Evidence for a Localised Source of the Argon in the Lunar Exosphere

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Introduction: The Moon possesses our nearest example of a surface-bounded exosphere, the most common type of atmosphere in the solar system. As the molecules constituting an exosphere do not interact with one another during their ballistic trajectories over the surface, different species form independent systems. Their exospheric densities and variation with local time depend upon the sources, sinks, and surface interactions for that particular species. Hence, studying the lunar exosphere can teach us about the solar wind, the lunar interior and outgassing, the efficiency of volatile sequestration in polar cold traps, and the kinetics of adsorption and desorption in low pressure environments [1, 2, 3, 4].

Argon is a particularly well-studied species in the lunar exosphere, having been first detected by the Lunar Atmosphere Composition Experiment (LACE) on Apollo 17 [5], then observed in vastly improved detail by the Lunar Atmosphere and Dust Environment Explorer (LADEE) [6]. As well as measuring the daily and long-term variations in argon density during its 5 month mission, LADEE also determined the vertical structure of the exosphere and the variation with selenographic longitude [7]. This led to the discovery that there was an enhancement in the argon exospheric density over the western maria, dubbed the argon "bulge" [8]. The long-term variation in the argon abundance was ∼28% during the LADEE mission, much smaller than had been seen 40 years earlier by LACE over similar time periods.

Competing ideas have been proposed to explain both the bulge and the long-term variation, with implications also for the behaviour at different local times of day. We developed a new Monte Carlo model of the lunar argon exosphere and performed the first tests of these hypotheses, including: spatially varying surface interactions; a source that reflects the lunar near-surface potassium distribution; and temporally varying cold trap areas [1].

Competing hypotheses: For the bulge, Benna et al. (2015) [8] noted the similarity between the longitudinal variation and the distribution of near-surface potassium [9], so suggested a localised source. Hodges & Mahaffy (2016) [10] proposed that the bulge results from lower desorption energies in the maria, causing argon to spend less time residing undetected on the surface.

For the long-term variation, transient phenemona such as sporadic moonquakes [11] or tidal stress [8] have been suggested as the source of the LADEE variation. An alternative hypothesis is that seasonal fluctuations in the total cold trap area are responsible [10].

Methods: The central idea is to follow one particle throughout its life, then repeat this for many particles to build up a model exosphere. Each simulation particle represents a number of argon atoms, and in between its creation and loss from the system, it migrates in a series of surface interactions and ballistic hops. These simulations are broadly similar to previous models of exospheres [12, 13, 14].

Argon originates from the decay of ^{40}K to ^{40}Ar. We ran simulations with either a global or a localised source, such that a particle has a higher probability of being created over the mare to test if this can explain the bulge. Argon is eventually lost either from solar radiation while in flight or by landing in the extremely stable cold traps near the poles. In addition to the permanent traps, we tested seasonal traps that grow and shrink throughout the year owing to the Moon's 1.54° obliquity.

When an argon atom lands, it adsorbs to the lunar surface and resides there for some amount of time be-

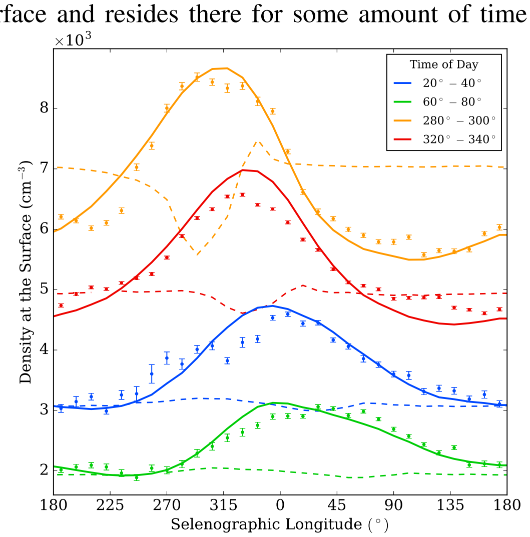

Figure 1: The variation of argon density with selenographic longitude for a representative selection of local times of day, shown by the different colours as defined in the legend (where 0° is noon, 270° is sunrise, etc.). The solid lines show the bulge from the local source model with high rates of source and loss, the LADEE data are shown as points, and the dashed lines show the results for the global source with a lower desorption energy in the mare region than in the highlands (26 and 28 kJ mol^{-1}).

fore being released, depending on the temperature and the desorption energy. During the night, the simulated particle may also "squirrel" down into the regolith, to resurface at some time the following day.

Results: Argon particles stick on the cold nightside and rotate with the Moon until they are warmed up at dawn, creating a huge density peak near sunrise. The timing and shape of this feature is very similar at all longitudes across the mare and the highlands and depends sensitively on the desorption energy, fixing it around 28 kJ mol^{-1}. This is in rough agreement with experimental values [16]. With the squirrelling process, our model matches the LADEE and LACE distributions to within a factor of 2 at all times of day. We note also that all the following results are insensitive to these models.

The bulge is remarkably well reproduced by a localised source, as shown in Fig. 1. The model was only tuned to match the size of the post-sunrise argon bulge, yet the sizes at all other times of day, the position, width, shape, and shift of the bulge to the east during the day also fit well. However, the size of the bulge requires either unexpectedly high source and loss rates of argon or a highly localised source [17, 15]. Diffuse and point-like sources would require source and loss rates of around 10^{22} and 10^{21} atoms s^{-1}, respectively.

The hypothesis of spatially varying desorption energies [10] fails to reproduce the observations (Fig. 1). It also cannot explain the ubiquitous timing and shape of the sunrise peak, which requires that surface interactions are very similar everywhere. This model also requires a temperature-dependent desorption energy up to $\sim$120 kJ mol^{-1}, far beyond the bond strengths that argon has been measured to make [18]. It appears that a local

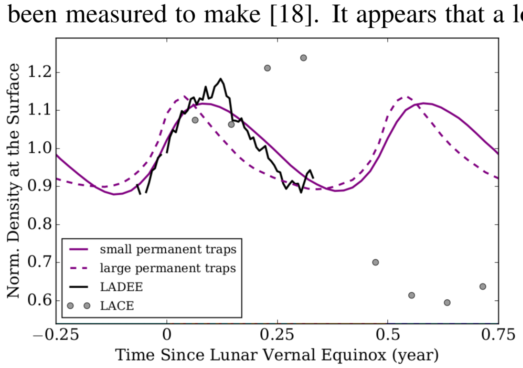

Figure 2: The long-term variation of the argon population within 30° latitude of the equator, normalised by the mean density. The purple solid and dashed lines show the normalised simulated density at the surface for a low and high loss rate model, respectively. Time is measured from the last lunar vernal equinox. The LADEE data are shown by the black line for comparison, the points show the magnitudes of the LACE sunrise densities relative to the mean measured by LADEE [15].

source is the only way to explain the observed bulge and its persistence at all times of day.

The long-term variation seen by LADEE can be explained by seasonally varying cold traps [10]. Fig. 2 shows how low permanent loss rates [17] reproduce the LADEE data well, including predicting the time delay of the peak after the equinox. High loss rates do not fit quite as well, but this could be affected by unaccounted-for factors in our simple cold-trap model such as thermal inertia. Unfortunately, this model fails to reproduce the long-term variation measured by LACE (Fig. 2). The seasonal change acts in the opposite way to the trend seen in 1973. Therefore, these data (if not artefacts) can only be explained by a large transient loss event or the decay of a large transient source event [11]. The rapid variation of the LADEE data could also be explained by transients but would require extremely high source and loss rates.

Summary: We studied the LADEE (and LACE) measurements of the lunar argon exosphere and investigated the sources, sinks, and surface interactions of the system, including performing the first tests of various hypotheses proposed to explain the observed features.

The variation with local time of day is similar at all longitudes and is well reproduced by a simple desorption energy of 28 kJ mol^{-1}. It cannot be explained by spatially varying surface interactions, which also fail to reproduce the persistent argon enhancement over the maria. A localised source appears to be the only model that can fit these observations, but requires a highly localised source or a very brief lifetime of argon atoms in the exosphere. Large, seasonally varying cold traps could explain the long-term global fluctuation observed by LADEE, but not that by LACE.

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