New upper limits on numerous atmospheric species in the native lunar atmosphere

Jason C. Cook, a,b S. Alan Stern, a Paul D. Feldman, b G. Randall Gladstone, c Kurt D. Retherford, c Constantine C.C. Tsang

a Southwest Research Institute, 1050 Walnut St. Suite 300, Boulder, CO 80302, United States
b Johns Hopkins University, Department of Physics and Astronomy, Baltimore, MD 21218, United States
c Southwest Research Institute, 6220 Culebra Road, San Antonio, TX 78238, United States

Abstract

We report on our analysis of twilight observations of the lunar atmosphere as observed by the LAMP instrument aboard NASA’s Lunar Reconnaissance Orbiter. Using data collected between September 2009 and March 2013, we have examined over 7.7 million s of integration time obtained when the surface was in darkness, but the atmosphere between the spacecraft and the surface was in sunlight. Using these data, we have calculated upper limits for 27 species, primarily neutral atomic and molecular species, but also a few atomic ions. All of these species have either been predicted previously or were observed by LAMP after the LCROSS impact. Our upper limits are more constraining than previous upper limits by significant factors, providing new constraints on numerous species. Puzzlingly, we did not detect the previously detected noble gas species Ne and Ar, a subject we briefly touch on here and plan a full paper about.

1. Introduction

The lunar atmosphere, first detected in 1972, is extremely tenuous and classified as a surface boundary exosphere (SBE), with important similarities to Mercury’s atmosphere (Stern, 1999). The bound species in this atmosphere follow parabolic trajectories as they bounce across the surface, rarely interacting with one and other, because their mean free path is long compared to their scale height.

The first detection of the atmosphere was made in situ with the Lunar Atmospheric Composition Experiment (LACE) mass spectrometer deployed by Apollo 17 (e.g., Hoffman et al., 1973). The instrument, which conducted useful operations primarily during the lunar nights because of count saturation during the lunar daytime, functioned for nine lunations (December 1972 to October 1973) before failing. Among the masses detected by LACE during that time were masses 4 and 40 amu, which have been attributed to He and Ar, respectively. The surface density of these species was observed to vary strongly over the lunar night. In the case of He, which is too volatile to condense at night, the surface density increased from 1 to $2 \times 10^3$ cm$^{-3}$ when the Sun was up to about $5 \times 10^3$ cm$^{-3}$ by midnight before decreasing again just before sunrise (see Fig. 2 of Hoffman et al. (1973)). The behavior of Ar, however, was quite different from He because Ar is condensable. The surface density of Ar was seen to decrease at sunset from $7–8 \times 10^3$ cm$^{-3}$ to $<10^3$ cm$^{-3}$ as it condensed through the night and then rapidly rising to $3.5 \times 10^4$ cm$^{-3}$ before sunrise, attributed to the nearby sunlit surface being warmed and the resulting liberation of Ar (see Fig. 1 of Hoffman and Hodges (1975)).

The sensitive LAMP (Lyman Alpha Mapping Project) far-ultraviolet (FUV) spectrograph (Gladstone et al., 2010b) on NASA’s Lunar Reconnaissance Orbiter (LRO) was designed to map the Moon’s permanently shadowed regions but has also been used to search for gaseous species in the lunar atmosphere. Using LAMP, Stern et al. (2012) detected He for the first time by remote sensing. They estimated a surface number density of $7 \times 10^3$ cm$^{-3}$. While this number density may appear low compared to LACE measurements, the observations in Stern et al. (2012) were conducted at local dusk and are consistent with the findings of Hoffman et al. (1973). Further study of He by Feldman et al. (2012) using LAMP has shown that its number density decreases when the Moon crosses the Earth’s magnetotail, showing that most lunar He originates from the solar wind, as expected.

Besides He, LAMP was also used to detect Mg, Ca, Hg, H$_2$ and CO in the plume created by the LCROSS impact (Gladstone et al., 2010a; Hurley et al., 2012). These species were released in significant quantities from the surface because of the heat generated by the LCROSS impact. In the absence of impacting meteors the size of LCROSS, of which there are several per year, these species are generally not present in the atmosphere, except for a small fraction of native H$_2$ (Stern et al., 2013).
Concerning other lunar atmospheric species, although LACE was sensitive to masses between 1 and 110 amu, reports by Hoffman et al. (1973) and Hoffman and Hodges (1975) show that other than He and Ar, no other detected masses showed clear diurnal variations or enhanced pre-dawn concentrations, such as Ar. Hoffman et al. (1973) showed that cool down tests of LACE were capable of almost purging the instrument of possible hydrogenated halogens (HF and HCl) which contaminated measurements at mass 20, 36, and 38. Following these tests, they concluded that residual signal at mass 20 was due to Ne. Repeating the cool down tests four times, they gained confidence in a Ne detection, measured with a surface night time density of 7–9 × 10^{4} cm^{-3}. The same reports also showed that there were indeed some indication of a wide variety of species such as CH₄, NH₃, H₂O, N₂, CO, O₂ and CO₂. Additionally, Fastie et al. (1973) used data taken with the Ultraviolet Spectrometer (UVS) on the Apollo 17 command module to search for other species but were only able to derive upper limits for H, H₂, O, C, N, and CO, which were later revised by Feldman and Morrison (1991) after additional analyses. The Alpha Particle Spectrometer experiment, which was carried into orbit by Apollo 15 and 16, detected ²²⁸Ra and ²¹⁰Po (Gorenstein et al., 1974). These decay products of ²³⁸U were seen in greater concentration over a few mare and craters. Since the Apollo missions, ground based observations in 1988 showed that Na and K are also present in the lunar atmosphere (Potter and Morgan, 1988; Tyler et al., 1988).

In this paper we discuss the search for numerous atomic neutrals (e.g., H, O, Ne), ions (e.g., O⁺) and molecules (e.g., CO), including other species that were detected in the LCROSS plume (Gladstone et al., 2010a), suggested by the mass spectrometer LACE (Hoffman and Hodges, 1975) or predicted previously (Flynn and Stern, 1996). In an accompanying paper (Stern et al., 2013) we report the detection of native H₂ by this same search. The structure of this paper is as follows: in Section 2, we discuss our observations and how they were obtained. In Section 3, we describe how the data are extracted. In Section 4, we present our upper limit results. Finally, in Section 5, we briefly compare our results with previous measurements and discuss related findings.

2. Observations

In June 2009, NASA’s LRO entered a polar orbit around the Moon. As described in detail by Gladstone et al. (2010b), the photon-counting LAMP imaging spectrograph is comprised of a telescope and Rowland-circle spectrograph. LAMP has a 40 × 40 mm² entrance aperture that feeds light to the telescope section of the instrument. Light entering this aperture is collected and focused by an f/3 off-axis paraboloidal primary mirror at the back end of LAMP’s telescope section, onto a 0.3⁰ × 6.0⁰ spectrograph entrance slit. After passing through the slit, the light falls onto a toroidal holographic diffraction grating, which disperses the light onto a 2-D (1024 × 32)-pixel double-delay line (DDL) microchannel plate detector. This detector is coated by a CsI solar-blind photocathode, and covers a bandpass of 575–1965 Å. A spectral line that fills the slit has a spectral resolution (FWHM) of 28 Å. Normal LAMP operations take place in a nadir-staring push-broom scanning fashion so that the surface is continuously mapped.

LAMP observations of the lunar atmosphere were acquired in one of two ways. In the Stern et al. (2012) He detection paper, we used observations when LRO is pointed nearly tangent to the surface. This observing method both eliminated surface albedo contrast issues with weak atmospheric emission and also greatly increases the path length observed by LAMP; together these factors make the detection of weak emission lines possible. However, this observing mode is rarely used because LRO points toward the surface >95% of the time. Alternatively, Fig. 1 illustrates that there are also periods during the orbit when the surface is in darkness, but the atmospheric column below LRO is in sunlight. These “twilight” observations occur twice per 2-h orbit, about 11–12 times per day. In a typical orbit, the duration in this twilight is about 600 s (when the spacecraft is at low $\beta$ angle, the angle between the orbit plane and the vector to the Sun), but these periods are much longer around the solstices, reaching over 3600 s per orbit (i.e., when the orbit $|\beta| \sim 90°$). The total integration time from September 2009 to March 2013 for all LAMP nadir observations in twilight is about 18.0 × 10⁶ s. As a result, these twilight observations are far more sensitive to detecting weak emission features than the near surface tangent observations, because the latter has accumulated about an order of magnitude less observing time.

3. Data reduction

We employ in this paper LAMP twilight observations. Because the twilight atmosphere is illuminated, the species present in the atmosphere fluoresce. The brightness of a fluorescing line is a function of the column length of illuminated atmosphere, which is the distance between the top of the lunar shadow and the altitude of LRO. From September 2009 to December 2011 the altitude range of LRO was between 30 and 80 km. After December 2011, the orbit of LRO was changed to make it more elliptical, with an altitude range of 30–200 km and apoapsis at the north pole.

From the twilight observation set, we eliminate some of the observations for several reasons. First, we noticed in our analysis of the data, that observations obtained when Solar Particle Events (SPEs) passed the Earth and Moon have greater count rates at all wavelengths compared to data obtained under normal conditions. The greater count rate, however, does not improve the signal, instead the SPEs adversely affect the signal by being noisier than spectra taken under normal conditions and the detector dark signal measurably increases at these times. We use GOES satellite data to determine when proton fluxes triple the background rate of ~0.5 proton/(cm² s MrV), and remove these data from our atmospheric search dataset. This eliminates about 0.9 million s of integration time, or ~5%.

Second, we exclude data that may be contaminated by sunlight reflected from mountain peaks. We assume that when the solar zenith angle is 90°, then the surface is in darkness. This would only be true if the surface was smooth, which is certainly not the case. We

Fig. 1. Nadir observing geometry used in atmospheric exploration at twilight. The dashed red line represents the orbit of LRO. Fluorescence by species present in the illuminated atmospheric column near the terminator will be detectable by LAMP. Because the surface is dark, reflected sunlight is not an issue. These observations occur twice per orbit, with total integration times between 600 and 3600 s per orbit, depending on the $\beta$-angle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
noted that including observations that sampled the atmosphere below 6 km produces spectra that increase in brightness at longer wavelengths, indicative of contamination from sunlight. Of the 18.0 million s, another 6.3 million s are contaminated by reflected sunlight, or ~35%.

Finally, we do not include observations with a latitude >75°, as will be discussed in Section 3.2, we model and remove background sources. We are only able to accurately model the background sources for latitudes where comparable night-time spectra are also obtained. The atmosphere is always seen in sunlight at latitudes >75°. We find that interpolating the background signal around the poles was insufficient, and led to a final spectrum that was noisier. By excluding the data poleward of 75° latitude, we eliminate yet another 3.1 million s of observations. Thus our final spectrum is about 43% of the available twilight observations, or 7.7 million s.

3.1. Wavelength calibration

In order to set sensitive upper limits and search for extremely weak emission lines, we need to be sure that LAMP’s wavelength calibration is highly accurate; this is because we must carefully remove scattered light from the wings of the strong Lyman-α feature in all of our data. A wavelength calibration was initially derived by comparing LAMP spectra to stellar reference spectra. Because the instrument shows slight wavelength shifts that vary with instrument temperature, we had to solve for the wavelength solution frequently in the dataset using three fiducial lines, He I (584 Å), O I (1304 Å) and a ghost signal of Lyman-α (near 1000 Å), which are always in our data.

The Lyman-α ghost is a known artifact of the LAMP instrument, caused by internal scattering of the light. We do not use the actual Lyman-α line for wavelength calibration because the detector has experienced charge depletion (a.k.a. gain sag) at that wavelength, which has considerably altered the Lyman-α line shape. This would make centering on Lyman-α itself difficult.

The examination of our wavelength fiducial lines show that their positions vary with instrument temperature. As the instrument approaches equinox, LRO instrument temperature increases, and conversely near solstice. An increase (decrease) in temperature causes the spectrum to shift to a greater (lesser) pixel index along the array. Upon subsequent heating and cooling cycles, the spectrum does not necessarily return to the initial position. An additional shift was seen in the data when the high voltage setting was changed in late-May 2011.

To characterize these shifts with temperature we measure the position of the He I, O I and Lyman-α ghost lines. The He I line is weakly detected only in twilight spectra when the instrument is warmest (ingress) and coldest (egress) for each orbit. We average three consecutive days of He observations and temperature measurements at ingress and egress using the exposure time as weights to build signal. The O I line is due to reflected terrestrial dayglow, and has considerable altered the Lyman-α line shape. This would make centering on Lyman-α itself difficult.

The IPM contributes greatly to the most prominent feature in the LAMP data, i.e., the Lyman-α feature at 1216 Å. LRO’s orbit is approximately inertial, with a normal about the ecliptic longitude 102° and latitude 0°. This means that the same region of sky is reflected from the lunar surface for a period of about 6 months. Witte (2004) has shown that the Lyman-α sky from the IPM is 2–3 times brighter in the upstream direction near the ecliptic latitude and longitude ~9° and 252°, respectively. This region of sky illuminates the lunar surface from about the winter solstice to summer solstice (hereafter referred to as the “spring sky”). In addition to containing the brightest part of the IPM, the spring sky also contains the majority of the UV bright stars from the plane of the Milky Way. These UV bright stars are mainly found in the southern hemisphere.

To model the contribution by the IPM and UV bright stars to the data, we use the observations of the Moon obtained when LRO and the surface were in darkness and the phase angle between Earth–Moon–LRO was >90°. This excludes data contaminated with reflected dayglow from the Earth. We use these data to (i) measure day-to-day variations in the reflected sky spectrum and (ii) map out changes in the spectrum with respect to the ecliptic latitude and longitude of the instrument boresight. Both of these steps are performed on each wavelength bin. To accomplish the first step, we examine the data confined to a 20° region of ecliptic latitude over a 5 day time span in each of the two sky conditions (i.e., fall and spring). This allows us to examine the same region on the Moon under the same illumination conditions. By measuring the average of these data against longitude we see that the primary source of variation is due to lunar albedo variations. Once these variations are divided out, the resulting ratio is a scale of brightness changes at each wavelength bin over time. The brightness variations are then interpolated for all times and latitudes, and the scale is divided out of the night side observations. We then map the sky brightness in ecliptic longitude and latitude. From this, we can create high SNR models of the sky brightness for a range of illuminations. Our technique to map the sky to make background model spectra is based on observations from longitudes 90° to 270° and latitudes 75° to ~75°, and therefore average over variations in the reflectivity of the lunar surface.

The second most important source we see in the data is due to reflected telluric dayglow. The appearance of emission lines from O I (1304 and 1356 Å), N2, LBH bands (e.g., (2,0) 1384 and (1,0) 1416 Å) and H I (Lyman-α at the ghost wavelength) (Meier, 1991) are apparent in spectra obtained on the Earth facing side of the Moon. These lines are seen to vary with the synodic period of the Moon (~29.5 days) and with phase angle from the sub-Earth point on the Moon.

Prior to wavelength correction, we saw that the full range of the He I, O I and Lyman-α ghost position was 7 pixels (~12.7 Å). After the correction, the variation is reduced to 2 pixels, or about 3.6 Å. This variation is similar to that seen with the Lyman-α ghost and ~10% of the 28 Å filled slit.

3.2. The removal of reflected celestial, telluric and lunar surface backgrounds

All of the LAMP data we analyze contain signals from several sources. The non-atmospheric spectral signals must be accounted for because the spectral features we are seeking in the lunar atmosphere are weak. The sources of background signals include reflected signals from the IPM (interplanetary medium), UV bright stars, Earth shine and changes in the Moon’s reflectivity. Despite the low albedo of the Moon (2–6% at these wavelengths; Gladstone et al., 2012), these signals are bright enough for the sensitive LAMP instrument to detect since these are indeed its primary method for measuring PSR albedos, and thus must be removed.
To derive a model of the telluric contribution, we subtract an IPM and bright UV star spectral model from observations obtained at night when the Earth–Moon–LRO angle was <90°. The residual spectrum contains the remaining telluric signal. As with deriving the IPM and bright UV star spectral model, we use observations over a variety of surface reflectivity and thus average out their effect. At each wavelength bin, we map the count rate to the phase of the Moon and the phase angle between the Earth–Moon–LRO angle. As expected, the lines detected are brightest near the sub-Earth point during new Moon (i.e., full Earth). The brightness of each line decreases with distance from the sub-Earth location and as the lunar phase nears full Moon (new Earth).

The final important background source is the lunar surface itself. As stated earlier, at these wavelengths, the lunar surface has known albedo variations from 2% to 6% (Gladstone et al., 2012). Our procedure so far has averaged out variations in lunar reflectivity. These variations (~±5%) must be accounted for to avoid over or under estimating the signal from reflected IPM, UV bright stars and the Earth. In addition, by accounting for the lunar reflectivity, we can correct any wavelength to wavelength variations which may be the case when examining spectra from different terrains (mare vs. highlands). We estimate the differences in surface reflectivity by taking the ratio between the spectra obtained at night with the summation of the IPM/UV star signal and the telluric dayglow signal. The ratio shows the differences due the surface reflectivity.

For illustrative purposes, we show in Fig. 2 our UV map of the Moon with a superimposed visible wavelength image. This figure shows that many, but not all, of the mare appear brighter than the average (colored yellow and red in Fig. 2) surface (green). We note that because there are uncertainties disentangling the IPM, telluric and albedo variations poleward of 75°, we do not directly compare this map with those shown in Gladstone et al. (2012). However, we can state that our observations are in agreement with Lucke et al. (1974) and Henry et al. (1976) who also concluded that the mare are brighter than the highlands at these wavelengths.

3.3. Mission averaged spectrum

We show in Fig. 3 our mission averaged spectrum after all of the background signals are removed. Apparent in this spectrum are several features, including the He I line at 584 Å which has been reported earlier (Stern et al., 2012; Feldman et al., 2012). This He line also appears as a third order reflection at 1752 Å and likely as a second order reflection at 1168 Å, near the blocked out Lyman-α area, and blended with the (6,3) line of H₂. For the first time, we detect H₂ in the lunar atmosphere as reported in Stern et al. (2013). This spectrum also shows a known instrumental artifact around 783 Å. The spectrum shows very little evidence for the Lyman-α ghost. Other than the afore mentioned features, there is little evidence for anything else in the spectrum.
4. Calculation of species upper limits

To calculate the surface density upper limits we first calculate the upper limit on the brightness of each line. This is measured from the summation of the average spectrum and its $3\sigma$ error. The average spectrum is shown in Fig. 3 with the shaded points representing the $3\sigma$ error range. The spectrum is converted from counts/s to Rayleighs/A using the effective area (Fig. 4) and solid angle of the instrument. We integrate the signal at the wavelength of interest over a full width of 28 Å. This is the measured filled slit spectral resolution (Gladstone et al., 2010a). We list the upper limits on the line brightness in the fourth column of Table 1.

We next calculate the upper limit on the line-of-sight column number density using,

$$B = gN,$$

and solving for $N$. In Eq. (1), $B$ is the line brightness in Rayleighs, $g$ is the fluorescence efficiency factor and $N$ is the line-of-sight column number density in cm$^{-2}$. When possible, we estimate the $g$-factor of a line at the time of the observations. Many of the initial values for the $g$-factors are taken from Gladstone et al. (2010a), when LORRY impacted the Moon on October 9, 2009. For species not examined by Gladstone et al. (2010a), we calculate the initial $g$-factors using the BASS2000 solar spectrum (Palouet et al., 2009). Those $g$-factors are scaled using the ratio of the Lyman-$\alpha$ $g$-factor derived from the BASS2000 solar spectrum and the Lyman-$\alpha$ $g$-factor listed in Gladstone et al. (2010a). For Ne I, we are unable to calculate the $g$-factor because the BASS2000 solar spectrum does not cover 630 Å. Instead, we use a $g$-factor from Krasnopolsky and Mumma (2001) and leave it constant.

Using data from the Solar Dynamics Observatory’s EVE (Extreme Ultraviolet Variability Experiment) instrument, we first calculate the Lyman-$\alpha$ $g$-factor and note that it has a 30% variability. Using Lyman-$\alpha$ as a proxy for the variation in each of the lines, we scale the $g$-factors of each line in proportion to the Lyman-$\alpha$ $g$-factor we calculate for each day of the mission. We can apply this scale to the LAMP data obtained after April 2010, shortly after the launch of EVE. For the LAMP observations obtained prior to April 2010, we assume a constant value scaled with the median Lyman-$\alpha$ $g$-factor between April 2010 and January 2011, when solar activity was relatively stable. We list the wavelength at line center and our adopted $g$-factor in the second and third columns of Table 1, respectively. Many of the species we searched for using these data have multiple lines in our wavelength range. We chose only to list the results of the brightest line because these give the most stringent upper limit.

The next step is to convert the column density to surface density so we can compare our results with previous upper limits. To calculate the surface density, we apply a Chamberlain Model (see Chapter 7 of Chamberlain and Hunten (1987)).

$$N (\text{cm}^{-2}) = \int_{z_0}^{z_1} N(z)dz,$$

where $z_0$ is the shadow height and $z_1$ is the altitude of the spacecraft and $N(z)$ is defined as

$$N(z) = N (\text{cm}^{-3}) e^{-\frac{z}{\text{scale height}}},$$

We use the measured line-of-sight columns for $N (\text{cm}^{-2})$, $\zeta$ is the partition function and $\lambda_c = \frac{Gm}{kT}$ where $G$ is the universal constant, $M$ is the mass of the Moon (7.36 × 10$^{25}$ g), $m$ is the mass of the molecule, $k$ is the Boltzman constant, $T$ is the temperature and $r$ is the radius of the Moon (1.7374 × 10$^8$ cm). $z$ replaces the $r + z$ where $z$ is the integration variable. For our analysis we use a static temperature of 120 K, which is appropriate for our twilight observations. We note that only $\zeta$ and $\lambda_c$ are functions of $z$, which allows us to take $N (\text{cm}^{-2})$ out of the integral in Eq. (2) when using Eq. (3) for $N(z)$. Since the spectrum that we present in Fig. 3 is an average spectrum weighted by the exposure time over many different shadow heights ($z_0$) and altitudes ($z_1$), we calculate values for the integrand in Eq. (2) for each shadow height/altitude combination and average them using the exposure time as weights.

The partition function, $\zeta$, is a sum of several partition functions describing particles on ballistic orbits, satellite orbits, and those which escape. These partition functions are given by

$$\zeta_{\text{bal}} = \frac{2}{\pi^{1/2}} \left( \gamma \left( \frac{3}{2}, \lambda_c \right) - \frac{(\lambda_c^2 - \lambda)^{1/2}}{\lambda_c} e^{-\gamma(\frac{3}{2}, \lambda - \psi)} \right),$$

$$\zeta_{\text{sat}} = \frac{2}{\pi^{1/2}} \left( \frac{(\lambda_c^2 - \lambda)^{1/2}}{\lambda_c} e^{-\gamma(\frac{3}{2}, \lambda - \psi)} \right),$$

$$\zeta_{\text{esc}} = \frac{1}{\pi^{1/2}} \left( I(\frac{3}{2}, \lambda) - \gamma(\frac{3}{2}, \lambda) \frac{(\lambda_c^2 - \lambda)^{1/2}}{\lambda_c} e^{-\gamma(\frac{3}{2}, \lambda - \psi)} \right),$$

where $\psi = \gamma(\lambda + \lambda_c)$, $\zeta = \zeta_{\text{bal}} + \zeta_{\text{sat}} + \zeta_{\text{esc}}$ and $\gamma$ and $I$ are the incomplete and complete $\gamma$ functions. In column 5 of Table 1, we list our 3$\sigma$ upper limits for each species following from the above algorithm.

5. Discussion

Table 1 depicts the upper limits we derive, and compares them to the most stringent previously derived values for surface number density. Table 1 is arranged by species mass. As noted above, our upper limits are computed for a common reference temperature (which sets the scale height conversion of column density to surface density) of $T = 120$ K. It should also be noted that the previously derived upper limits listed in Table 1 are not strictly at the same local time as our measurements. Number densities can vary for a variety of reasons, for example if a species is condensable during the lunar night. This, however, turns out to be a minor issue with our observations because over 75% of the total integration time occurs two hours before dawn, and two hours after dusk. At these times, condensable species, such as Ar, are most likely to be detected because the atmosphere is cooling and the scale height of many species is below LRO. Finally, Fig. 3 shows that there is very little difference between the dawn spectrum (red curve) and dusk spectrum (blue curve).
We clearly detect the presence of He and H2. The detection of He was previously reported in Stern et al. (2012). Based on those limb observations, we measured a surface density of \( 7 \times 10^3 \) cm\(^{-3}\). In these nadir observations, we report a number density of \( 6.5 \times 10^3 \) cm\(^{-3}\) at dusk and \( 10.6 \times 10^3 \) cm\(^{-3}\) at dawn with errors of 50 cm\(^{-3}\). These numbers are in agreement with Stern et al. (2013). The presence of H2 had been predicted at \( 1.2 \times 10^4 \) cm\(^{-3}\) at night (Hodges, 1973). LACE had measured a surface density of \( 6.5 \times 10^4 \) cm\(^{-3}\) at night (Hoffman et al., 1973). These measurements were conducted after several cool down tests, and Hoffman et al. (1973) considered this to be an upper limit. Our observations show that H2 is more than an order of magnitude lower than either of these values, with a surface density of \( 1.7 \pm 0.4 \times 10^3 \) cm\(^{-3}\) at dusk and increasing to \( 2.1 \pm 0.3 \times 10^3 \) cm\(^{-3}\) at dawn.

In total, 27 species upper limits are presented in Table 1. Of these, 13 species have never before published upper limits, the other 14 having been previously published and many with higher upper limits than we derived. In almost every case for the 14 species with previously published upper limits, our revised upper limit is one to two orders of magnitude more stringent than the previous value, and sometimes more so.

Absent from our discussion thus far are Ar and Ne. In our wavelength range, each species have two lines. In the case of Ar, they are 1048 and 1066 Å and for Ne they are 630 and 735 Å. As discussed in the introduction, both Ar and Ne were certainly anticipated based on LACE results. However, as can be seen in Fig. 3, neither species are detected at the level of our noise. Our measured upper limits for Ar and Ne are \( 2.3 \times 10^3 \) cm\(^{-3}\) and \( 4.4 \times 10^3 \) cm\(^{-3}\), respectively. Compared to the upper limits derived from the average spectrum, the upper limits for the spectrum at dawn and dusk are lower by 5\% and 38\%, respectively. In both cases, our upper limits are lower than the LACE upper limits. In the case of Ar, the upper limit may be slightly inflated since the spectrum in Fig. 3 shows there residual continuum flux. In the case of Ne, our upper limit is over a magnitude smaller than the measured LACE value. The reason for our non-detection of Ne and Ar is uncertain. Several possible reasons include: (i) the lunar atmosphere has changed since the LACE measurements, (ii) both the Ne and Ar sources were localized near the Apollo 17 site but their presence is averaged out in our spectrum or (iii) the detection or identification of Ar and Ne in the LACE data was incorrect. We plan to explore this mystery in greater detail by searching for Ar and Ne at different local times and locations on the Moon. This will also be the subject of a future paper (Cook et al., 2014).

Our upper limits on several species (O, Mg, Al, and Ca) are near the predicted levels for an atmosphere where sputtering is a significant component. Wurz et al. (2007) used Monte Carlo models to estimate the surface density of several species such as O (6–10 cm\(^{-3}\)), Mg (1–1.5 cm\(^{-3}\)), Al (0.5–1.5 cm\(^{-3}\)) and Ca (1–2 cm\(^{-3}\)). We find that our upper limit on O, Al is in the predicted range. However, our results for Mg and Ca are slightly greater than the predictions. Our results are unable to constrain the significance of the sputtering process in maintaining the lunar atmosphere. Additional data that will be collected as the mission continues may help to answer this question.

6. Conclusion

Using data collected by the LAMP instrument aboard NASA’s LRO spacecraft in lunar orbit since 2009, we analyzed 7.7 million s
of integration time useful for studying the lunar atmosphere. From these data, we calculated the upper limits surface densities for 27 species. These upper limits are lower than previous upper limits by significant factors, providing new constraints on numerous species.

Our new upper limits represent a new contribution of the LRO mission to lunar science, and constrain the composition and total mass of the modern-day steady-state daytime lunar atmosphere.

Acknowledgments

We thank the Lunar Reconnaissance Orbiter project and project team at NASA's Goddard Space Flight Center for conducting the LAMP atmospheric observations. This work was supported under a contract NNG05EC87C from NASA. We also thank the EVE and GOES teams for providing their data on line.

References


