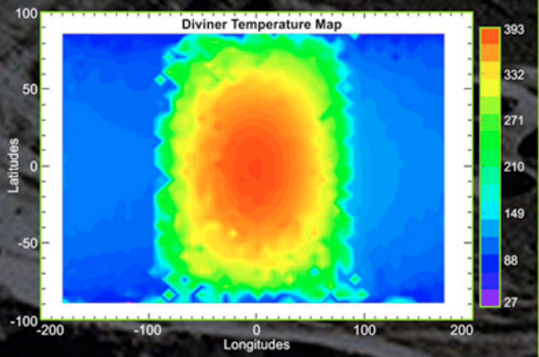

Figure 2: Diviner temperature map shifted to have noon at 180 deg. Sunrise is at -90 deg and sunset is at + 90 deg of longitude.

Description of the exospheric model

Our Monte Carlo simulation follows the fate of argon atoms from their creation to annihilation or implantation on the surface. Particles are emitted throughout the lunar surface with a Maxwell-Boltzmann flux distribution [5] and their trajectories are computed using a Runge-Kutta algorithm. Once a particle impacts the regolith, it resides for certain residence time, defined by the formula:

$$t = \frac{C}{T^2} \exp\left(\frac{Q}{RT}\right)$$

Where $C = 10^{-10}$ sK^2 is a constant, Q is the activation energy, R is the gas constant and T is the surface temperature. We used formula b) from [15] and found that a Qactiv of 9000 cal/mole is required to fit the observations. Moreover, the required quantity of argon atoms present in the exosphere at initial time in order to reproduce initial LACE measurements is 3.7×10^{28} atoms.

Fundamental parameters such as position, velocity, distribution of energy and velocity are stored at regular time steps.

Temperature maps

We use a LRO – Diviner surface temperature map (see figure 2). In this case we don't have to reproduce the surface temperature with an analytical expression, as it is often done in many Monte Carlo simulations (e.g. [19]).

Preliminary results

Our preliminary results show a satisfactory agreement with the measurements of the Apollo mass spectrometer (which were performed only at night): in figure 3 the density of argon at initial time (i.e. after the simulation reaches the steady state) is overplotted to the initial argon density measured by LACE (green line).

In figure 4 we plot the density of Argon after 4 months. The model (black asterisks) should match the red line if photo-ionization is an important loss process. This is not the case. The time required for photo-ionization to reduce Argon density to the value reported by [4] is greater than 120 days. That is, other mechanisms are required to explain the observed decrease. We thus want to investigate the trapping at the Permanently Shaded Regions.

The model results showed no appreciable difference if we take into account radiation pressure due to resonant scattering of sunlight.
This mechanism is responsible for the creation of an anti-sunward tail of lunar sodium atoms [6]. The low efficiency of this process is due to the extremely low g-value (resonant scattering coefficient) for argon compared to that for sodium (~10^{-7} s^{-1} vs ~1 s^{-1} at 1 AU, respectively).

Our preliminary estimate of photo-ionization rate is in very good agreement with the value inferred from LACE observations. We find that after 3 months the argon density is halved, so that the number of argon atoms still present in the simulation is ~1.8×10^{28}. This gives a mean photo-ionization rate of ~2×10^{21} atoms s^{-1}, in very good agreement with [4].

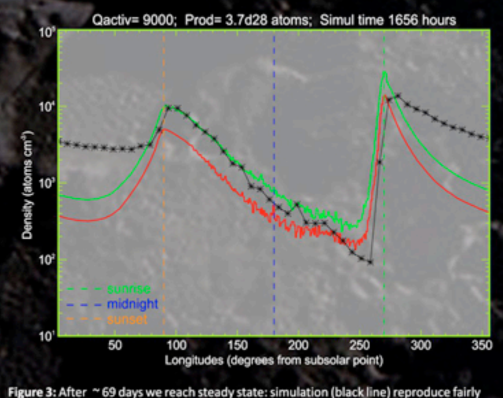

Figure 3: After ~69 days we reach steady state: simulation (black line) reproduce fairly well the decrease in argon density observed during one lunar night in Mar-Apr 1973.

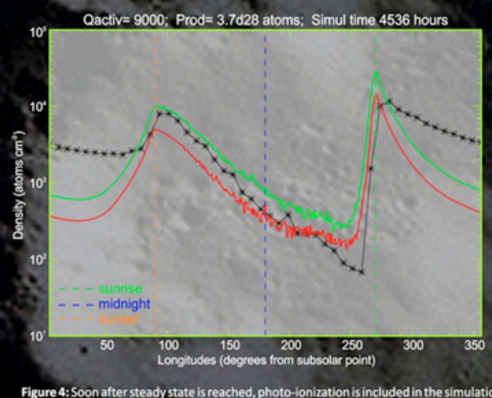

Figure 4: Soon after steady state is reached, photo-ionization is included in the simulation. After 120 days from the steady state the density did not reach the red line, which is the value of argon density measured from LACE four months later (Jul-Aug). That is, photo-ionization is not enough to explain the decrease in density observed with time. Other processes are required.

Permanently Shaded Regions

The idea of stable deposits of volatiles in cold permanently shaded regions (PSR), first advanced by [7], has been revived after observations by Lunar Prospector suggested large amounts of hydrogen exist in the polar caps [8]. Previous studies have mainly focused on hydrogen (and water) [9] but other important volatiles such as argon could also be trapped: the permanently shaded regions in the coldest polar craters can reach temperatures below 30 K [10], low enough to create a reservoir of trapped argon [11].

The Lyman Alpha Mapping Project (LAMP) ultraviolet imaging spectrograph aboard LRO is a compact but sensitive far-ultraviolet (FUV) instrument designed primarily to study the lunar surface. It has detected so far several elements of lunar atmosphere, such helium [12, 14] and molecular hydrogen [14] and additional elements (CO, Hg, Ca and Mg) were detected in the LCROSS plume [12]. Argon, however, is not within them. Although very faint (brightness expected of the order of 0.1 Rayeighs), the argon emission line at 1048 Å would be within LAMP sensitivity [13].

The model will investigate the flux of particles trapped in PSR to explain the observed decrease in density (first part). Subsequently, it will estimate the amount of argon which can be preserved in these regions and study their contribution to the lunar atmosphere (second part).

This model will mimic the space weathering model developed by [16] , using the argon deposit flux given by the exospheric model as an input, and describing loss rates due to various processes: EUV interplanetary radiation, thermal desorption, sputtering and soil gardening by meteoroids, as summarized in Figure 5. This model will be used to derive the mixing ratio of argon expected in the PSR soil, and any possible frost accumulations.

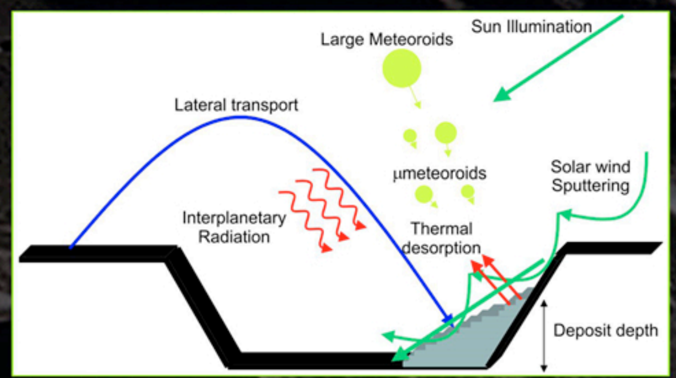

Figure 5: Schematic view of the main processes controlling the stability of argon deposits in permanently shaded regions.

Next Steps

A primary prediction of our model will be an estimate of the emission of the argon lines at 1048 Å and 1067 Å. The excitation of these lines is due to both resonance scattering of solar photons and solar wind electron impacts [17]. These authors demonstrated that a radiative transfer model is needed to derive the brightness of this optically thick emission. The coupling of the argon exospheric density given by the exospheric model and the radiative transfer will be used to estimate the argon emission lines brightness for various models and geometries. This will be used to help explain why several attempts to investigate exospheric argon have not proven successful.

Finally, this model will be modified to study the evolution of other volatiles, such as Hg, water and molecular hydrogen, known to be present in lunar atmosphere. In figure 6 we show that the model well reproduces Chamberlain atmospheres [18] of water and molecular hydrogen at four different longitudes. Squares are H_2O (blue model, red predicted), asterisks are H_2 (black model, orange predicted).

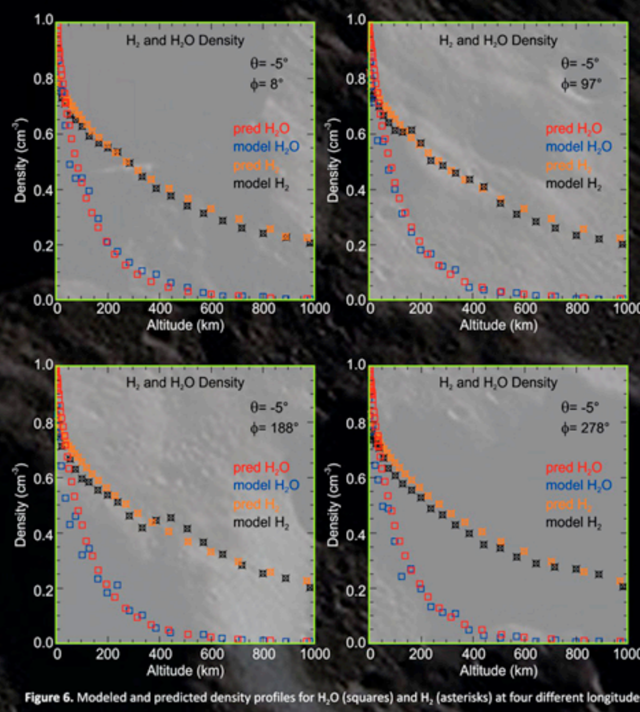

Figure 6. Modeled and predicted density profiles for H_2O (squares) and H_2 (asterisks) at four different longitudes

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