Possible Detection of Argon in the Lunar Atmosphere as Seen by the LAMP Instrument on the Lunar Reconnaissance Orbiter

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Introduction: The first indication that ^{40}Ar (hereafter Ar) was a part of the lunar atmosphere came from soil samples. An excessive Ar abundance suggested that the Moon's age was ~7 Gys (Kaiser 1972). It was therefore realized that Ar could not be attributed to the decay of localized ^{40}K, but rather Ar must be released from the Moon's interior to become a component of the lunar atmosphere (Signer et al., 1973).

The lunar atmosphere's presence was first detected using the Cold Cathode Gauge Experiment (Johnson et al., 1972). Following up on the initial detection, the mass spectrometer LACE (Lunar Atmospheric Composition Experiment) operated on the Moon's surface from December 1972 to October 1973. Among the masses detected by LACE were 4 and 40 AMU, and they were attributed to He and Ar, respectively. Spectroscopic confirmation of these species has only recently happened. Since September 2009, the Lunar Reconnaissance Orbiter (LRO) has used its sensitive UV-spectrograph, LAMP (Lyman Alpha Mapping Project), to observe the permanently shadowed regions (Gladstone et al., 2012), plumes caused by the LCROSS (Gladstone et al., 2010) and GRAIL impacts (Retherford et al., 2013), detected and measured variations of He in the lunar atmosphere (Stern et al., 2012; Feldman et al., 2012; Cook and Stern, 2014), detected H_2 (Stern et al., 2013) and provided stringent upper limits for 27 other species, including Ar (Cook et al., 2013). Here we report on our directed search for Ar in the lunar atmosphere and a possible detection by LAMP.

Observations: In June 2009, NASA's LRO entered a polar orbit around the Moon. LAMP, which observes from 575 to 1965 Å, has been used to observe the lunar atmosphere in three different modes. We focus on data obtained in our normal viewing mode, when LAMP is pointed at the surface. Figure 1 shows that in this nadir mode, there are periods of each orbit when the surface is in darkness, but the atmospheric column below LRO is in sunlight. These "twilight" observations occur twice per 2-hour orbit, about 11-12 times per day. A minimum of 600 seconds per orbit are spent observing in twilight. The total integration time from Sep. 2009 to Dec. 2013 for all LAMP nadir observations in twilight is about 19.1×10^6 seconds. As a result, these twilight observations are far more sensitive at detecting weak emission features.

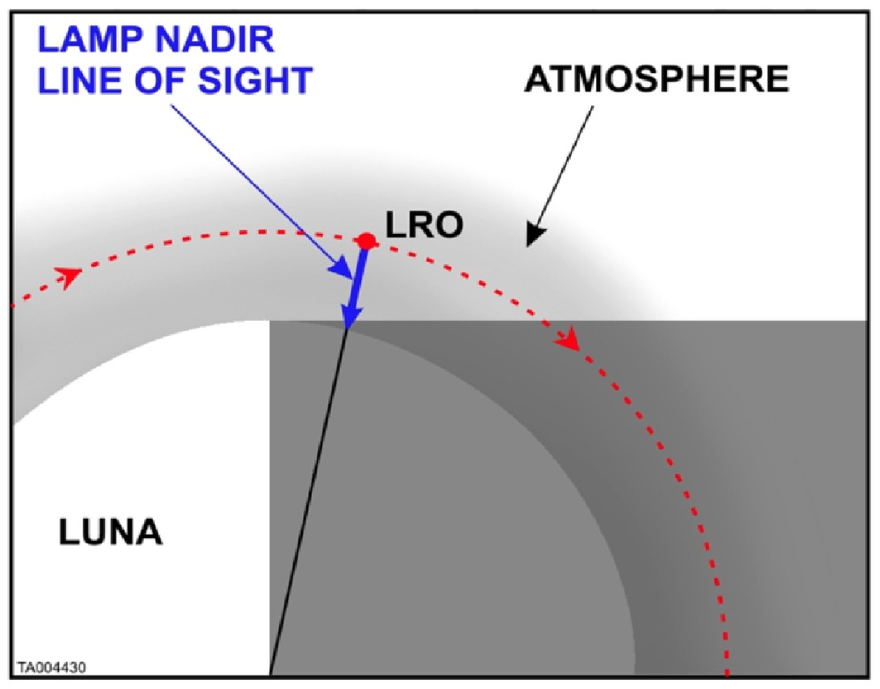

Figure 1: Nadir observing geometry used in atmospheric exploration at twilight.

To search for Ar, we only examine data obtained over a small range of (*i*) local time and (*ii*) latitude. The local time criterion requires that the data are acquired when the sun is between 4.5° and 19.5° below the local horizon (i.e. equivalent to a little more than 1 hour post-sunset or pre-sunrise on Earth). The second criterion is selected because recent models of Ar by Grava et al. (2014), show that the post-sunset Ar concentration is relatively higher near the equator. We list the dates and integration time of each observational window in Table 1.

semester	post-dusk (18:18 - 19:18 Local time)			pre-dawn (04:42 - 05:42 Local time)		
	Date		Integration time	Date		Integration time
	start (UT)	end (UT)	(days)	start (UT)	end (UT)	(days)
2009B	15 Dec 2009	25 Dec 2009	1.3	06 Jan 2010	14 Jan 2010	0.9
2010A	12 Jun 2010	24 Jun 2010	1.6	11 Jul 2010	14 Jul 2010	0.3
2010B	11 Dec 2010	21 Dec 2010	1.2	04 Jan 2011	11 Jan 2011	0.9
2011A	06 Jun 2011	19 Jun 2011	0.6	01 Jul 2011	10 Jul 2011	1.3
2011B	06 Dec 2011	15 Dec 2011	1.0	29 Dec 2011	10 Jan 2012	1.9
2012A	28 May 2012	13 Jun 2012	2.4	22 Jun 2012	07 Jul 2012	2.3
2012B	26 Nov 2012	10 Dec 2012	2.2	21 Dec 2012	02 Jan 2013	1.8
2013A	21 May 2013	05 Jun 2013	2.1	14 Jun 2013	30 Jun 2013	1.8
2013B	17 Nov 2013	25 Nov 2013	1.2	11 Dec 2013	25 Dec 2013	2.0
total			13.6			13.1

Table 1: Table of Observations. A list of start and end dates for each period when β~90° and observations of the lunar atmosphere are made from 30°N to 30°S at post-dusk (left) and pre-dawn (right).

Data Reduction: We follow the data reduction used in Cook et al (2013). We use LAMP night time observations to model and remove the reflected signal produced by the IPM, UV-bright stars, and telluric signals and lunar albedo variations. We adjust the wavelength solution to fix spectral shifts associated with instrument temperature. We use the 584 Å He (lunar) and 1306 Å OI (telluric) lines as fiducials for correcting for the changes in the wavelength solution.

Calculation of Ar Number Density: We convert from counts/s (Fig. 2) to Rayleighs/Å and then calculate the line-of-sight column number density (N). We use B=gN, where B is the brightness, and g is the fluorescence efficiency factor for Ar. We calculate B by integrating each of the observed lines. For the 1048 Å line, we integrate from 1035 to 1060.5 Å. For the 1068 Å line, we integrate from 1060.5 to 1083 Å.

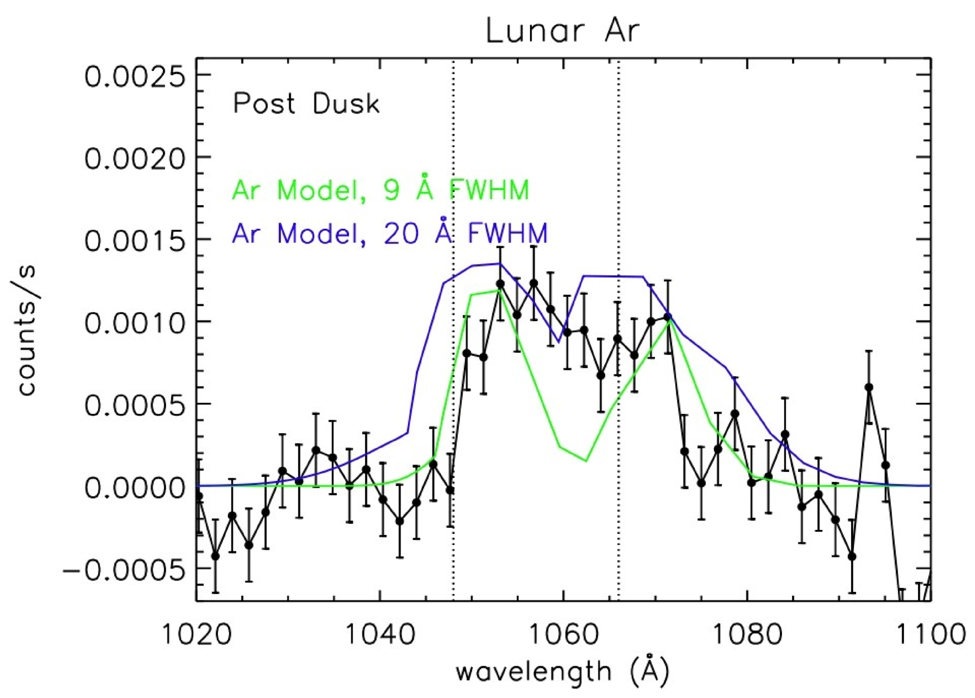

Figure 2: The average post-dusk (black) spectrum with two Ar models (green and blue).

Ar g-factor: We use solar spectra obtained from the TIMED/SEE instrument at the time of our observations to calculate the g-factor. Figure 3 shows the results.

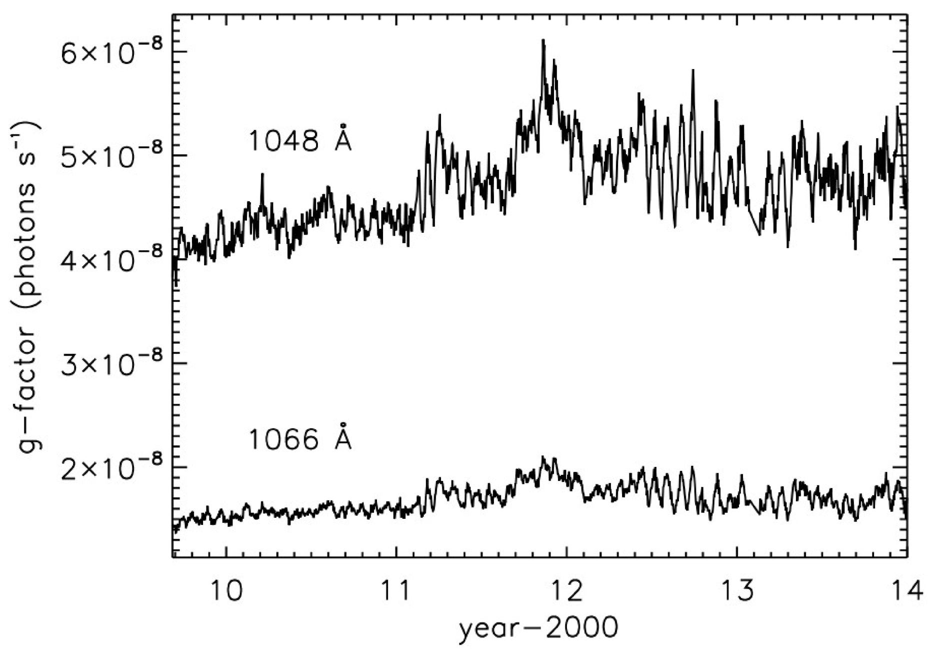

Figure 3: The calculated g-factors for the 1048 and 1066 Å lines from September 2009 to December 2013.

Ar line width: We estimate the full width half maximum (FWHM) of the Ar lines seen in Fig 2 is <20 Å, narrower than the He line (20 Å) in the same spectrum and OI (24 Å) in the telluric reflected spectum. Gladstone et al. (2010) measured the filled slit FWHM at 28 Å. Given the slit's east-west orientation, one can imagine a gradient in Ar abundance along the spatial direction. However, an under-filled slit in the spectral direction would require an Ar point source, *i.e.,* a vent. Examination of the data show that no spectra have unusually bright (>3σ) Ar emission. The only other case of LAMP observing narrow lines occurs near β~0° when a solar glint is detected. Since the Ar lines appear free of solar or telluric contamination, the possibility of Ar seen via a lunar glint remains real. Future observations should help us determine if Ar is due to stray light contamination.

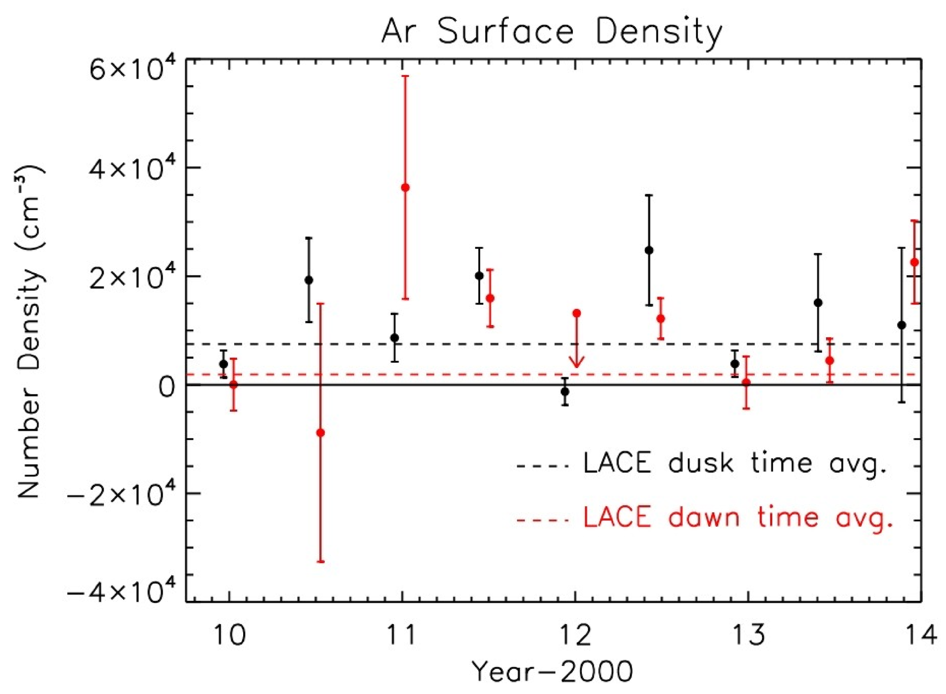

Figure 4: Ar surface density as a function of time at dusk (black) and dawn (red).

Ar Number Density vs. Time: Fig. 4 shows that the Ar number density may have 6 month long variations with some observations consistent with zero. At maximum, the number densities appear consistent with the original LACE detection. The time scale for changes appears to be in agreement with Grava et al (2014).

Ar Number Density vs Local Time: We approximate the LACE measurements from March 24 (sunset) to April 7, 1973 (sunrise) with the equation

$$n(\lambda)=10^{4.950-0.011\lambda}+10^{0.129\lambda-30.438},\ 90° < \lambda < 270°,$$

where λ is the longitude of the sun from the sub-solar point. We integrate this equation over the time range of our LAMP observations to obtain an average LACE surface density of 7500 and 1900 cm^{-3} at dusk and dawn, respectively.

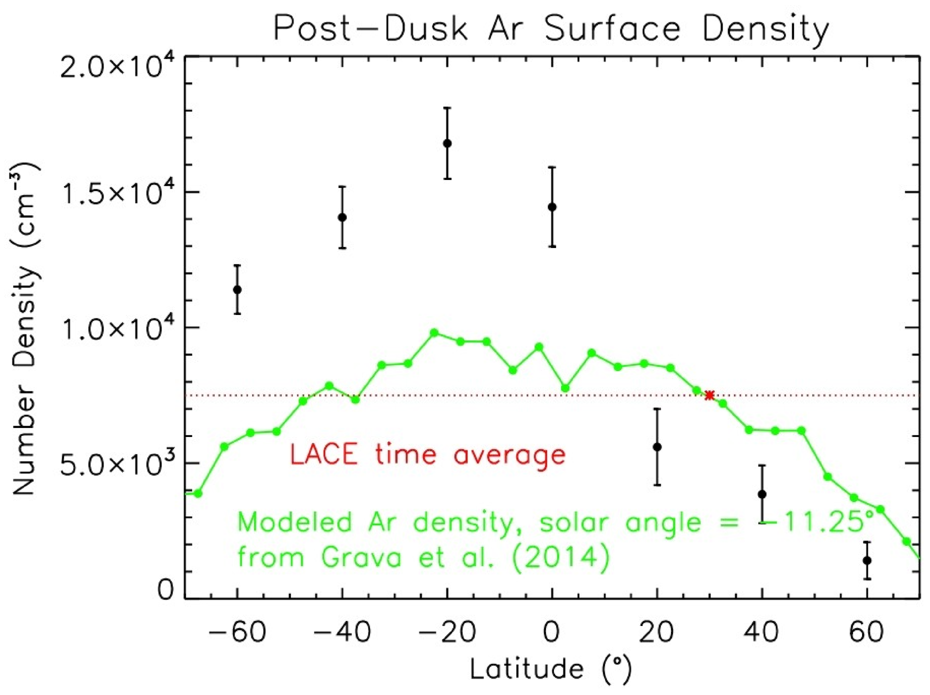

Figure 5: Surface density of Ar vs. latitude. The red dashed line shows the LACE time average at post-dusk. Green points are based on models from Grava et al. (2014).

Ar Number Density vs. Latitude: We bin the LAMP observations into exclusive 20° latitude bins from 70°N to 70°S. We find that the peak emission is very near the equator, perhaps centered near 10°S. We show this in Fig. 5 and compare this to models based on Grava et al. (2014). The depletion of Ar toward the lunar poles might suggest that Ar is getting cold trapped, which is also in agreement with predictions (Hodges, 1980; Grava et al., 2014).

Discussion & Conclusion: We have used LAMP data to search for Ar. We examined data obtained at local dawn and dusk within 30° of the equator.

We find several instances where emission from Ar may have been detected by LAMP. These spectral features appear to be separated by 18 Å, as would be expected from Ar. They also appear to have the right line strengths and are only detected at post-dusk, as it might also be expected.

This detection, however, is not without issues. We find the spectral lines are too narrow to be explained by a signal that fills the slit. We also find the peak in emission is shifted about ~4 Å redward.

We believe the preponderance of evidence favors the detection of Ar in the lunar atmosphere. If confirmed, LRO-LAMP observations of Ar enable continued investigations of this diagnostic species for internal gas release processes beyond the era of the LADEE mission. A paper is in preparation for submission later this month to Icarus.

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