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Lunar exospheric argon modeling

Cesare Grava [a,*], J.-Y. Chaufray [b], K.D. Retherford [a], G.R. Gladstone [a], T.K. Greathouse [a], D.M. Hurley [c], R.R. Hodges [d], A.J. Bayless [a], J.C. Cook [e], S.A. Stern [e]

[a] Southwest Research Institute, 6220 Culebra Rd., San Antonio, TX 78238, USA
[b] LATMOS/IPSL, CNRS, Paris, France
[c] Johns Hopkins University, Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD 20723, USA
[d] LASP, University of Colorado, PO Box 4384, 130 W. Main St., Frisco, CO 80443, USA
[e] Southwest Research Institute, 1050 Walnut St., Suite 300, Boulder, CO 80302, USA

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ABSTRACT

Argon is one of the few known constituents of the lunar exosphere. The surface-based mass spectrometer Lunar Atmosphere Composition Experiment (LACE) deployed during the Apollo 17 mission first detected argon, and its study is among the subjects of the Lunar Reconnaissance Orbiter (LRO) Lyman Alpha Mapping Project (LAMP) and Lunar Atmospheric and Dust Environment Explorer (LADEE) mission investigations. We performed a detailed Monte Carlo simulation of neutral atomic argon that we use to better understand its transport and storage across the lunar surface. We took into account several loss processes: ionization by solar photons, charge-exchange with solar protons, and cold trapping as computed by recent LRO/Lunar Orbiter Laser Altimeter (LOLA) mapping of Permanently Shaded Regions (PSRs). Recycling of photo-ions and solar radiation acceleration are also considered. We report that (i) contrary to previous assumptions, charge exchange is a loss process as efficient as photo-ionization, (ii) the PSR cold-trapping flux is comparable to the ionization flux (photo-ionization and charge-exchange), and (iii) solar radiation pressure has negligible effect on the argon density, as expected. We determine that the release of 2.6×10^{28} atoms on top of a pre-existing argon exosphere is required to explain the maximum amount of argon measured by LACE. The total number of atoms (1.0×10^{29}) corresponds to ~6700 kg of argon, 30% of which (~1900 kg) may be stored in the cold traps after 120 days in the absence of space weathering processes. The required population is consistent with the amount of argon that can be released during a High Frequency Teleseismic (HFT) Event, i.e. a big, rare and localized moonquake, although we show that LACE could not distinguish between a localized and a global event. The density of argon measured at the time of LACE appears to have originated from no less than four such episodic events. Finally, we show that the extent of the PSRs that trap argon, 0.007% of the total lunar surface, is consistent with the presence of adsorbed water in such PSRs.

1. Introduction

The lunar atmosphere was first detected by Apollo 12, 14 and 15 with the Cold Cathode Gauge Experiments (CCGE) deployed on the lunar surface. These CCGE measurements determined a density of 10^7 cm^{-3} and 2×10^5 cm^{-3} in daytime and nighttime, respectively (Johnson et al., 1972). CCGE showed a large day/night density ratio, opposite to what is expected for non-condensable gases. Therefore, it was clear that the dominant gases in lunar atmosphere were adsorbed at night and released on the dayside.

1.1. Past observations with Lunar Atmosphere Composition Experiment (LACE)

The Lunar Atmosphere Composition Experiment (LACE) was a mass spectrometer deployed on the lunar surface in December 1972 during the Apollo 17 mission as part of the Apollo Lunar Surface Experiments Package (ALSEP). LACE was the first and, until very recently (Benna et al., 2014a), the only instrument to convincingly detect argon in the lunar exosphere. The argon density at the Apollo 17 site was seen to vary cyclically and also to show an overall decrease in density during 9 lunations. Fig. 1 of Hodges and Hoffman (1974) is the only published measurement of lunar argon during all 9 lunations, although efforts to restore the ALSEP data stream are ongoing (Williams et al., 2013). It was soon clear that

* Corresponding author.
E-mail address: cgrava@swri.edu (C. Grava).

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argon showed the typical behavior of a condensable gas given the cold nighttime surface temperature of the Moon. The density decreased soon after sunset because of the increasing adsorption, and increased before sunrise due to atoms coming from the already illuminated portion of the dayside surface. This pre-sunrise increase of argon occurred 50 km before the terminator (Hodges, 1973) because LACE was located in the floor of Taurus–Littrow valley and the mountains to the East delayed the illumination of the site by 8 h (Hoffman et al., 1973). There is also a smaller peak at sunset, resulting from a contribution of atoms migrating from the hot dayside. The fact that the peaks are not symmetric, as one might expect from the $T^{-5/2}$ dependence of the density in the horizontal transport assumption (Hodges and Johnson, 1968), is due to sequestration at nightside, which increases with decreasing temperature, and, to a lesser extent, at dayside microscale cold-traps (Henderson and Jakosky, 1997; Paige et al., 2010).

1.2. Origin of argon

On the Moon, argon is released from the interior by radioactive decay of ^{40}K. Therefore, its production depends on the quantity of potassium present in the crust. With a concentration of K within the crust of 100 ppm (Taylor and Jakes, 1974), the argon production within the Moon was inferred to be 2.4×10^{22} atoms s^{-1} (Hodges, 1975). From simulations it was initially determined that effusion of argon from the interior to the atmosphere was $\sim 2 \times 10^{21}$ atoms s^{-1}, meaning that 8% of the argon production rate for the entire Moon escapes to the exosphere while the majority of argon atoms is retained within the crust.

This effusion rate was later revised to be 1.4×10^{21} atoms s^{-1} (Hodges, 1977), corresponding to 3 ton/year. However, the mechanism for release for such a large amount of argon remained uncertain. Hodges (1977) initially excluded diffusion among the sources, on the basis that (a) it is too slow and (b) the returned lunar rock samples would show a paucity of ^{40}Ar instead of the excess reported by Heymann and Yaniv (1970). Hodges (1977) further concluded that argon must be released from small, warm regions at greater depth than the crust, in the molten asthenosphere, ~1000 km in depth, where Latham et al. (1973) identified a highly attenuating zone for seismic shear waves. This depth has been recently revised to be 1250 km by Weber et al. (2011).

The deep source origin for argon was first questioned by Hodges (1981) and, 25 years later, by Killen (2002). Applying a sophisticated multipath diffusion code, Killen (2002) showed that diffusion *from the crust* (i.e., a source much closer to the surface, ~25 km) could account for the effusive flux of argon into the lunar atmosphere. The proposed mechanism was the release of argon from opening of micropores and cracks, i.e. natural diffusion out of grains to pore spaces in the rocks with subsequent spilling into the exosphere after shallow moonquakes. A deep source was no longer necessary. We discuss moonquakes in more detail in Section 4.1 in light of our model's assumed population being consistent with the amount of argon that can be released during a moonquake.

1.3. Fate of argon

Fig. 1 in Hodges (1975) shows two diurnal profiles of the densities of argon measured by LACE just above the surface during lunations separated by 120 days, starting with the maximum argon density measured during the month of April 1973. We report it in Fig. 1.[1] The argon density is seen to decrease by a factor of ~2

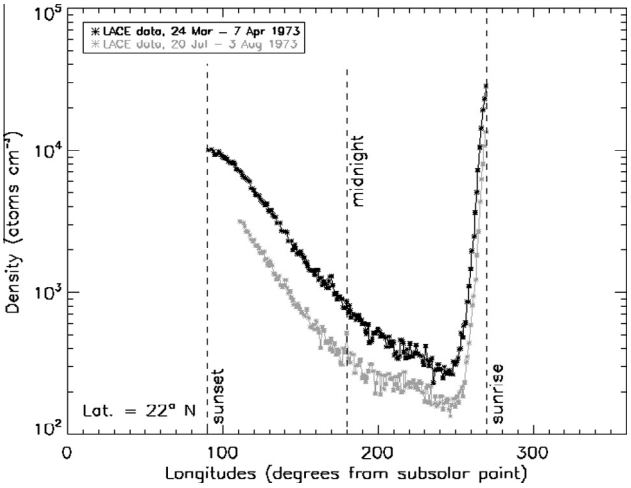

Fig. 1. The argon density measured by LACE over two different lunations, separated by 120 days. The *y* axis has a logarithmic scale; the *x* axis is the local time, measured in degrees from subsolar point. Digitized from Hodges (1975). The data from the more recent lunation start slightly later, at ~110° longitude.

in 120 days, with minor short-term variations in the intervening lunations. Our modeling work aims to identify what caused this decrease. As the past works based on these measurements, we assume that there was no degradation in the instrument, and that all calibration errors were taken into account (for a detailed description of the calibration of LACE, see Hoffman et al., 1973).

Loss of argon through ionization by solar UV photons is far more efficient than gravitational escape, and has previously been determined to be the primary loss mechanism (Hodges, 1977; Killen, 2002). Once argon atoms are ionized, the photo-ions are instantly entrained by the convective electric field $\mathbf{E}_{sw} = -\mathbf{v}_{sw} \times \mathbf{B}_{IMF}$ ($\mathbf{v}_{sw}$ is the velocity of the solar wind, and $\mathbf{B}_{IMF}$ is the interplanetary magnetic field). Roughly half of these photo-ions are thought to impact the surface and to be neutralized because of their large gyroradius (Manka and Michel, 1970) combined with the low scale height of neutral Ar (in fact, the pickup ion velocity distribution is dependent upon the velocity of the ion and the gyroradius/scale height ratio, which in turn varies as the mass squared (Hartle and Killen, 2006; Hartle et al., 2011). This process is termed "recycling" since these particles may again be released from the surface as neutrals. The short-term variations from lunation to lunation were first (Hodges, 1977) attributed to High-Frequency Teleseismic (HFT) events measured by other Apollo stations (Nakamura et al., 1974) but Hodges (1980) proposed that seasonal (i.e., 1–10 years) storage of argon in Permanently Shaded Regions (PSR) could explain, at least partially, the time variations measured by LACE. The trapped argon would then be occasionally released from PSRs following shallow moonquakes, meteor impact, or seasonal warming of polar caps (Hodges, 1982). The argon PSR cold-trapping hypothesis followed the analogy for water retention in PSRs, which was proposed well before the beginning of the Apollo program itself (Watson et al., 1961; Arnold, 1979). Hodges (1980) demonstrated that argon retention on water contaminated rocks for a year or more is mainly in doubly shielded regions of large, flat-floored craters located at latitudes greater than 75°. The area affected by this argon retention is 0.5% of the area of the lunar surface at latitude greater than 75°, or about 0.05% of the total lunar surface. The reason for this double-shielded argument is that the heat reradiated by nearby orographic features (such as rims exposed to sunlight) would liberate argon from the surface. More recent observations with LRO/LOLA and modeling (Mazarico et al., 2011) suggest PSRs cover an area of ~13,000 and

[1] Hereafter, we use LACE's convention for the "local time": 0° (from the subsolar point) means noon, 90° means sunset, 180° means midnight, and 270° means sunrise.