LRO/LAMP OBSERVATIONS OF LUNAR EXOSPHERIC HELIUM: CONSTRAINTS ON ITS THERMAL ACCOMMODATION AND OUTGASSING RATE.

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Introduction: Helium was among the first elements discovered in the lunar exosphere. The Lunar Atmosphere and Composition Experiment (LACE) mass spectrometer deployed on the lunar surface during the Apollo 17 mission reported densities of ~100,000 cm^{-3} [1]. Together with ^{40}Ar, He is one of the most abundant species in the lunar exosphere. Since then, helium was measured via remote sensing [2,3,4,5] by the UV spectrograph LAMP [6] onboard the Lunar Reconnaissance Orbiter (LRO) and in situ by the LADEE-NMS mass spectrometer [7].

Source of helium. Helium density is correlated with the solar wind alpha particle (He^{++}) flux, indicating that the main source process of lunar exospheric helium is neutralization, upon impact on the lunar surface, of these particles [8]. However, a small but non-negligible contribution is outgassing from the lunar interior, as ^{4}He is the daughter product of the radioactive decay of ^{232}Th and ^{238}U within the crust [9]. Supporting this hypothesis is the detection of sudden bursts of helium, detected by LAMP, that are uncorrelated to solar wind alpha particles [10]. Just how much helium is outgassing from the lunar interior, however, is still unclear. The fraction of this source process compared to the main one (solar wind) ranges from ~15% [7] to ~40% [4,5].

Thermal accommodation of helium. Moreover, there is an old but unresolved debate over whether [11] or not [12] the helium atoms are fully thermally accommodated to the lunar surface temperature. Thermal accommodation can be quantified with the accommodation coefficient $\alpha = (E_0-E_i)/(k_BT-E_i)$, where E_i is the energy of the impacting helium atom, E_0 is the energy of the atom leaving the surface, and T is the surface temperature. $\alpha = 1.00$ means that the atoms are fully thermalized with the lunar surface temperature. Thermal accommodation has implication for thermal escape and density.

Observations: To decrease uncertainty over the outgassing rate and to have a better understanding of the spatial and temporal structure of the lunar exospheric helium, the LAMP UV spectrograph onboard LRO has performed a series of observations to detect the helium (HeI) resonant scattering line at 58.4 nm. The LAMP detection of this line requires the helium atoms within LAMP's line of sight to be sunlit while the field of view terminates on the lunar nightside, suppressing extraneous background emission. To enhance the signal, the spacecraft was tilted relative to its nominal nadir pointing effectively increasing the column of sunlit helium. LAMP collected about 170 orbits' worth of data over 4 years (from 2013 to 2016) using this strategy. The observed helium brightness is converted to column density using g-values from SDO/EVE solar irradiance [13].

Helium Thermal Accommodation: LAMP-derived column densities are compared to those of an exospheric model previously applied to other helium observations [5]. The source rate in the model is held constant at $8\cdot10^{6}$ cm^{-2} s^{-1}, representative of the delivery of alpha particles from a nominal solar wind flux. To account for variations in the solar wind flux, we have scaled the model by the measured variations in solar wind alpha particle flux taken by the in-situ electrostatic analyzers of ARTEMIS twin spacecraft orbiting the Moon in highly elliptical orbits [14]. We used different accommodation coefficients: $\alpha = 1.00$, $\alpha = 0.75$, and a combination of these, to address the hypothesis that the nightside accommodation coefficient might be lower than that of the dayside [15]. The scatter plot in Fig. 1 shows that the best fit of the LAMP observations is with the $\alpha = 1.00$ model.

Helium Internal Source Rate: Having found the best fit model to our observations, we use it to constrain the amount of helium which is outgassing from the lunar interior. We do this by comparing the LAMP-constrained source rate (using the model with $\alpha = 1.00$) with the solar wind alpha particles flux measured by ARTEMIS. Fig. 2 shows that the two source rates are consistent with a linear relationship, but are not 1:1. The best linear fit includes a non-zero intercept and a slope. The intercept indicates the amount of helium which does not come from the solar wind: the linear fit constrains this to be $(1.49\pm0.08)\cdot10^{6}$ cm^{-2} s^{-1}. The slope of 0.42±0.02 is indicative of the fraction of helium atoms that LAMP cannot detect (in this case, 42%), either because solar wind alpha particles are backscattered or because they are released as energetic neutral atoms.

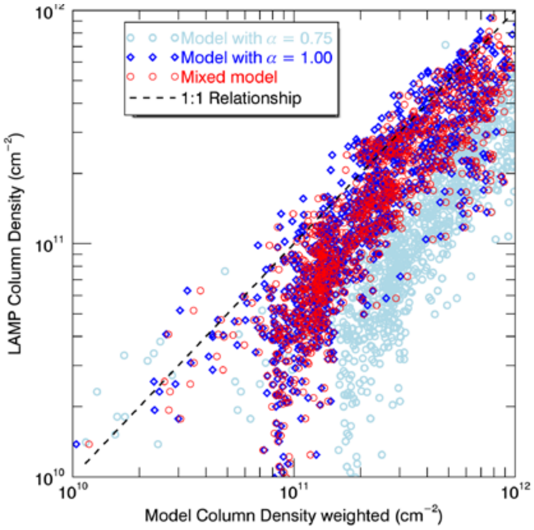

Figure 1 Scatter plot of LAMP-derived column density vs modelled column density, for three different values of accommodation coefficient α.

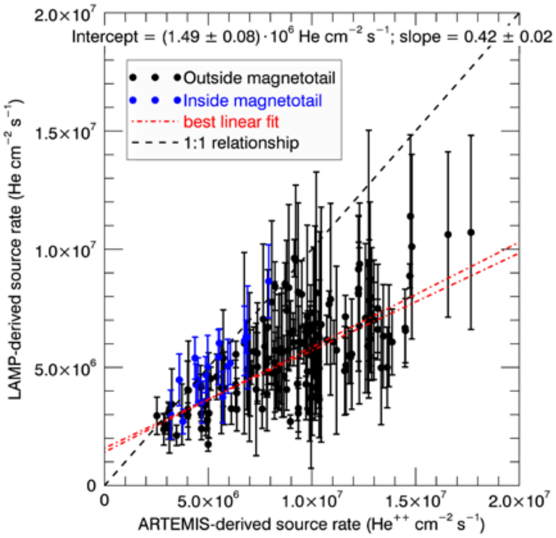

Figure 2 Scatter plot of helium source rates. Blue points are measurements taken inside Earth's magnetotail.

Helium Time Decay: There were three occasions when the Moon and LRO were inside Earth's magnetosphere, shielding the Moon from the solar wind. Fig. 3 shows one of such example. The surface density derived by LAMP using our best model shows the expected exponential decay of 4.5 days (the dashed line) as the influx of solar wind alpha particles is effectively turned off.

Conclusions: LRO LAMP carried out a campaign to map the spatial distribution and temporal evolution of helium in the lunar exosphere. LAMP-derived helium column densities, constrained with the help of an exospheric model and ARTEMIS in situ measurements, are consistent with a helium accommodation coefficient of 1.00 and an internal source rate of $(1.49\pm0.08)\cdot10^6$ cm^{-2} s^{-1}, or 21% of the solar wind alpha particles flux. These measurements further constrain previous in-situ measurements by mass spectrometry [7] and are consistent with theoretical predictions [9] based on the assumption that the pathway for outgassing of ^{4}He from the interior of the Moon into the exosphere is the same as that of ^{40}Ar, which has a source rate of $6.3\cdot10^4$ cm^{-2} s^{-1} [9].

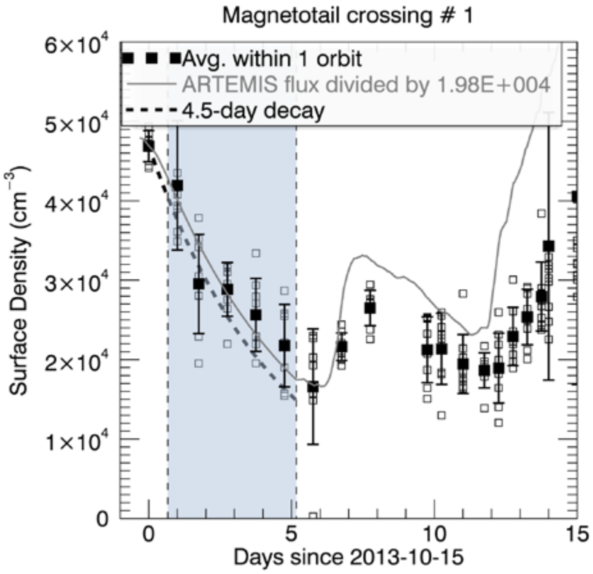

Figure 3 LAMP-derived surface density (filled squares, which are the average of the hollow squares) for one of the three occasions in which the Moon was inside the Earth's magnetosphere.

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