THE SPECTROSCOPIC DETECTABILITY OF ARGON IN THE LUNAR ATMOSPHERE

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ABSTRACT

Direct measurements of the abundance of argon in the lunar atmosphere were made in 1973 by instruments placed on the Moon during the Apollo 17 mission, but the total daytime abundance is unknown because of instrument saturation effects; thus, until we are able to return to the Moon for improved direct measurements, we must use remote sensing to establish the daytime abundance. In this Letter, we present a complete analysis of the potential for measuring argon in the lunar atmosphere via emission-line or absorption-line observations. We come to the surprising conclusion that the lower limit established by the in situ lunar argon measurements implies that any absorption-line measurement of argon in the lower, dayside lunar atmosphere requires analysis in the optically thick regime. In light of this result, we present the results of our extreme-ultraviolet spectrograph sounding rocket observations of the lunar occultation of Spica, which provide a new upper limit on the abundance of argon in the daytime lunar atmosphere. We also reanalyze a recently reported weak detection by the ORFEUS satellite of lunar atmospheric Ar\textsuperscript{+} \textlambda1048 in emission and show that those data are inconsistent with the emission being due to argon over a wide range of temperatures (up to at least 2000 K). This result is primarily due to our use of a more complete curve-of-growth analysis and improved values for the argon fluorescent emission rates from radiation and solar wind interactions. We find that the detection reported by ORFEUS would imply an argon surface density significantly greater than the total surface density of the lunar atmosphere for argon accommodated to typical daytime surface temperatures (\textapprox 400 K) and also is inconsistent with a high-density transient event. Therefore, we conclude that the reported argon detection is untenable.

Subject headings: atomic data — line: formation — methods: data analysis — Moon — radiative transfer — ultraviolet: solar system

1. INTRODUCTION

The atmosphere of the Moon is a tenuous, surface-boundary exosphere. The known neutral constituents of that atmosphere include He, Ar, Ne, Po, Na, and K (Hoffman, Hodges, & Evans 1973; Gorenstein & Bjorkholm 1973; Potter & Morgan 1988; Tyler, Kozlowski, & Hunten 1988) with surface number densities that vary with local time of day and other factors. The total inventory of the identified lunar atmospheric neutral species\textsuperscript{2} has a number density at the surface of \textless 5 \times 10\textsuperscript{4} cm\textsuperscript{-3}. By contrast, cold cathode gauges placed on the lunar surface during Apollo missions measured total pressures of the lunar atmosphere corresponding to a total number density near the surface of \textapprox 2 \times 10\textsuperscript{5} cm\textsuperscript{-3} at nighttime and possibly almost 2 orders of magnitude higher during the daytime (\textapprox 5 \times 10\textsuperscript{6} to 1 \times 10\textsuperscript{7} cm\textsuperscript{-3}), although much of the daytime values appear to be due to equipment contamination in the landing area (Johnson, Carroll, & Evans 1972). These number density and total pressure results indicate that most of the lunar atmosphere remains compositionally unidentified (see Stern 1998 for a detailed review of the lunar atmosphere). There are ongoing efforts to determine and observe the remaining constituents of the lunar atmosphere (e.g., Flynn & Stern 1996; Stern et al. 1997; Mall et al. 1998).

One long-standing possibility for resolving this “missing-mass” discrepancy is that argon could comprise a greater fraction of the lunar atmosphere than existing measurements indicate. The most direct measurements of the abundance of argon in the lunar atmosphere were made by the Apollo 17 surface-based mass spectrometer, LACE. Argon, which is adsorbable on the cold-trapped lunar surface at night (\textapprox 100 K), was observed by LACE to follow a diurnal pattern with a nighttime minimum near 2 \times 10\textsuperscript{7} cm\textsuperscript{-3}, followed by a rapid increase around sunrise to values as high as 4 \times 10\textsuperscript{7} cm\textsuperscript{-3} before LACE became saturated by gas evolving off the warming lunar surface and outgassing products of nearby Apollo equipment (Hoffman et al. 1973; Hodges & Hoffman 1974; Hodges, Hoffman, & Johnson 1974). Because LACE became saturated due to such contamination shortly after each sunrise, it is not known how far the daytime column abundance of argon increases above the saturation limit of the instrument, and it is conceivable that argon provides the bulk of the missing mass of the daytime lunar atmosphere.

Flynn (1998; hereafter F98) recently reported results of an experiment to measure the abundance of lunar argon. That experiment was a search for the \textlambda 1048 and \textlambda 1067 resonance...
fluorescence emission lines of Ar i using the Berkeley spectrograph (Hurwitz et al. 1998) aboard the ORFEUS-SPAS II satellite, which flew for several days during shuttle mission STS-80 in late 1996. F98 reported a weak (3 σ) detection of the Ar i λ1048 line; the λ1067 line was not detected, a point we will discuss later. F98 analyzed this detection assuming optically thin emission and deduced a surface density of \( n_{\text{Ar}} = (8 \pm 3) \times 10^3 \text{ cm}^{-3} \). Because this density is at odds with thermal model predictions (Hodges et al. 1974), F98 interpreted the result as evidence for a nonthermal source of argon.

In what follows, we present analyses of Ar i absorption-line measurements (such as have been made with our extreme-ultraviolet spectrograph sounding rocket instrument during a recent lunar occultation of Spica) and emission-line measurements (such as the ORFEUS observations). We show that the LACE results imply that any absorbion measurement of argon on the dayside limb of the Moon will be optically thick. Similarly, the argon emission line reported by F98 would correspond to a line-of-sight column density too large to be analyzed in the optically thin limit and in fact would correspond to a surface density of \( n_{\text{Ar}} \simeq 5 \times 10^7 \text{ cm}^{-3} \) in the case of argon at a typical daytime surface temperature of 400 K. This number density substantially exceeds the total lunar atmospheric surface number density (Johnson et al. 1972). We further show that the nondetection of the Ar i λ1067 line in the ORFEUS data rules out the possibility of this detection being a real signal of a fortuitously observed, high-density transient event or of a hot component produced by nonthermal processes.

2. ANALYSIS

2.1. Absorption Measurements

Curves of growth, relating the equivalent width (\( W_e \)) versus line-of-sight column density (\( N_{\lambda\nu} \)), for the Ar i λ1048 and λ1067 lines for the case of absorption measurements are shown in Figure 1. The plot shows the three well-known regions: the optically thin ("linear"), the Doppler ("flat" or "logarithmic"), and the damping ("square-root") regimes of the curve of growth. To determine the transition points between optically thin and Doppler regions, we use the definition of the optical depth at line center for a single-component Gaussian line profile:

\[
\tau_0 = \frac{\sqrt{\pi}e^2}{m_c \sigma_b} N_{\lambda\nu} f_{\lambda\nu},
\]

where \( f_{\lambda\nu} \) is the oscillator strength for the transition at wavelength \( \lambda \) and \( b = (2kTB_{\text{rot}})^{1/2} \) is the Doppler velocity parameter; other symbols have their conventional meanings. We assume a Maxwellian velocity distribution at a lunar surface (exobase) temperature of \( T = 400 \text{ K} \) (the same temperature as is used by F98), which implies a velocity of \( b = 0.407 \text{ km s}^{-1} \) for argon atoms. This temperature is appropriate for a gas accommodated to the lunar surface daytime equilibrium temperatures. The argon oscillator strengths are \( f_{1048} = 0.244 \) and \( f_{1067} = 0.067 \), respectively (Federman et al. 1992); other published values for the oscillator strengths (e.g., Wiese, Smith, & Miles 1969; Morton 1991; Chan et al. 1992; and other references in Table 1 of Federman et al. 1992) typically differ by less than 10% from this adopted value. The resulting critical column densities that correspond to the onset of saturation at \( \tau_0 = 1 \) in the transition from the optically thin to the Doppler regime are \( N_{\lambda\nu}^{-1}(\lambda1048) = 1.1 \times 10^{12} \text{ cm}^{-2} \) and \( N_{\lambda\nu}^{-1}(\lambda1067) = 3.8 \times 10^{12} \text{ cm}^{-2} \).

To convert column densities (as one observes remotely) into surface densities (as LACE measured in situ), we use \( n_{\text{Ar}} = (N_{\lambda\nu}/H_{\text{Ar}}) \), where \( H \) is the barometric scale height (for \( T = 400 \text{ K} \), the argon scale height at the surface is \( H = 50.9 \text{ km} \)). The factor \( \xi \) is the relationship between vertical and line-of-sight column densities in cases in which the scale height of the atmosphere is much smaller than the size of the object: \( \xi = (2\pi dH)^{1/2} \), where \( d \) is the distance of the observation from the lunar center. At a height of 1 scale height above the lunar limb, \( \xi = 14.5 \). These are the values that have been used to convert the column densities to the surface density scale shown on the top axis of Figure 1.

Thus, the critical surface densities for which the corresponding line-of-sight optical depths reach unity are \( n_{\text{Ar}}^{-1}(\lambda1048) = 1.5 \times 10^4 \text{ cm}^{-3} \) and \( n_{\text{Ar}}^{-1}(\lambda1067) = 5.0 \times 10^4 \text{ cm}^{-3} \). Recall that the argon reported by the LACE mass spectrometer saturated the instrument at \( 4 \times 10^4 \text{ cm}^{-3} \) while increasing just after sunrise. Therefore, our analysis implies that any absorption-line measurement of argon in the lower, daytime atmosphere must use an optically thick curve-of-growth analysis. This is a significant result that has not been previously recognized.

In 1995 we used the extreme-ultraviolet spectrograph (EUVS) (Slater et al. 1995; Stern et al. 1996), flown aboard a sounding rocket, to perform such an absorption-line experiment. The EUVS consists of a 40 cm diameter Wolter Type II grazing-incidence telescope feeding a Rowland-circle spectrograph. On 1995 April 15, we flew EUVS out of White Sands Missile Range to observe the lunar occultation of the bright
B1 V star, Spica (α Vir). One aspect of this experiment was its ability to search for lunar argon in absorption using light from Spica as the incident beam. Our EUVS experiment did not detect argon and set a 3σ upper limit of $W_i < 0.043$ Å, determined by the background fluctuation in the spectrum around the argon line wavelengths. For the expected 400 K atmospheric daytime temperature, this nondetection implies a line-of-sight density upper limit of $N_a = (1.3 \times 10^{16} \text{ cm}^{-2})$ (see Fig. 1) and an associated argon surface density upper limit of $n_a < 1.8 \times 10^8 \text{ cm}^{-2}$.

2.2. Emission Measurements

Figure 2 shows the curves of growth for emission lines. The results are presented in the figure by using units that are readily comparable to the data presented in F98, with line brightness as a function of surface density (rather than equivalent width as a function of column density as shown in the curve of growth in Fig. 1). The curves display the familiar optically thin/Doppler/damping progression of regimes as the surface density is increased.

To calculate the data for Figure 2, the resonance line radiative transfer model of Gladstone (1988) was used to simulate the limb-viewing brightnesses of the two lunar argon lines at the subsolar position. The solar flux at these wavelengths is dominated by the carbon continuum. We used flux values of $2.02 \times 10^2$ and $3.20 \times 10^2$ photons cm$^{-2}$ s$^{-1}$ Å$^{-1}$ at λ1048 and λ1067, respectively, based on SÖHO/SUMER measurements obtained in 1996 (Wilhelm et al. 1998). These fluxes correspond to radiation g-factors of $5.0 \times 10^{-8}$ and $2.0 \times 10^{-8}$ s$^{-1}$, respectively. We also calculated the effect of solar wind electron impact based on the Wind three-dimensional plasma instrument (Lin et al. 1995) data from 1996 November to December and accepted electron impact excitation cross sections (Ajello et al. 1990). Our calculations and those of D. Shemansky (1998, personal communication) using these observed flux values show that the total g-factors (radiation plus solar wind, as would be appropriate for the lunar atmosphere during the ORFEUS observations) are about $6.0 \times 10^{-8}$ s$^{-1}$ for the Ar i λ1048 line and $2.6 \times 10^{-8}$ s$^{-1}$ for the Ar i λ1067 line.

F98 used a g-factor of $2.2 \times 10^{-7}$ s$^{-1}$ for Ar i λ1048, which was based on radiation and solar wind flux values that were not appropriate for the date of the ORFEUS observations. In particular, the Wind data show that the actual electron temperature in the solar wind was lower than the temperature used to calculate the g-factor given in F98. The result is that our g-factor, based on the measured solar radiation and wind fluxes, is 3.7 times lower than that used by F98.

The ORFEUS observations were made using a scanning technique over the Moon. The spectrum in F98 showing the line around λ1048 was obtained primarily from data within 90° of the lunar day-side limb; 90° corresponds to about 175 km (roughly 3.5 scale heights) at the Moon. To calculate the brightness of a line that would be observed in such a scanning observation, we averaged values from lines of sight with tangential heights ranging from $z = 0$ to $z = 175$ km in our model. Assuming an isothermal atmosphere at the given temperatures, the model surface density of argon was varied to obtain the curves of growth for the lines shown in Figure 2.

F98 gives a purported Ar i λ1048 line flux of $F = (1.3 \pm 0.4) \times 10^{-7}$ photons cm$^{-2}$ s$^{-1}$; the solid angle of the ORFEUS-SPAS II 20° aperture is $\Omega = 7.4 \times 10^{-7}$ sr, implying a line brightness of $B = 4\pi (F/\Omega) 10^{-6} = 2.2 \pm 0.7$ R. Our results, shown in Figure 2, suggest that in the case of $T = 400$ K, the surface density of argon that would be required to produce the observed emission is $n_a \approx 5.2 \times 10^7$ cm$^{-3}$, which is more than a factor of 60 greater than the density calculated by F98 using the optically thin approximation at the same temperature, which substantially exceeds the total lunar atmospheric number density. Also, for a wide range of temperatures up to at least 2000 K, the Ar i λ1067 line (not detected in the ORFEUS data) would be brighter than the Ar i λ1048 line.

Most of this discrepancy between our results and those of F98 for the global surface density of argon is due to the different g-factors used, as discussed above. If in our calculations we used the g-factor used by F98, we would find a surface density of $n_a \approx 9.3 \times 10^4$ cm$^{-3}$ (at the transition between the optically thin and Doppler regimes of the curve of growth), consistent with the value calculated by F98. But as we have shown above, the g-factor used by F98 was based on solar radiation and wind flux values that were not correct for the date of the observations.

Is it possible that the emission line seen in the ORFEUS data could have been the result of observing a transient event that significantly enhanced the local density of argon? Figure 2 shows that the brightness of the Ar i λ1067 line, at the implied density ($5.2 \times 10^7$ cm$^{-3}$) and $T = 400$ K, would be significantly brighter than the Ar i λ1048 line. The model results suggest that if the emission at λ1048 in the ORFEUS data were

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*At low surface densities (in the optically thin regime of Fig. 2), the brightness of the Ar i λ1067 line is less than the brightness of the Ar i λ1048 line by the ratio of the g-factors. However, as the line cores become optically thick, the oscillator strength ceases to matter and the λ1067 line becomes brighter due to the larger (factor of 1.6) solar flux. Since the λ1048 line has a larger damping constant (γ) than the λ1067 line, it enters into the square-root region relatively early and so again becomes the brighter emission.*
due to Ar i, then the $\lambda 1067$ line should have been readily detected at a brightness of about 3.2 R. Yet, no emission line at $\lambda 1067$ was detected in the ORFEUS data, implying that argon was not observed at this density under any circumstances.

We also considered the possibility of an unknown, nonthermal argon source as postulated by F98. Potter & Morgan (1998) find that sodium in the lunar atmosphere has a hot component with a typical temperature of 1280 K and a maximum of 1736 K. However, unlike the case for sodium, there is no obvious mechanism for sufficient nonthermal heating (i.e., sputtering) of noble gases such as argon (R. Johnson 1998, personal communication). Among our considerations were the possibility of hot argon vapor production by micrometeorite impact on the lunar surface and argon from the solar wind. In the former case, calculations show that the amount of hot argon released into the atmosphere is an insignificant fraction of the total argon density (R. Killen 1998, personal communication), and in the latter case, the impacting argon is unlikely to get back into the atmosphere before it has thermalized. Still, for completeness, it is useful to address the possibility of a nonthermal component in case there may be other unknown methods to produce a significant source of hot argon. If we assume a suprathermal equivalent temperature of 2000 K, the density implied by the Ar i $\lambda 1048$ line would be $8.4 \times 10^4$ cm$^{-3}$ (see Fig. 2), consistent with the density calculated by F98. But even in this extreme case, the Ar i $\lambda 1067$ line still would be brighter than the Ar i $\lambda 1048$ line and should have been detected in the ORFEUS data at a brightness of 2.4 R. In any case, suprathermal heating of argon in the lunar atmosphere, if possible, is probably insignificant, and the argon is most likely to be at the accommodated temperature of 400 K as discussed earlier.

For these reasons, we conclude that the feature at $\lambda 1048$ seen in the F98 data is not due to lunar atmospheric Ar i. However, our analysis shows that the best available upper limit for the density of argon in the daytime lunar atmosphere comes from the nondetection of the Ar i $\lambda 1067$ line in the ORFEUS spectrum. As shown in Figure 3 of F98, the approximate 3 $\sigma$ limit for the nondetection of a line at $\lambda = 1067$ Å is about $1.5 \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$, corresponding to a brightness of 2.5 R. According to the $T = 400$ K model in our Figure 2, this implies an upper limit of $n_{Ar} < 2.0 \times 10^3$ cm$^{-3}$, which is approximately the same as the upper limit for the total density of the lunar atmosphere from the Apollo measurements (Johnson et al. 1972).

3. CONCLUSIONS

We find that any abundance measurements based on absorption observations of argon in the lower, daytime lunar atmosphere must be calculated in the optically thick regime of the curve of growth. The common assumption that argon in this part of the lunar atmosphere would be optically thin is invalid.

Also, it appears that the weak emission-line detection at $\lambda 1048$ in the F98 ORFEUS data is not due to lunar argon, since our analysis shows that (1) for argon accommodated to typical daytime surface temperatures of ~400 K, the implied argon surface density actually would be significantly larger than the known density of the entire lunar atmosphere and (2) at that density, the Ar i $\lambda 1067$ line would be brighter than the Ar i $\lambda 1048$ line, yet no line at $\lambda 1067$ is detected in the ORFEUS data, ruling out the possibility that the emission line is due to a high-density, transient event. In fact, even over a wide range of temperatures (up to at least 2000 K), the Ar i $\lambda 1067$ line would be brighter than the Ar i $\lambda 1048$ line, constraining the hot component of any potential suprathermal source of argon. Our results differ from those of F98 primarily because we applied a more complete curve-of-growth analysis, we used improved values for the argon g-factors from radiation and solar wind interactions, and the fact that the implied densities of argon are not in the optically thin regime.

The ultimate result of our analysis is that the global density of argon in the lunar atmosphere is still unknown, and the missing-mass mystery remains unsolved.

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