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This document constitutes the final report for NAG5-4647, "Planetary Astronomy" (S.A. Stern PI, Southwest Research Institute). This 1-year project was an augmentation grant to my NASA Planetary Astronomy grant. Some $20K in funding was provided in this grant as a bridge between a previous and subsequent 3-year Planetary Astronomy grants.

With the awarded funding, we accomplished the following tasks:

(*) Conducted two Na/K imaging runs in conjunction with the ILAW (International Lunar Atmosphere Week) Observing Campaigns in 1995 and 1997. In the first run, we obtained repeated imaging sequences of lunar Na D-line emission to better quantify the temporal variations detected in earlier runs (see Stern and Flynn 1995, AJ, 109, 835). In the second run we obtained extremely high resolution (R=960,000) Na line profiles using the 4m AAT in Australia. These data are being analyzed under our new 3-year Planetary Astronomy grant.

(*) Reduced, analyzed, and published our March 1995 spectroscopic dataset to detect (or set stringent upper limits on) Rb, Cs, Mg, Al, Fe, Ba, Ba, OH, and several other species. These results were reported in a talk at the LPSC and in two papers: (1) A Spectroscopic Survey of Metallic Abundances in the Lunar Atmosphere. Flynn, B.C., and S.A. Stern. Icarus, 124, 530, 1996; and (2) A Search for Magnesium in the Lunar Atmosphere. Stern, S.A., J.W. Parker, T.H. Morgan, B.C. Flynn, D. Hunten, A. Sprague, M. Mendillo, and M.C. Festou. Icarus, 127, 1997. Both reprints are attached.

(*) Wrote up an extensive, invited Reviews of Geophysics review article on advances in the study of the lunar atmosphere. This 70-page article, which is expected to appear in print in 1999, is also attached.

S. Alan Stern, PI 1 July 1998

Attachments
A Spectroscopic Survey of Metallic Species Abundances in the Lunar Atmosphere

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INTRODUCTION

The first results of an ongoing effort to search for new species in the lunar atmosphere are presented. The observations in terms of the degree to which atomic metal abundances in the lunar atmosphere are stoichiometric, that is, proportional to surface abundances (as the Na : K ratio is), are discussed. Na and K are the only atmospheric constituents to have been observed from Earth, and Apollo sample returns established that a variety of species are more abundant in the lunar surface than either Na or K. Simple stoichiometric arguments (i.e., assuming atmospheric production proportional to surface abundance) predict that relatively abundant lunar surface constituents such as Si, Al, Ca, Mg, Fe, and Ti should be more abundant in the lunar atmosphere than either Na or K. The 2.7-m coudé and 2.1-m cassegrain echelle spectrographs at the University of Texas McDonald Observatory were used to investigate this hypothesis by searching for solar resonant scattering lines of nine metallic species between 3700 and 9700 Å. Spectra were taken 20 arcsec above the apparent subsolar limb of the Moon near quarter phase on 30 July 1994 and 10–12 March 1995. Upper limits were obtained for the first time for the abundant lunar surface species Si, Al, Ca, Fe, and Ti, as well as Ba and the alkalis Li, Rb, and Cs. In the cases of Si, Ca, Fe, and Ti, the derived upper limits are more than an order of magnitude lower than the simple stoichiometric model predicts. The upper limits for Li and Al are less constraining. The Ba, Rb, and Cs upper limits lead to the conclusion that those species are not stoichiometrically overabundant above the detection threshold in the atmosphere. It is concluded that the stoichiometric Na : K ratio is peculiar in that the mechanism(s) that produce the lunar Na and K atmosphere somehow favor those atomic species over many more or comparably abundant lunar surface species.


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2 Now at University of California Center for EUV Astrophysics.

both Ar and He, with Ar densities reaching at least 4 × 10⁴ cm⁻³. The Apollo 17 UV spectrometer obtained daytime upper limits on the atmospheric abundances of several other species, including H, C, N, and O (cf. Feldman and Morrison 1991), but all of these were below the 2 × 10⁴ cm⁻³ level. In contrast, Apollo surface total pressure measurements indicated that even at night, when equipment outgassing is not a factor, densities exceeding 2 × 10⁵ cm⁻³ were routinely obtained. Together, these facts suggest that the composition of the lunar atmosphere remains largely unidentified (cf. Morgan and Stern 1991).

More recently, Potter and Morgan (1988a) discovered Na and K resonant scattering emissions from the lunar atmosphere through ground-based spectroscopy, making it possible to study the lunar atmosphere from the Earth: typical near-surface number densities for these species are ∼10⁵ cm⁻³ for Na and 10⁴ cm⁻³ for K. These number densities correspond to characteristic columns of 8 × 10⁸ cm⁻² for Na and 1.4 × 10⁸ cm⁻² for K, respectively. Subsequent observations and modeling of the distribution of Na around the Moon have shown that the Na is largely suprathermal in nature (e.g., Potter and Morgan 1988b, Mendillo et al. 1991, Sprague et al. 1992, Flynn and Mendillo 1995). Recently, however, it has been shown that the suspected, underlying thermal velocity component close to the surface (e.g., Potter and Morgan 1988a, Tyler et al. 1988, Kozlowski et al. 1990, Sprague et al. 1992) is in fact present with the high-velocity component (Stern and Flynn 1995). The suprathermal nature of the Na seen in most observations indicates that an energetic production process, such as solar wind sputtering, photodesorption, or micrometeorite impact vaporization, is responsible for releasing Na from the lunar surface (Morgan and Stern 1991, Sprague et al. 1992). Observations of Na made before, during, and after lunar passage through the Earth’s magnetotail have been used to argue that among these processes, solar wind sputtering may be the major source of Na in the lunar atmosphere (Potter and Morgan 1994). Recent observations made during lunar eclipse, however, indicate possibly a different source (Mendillo and Baumgardner 1995).
This paper reports the first results from a spectroscopic search for new species in the lunar atmosphere. Our survey is motivated by our desire to better understand the source mechanisms that generate the lunar Na/K exosphere and to rectify the present-day inconsistency between total atmospheric abundance measurements made by Apollo in situ instruments and the much lower total atmospheric abundance of the compositionally identified species. As noted above, whereas the Apollo surface cold cathode gauge experiments determined that the daytime surface number density can exceed $10^6$ cm$^{-3}$, the four species detected to date (He, Ar, Na, and K) together compose <10% of the total density. It is often not recognized that more than 90% of the lunar atmosphere remains compositionally unidentified.

Because atmospheric Na and K are generated primarily by exogenic source processes acting on the surface layer, it is natural to suspect that other species in the surface may also be injected into the lunar atmosphere by these source processes. Apollo lunar sample returns have shown that several metallic species are more abundant than, or are of comparable abundance to, Na and K (cf. Taylor 1982). For a surface that has reached an equilibrium composition under long-term bombardment by solar wind particles, one expects that the sputtering yields of surface species reflect the bulk composition of the surface (Johnson and Baragiola 1991). If such stoichiometry holds, then a sputtered lunar atmosphere should contain metal species derived from the lunar surface in rough proportion to their

### Table I: Estimated Lunar Resonant Scattering Intensities

<table>
<thead>
<tr>
<th>Species</th>
<th>$N_0$ (cm$^{-2}$)</th>
<th>Surf Abun Ratio</th>
<th>$g$-factor</th>
<th>Col Abun Brightness $^e$</th>
<th>Estimated Emission Brightness $^e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na I</td>
<td>3890</td>
<td>1</td>
<td>0.54</td>
<td>$4.5 \times 10^7$</td>
<td>2.6</td>
</tr>
<tr>
<td>K I</td>
<td>7699</td>
<td>0.3</td>
<td>1.7</td>
<td>$6.3 \times 10^8$</td>
<td>1.0</td>
</tr>
<tr>
<td>Si I</td>
<td>3986</td>
<td>50</td>
<td>0.058</td>
<td>$2.5 \times 10^{11}$</td>
<td>15.</td>
</tr>
<tr>
<td>Al I</td>
<td>3962</td>
<td>30</td>
<td>0.037</td>
<td>$5.7 \times 10^9$</td>
<td>0.21</td>
</tr>
<tr>
<td>Ca I</td>
<td>4227</td>
<td>16</td>
<td>0.49</td>
<td>$2.5 \times 10^{10}$</td>
<td>12.</td>
</tr>
<tr>
<td>Fe I</td>
<td>3720</td>
<td>8</td>
<td>0.0061</td>
<td>$6.3 \times 10^{11}$</td>
<td>3.8</td>
</tr>
<tr>
<td>Mg I</td>
<td>3859</td>
<td>8</td>
<td>0.012</td>
<td>$6.3 \times 10^{11}$</td>
<td>7.6</td>
</tr>
<tr>
<td>Ti I</td>
<td>5036</td>
<td>1</td>
<td>0.68</td>
<td>$2.5 \times 10^9$</td>
<td>1.7</td>
</tr>
<tr>
<td>Ba I</td>
<td>5536</td>
<td>0.03</td>
<td>11</td>
<td>$1.2 \times 10^4$</td>
<td>0.00013</td>
</tr>
<tr>
<td>Li I</td>
<td>6708</td>
<td>0.005</td>
<td>16</td>
<td>$2.9 \times 10^9$</td>
<td>0.046</td>
</tr>
<tr>
<td>Rb I</td>
<td>3780</td>
<td>0.0009</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cs I</td>
<td>8521</td>
<td>0.0009</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Wavelength of leading line of multiplet.
* Estimated resonance column abundance at 40 km (20°) above the subsolar limb of the Moon based on relative surface abundance, ionization lifetime, and altitude distribution from a Chamberlain exosphere at 1000 K.
* Estimated emission brightness at 40 km.
* Species has been observed via ground-based spectroscopy and direct imaging.

### Table II: Lunar Spectroscopic Observational Log

(McDonald 2.7 m)

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Surface</th>
<th>Off-Limb</th>
<th>Date</th>
<th>UT Range</th>
<th>Phase Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na 5890 Å</td>
<td>33</td>
<td>600</td>
<td>7/31/94 08:10-08:22</td>
<td>90°</td>
<td></td>
</tr>
<tr>
<td>Ca 4227 Å</td>
<td>120</td>
<td>2400</td>
<td>7/31/94 08:26-09:32</td>
<td>100°</td>
<td></td>
</tr>
<tr>
<td>Ti 5036 Å</td>
<td>30</td>
<td>780</td>
<td>7/31/94 09:50-10:04</td>
<td>100°</td>
<td></td>
</tr>
<tr>
<td>Li 6708 Å</td>
<td>30</td>
<td>2100</td>
<td>7/31/94 10:10-11:07</td>
<td>100°</td>
<td></td>
</tr>
</tbody>
</table>

(McDonald 2.1 m)

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Surface</th>
<th>Off-Limb</th>
<th>Date</th>
<th>UT Range</th>
<th>Phase Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>3705-3985 Å</td>
<td>2700</td>
<td>8335</td>
<td>3/12/95 02:15-07:21</td>
<td>60°</td>
<td></td>
</tr>
<tr>
<td>5510-6013 Å</td>
<td>50</td>
<td>4200</td>
<td>3/11/95 01:59-03:47</td>
<td>71°</td>
<td></td>
</tr>
<tr>
<td>6900-9675 Å</td>
<td>130</td>
<td>5100</td>
<td>3/11/95 04:35-07:21</td>
<td>70°</td>
<td></td>
</tr>
</tbody>
</table>

Note: Surface, 20° from apparent subsolar point of limb; Off-Limb, 20° above apparent subsolar limb, slit parallel to limb. Phase angle corresponds to midpoint of observation.
surface abundances. Of course, other factors, such as ion-cation lifetimes and scale heights, will modify their relative abundances in the atmosphere, but these effects can be accurately modeled.

A STOICHIOMETRIC MODEL

Because of their significant abundances in the lunar surface and their chemical similarity to Na, we have estimated the expected brightnesses of Si, Al, Ca, Fe, Ti, Ba, and Li in the lunar atmosphere. We predict resonant scattering intensities for these species based on a simple stoichiometric model, which we now describe. We begin with elemental surface abundances relative to Na, which have been obtained from Apollo regolith sample returns (Taylor 1982). Assuming stoichiometric production, we computed atmospheric abundances using an exosphere model (Chamberlain and Hunten 1987) at 1000 K (as is appropriate for the highly extended Na distribution) and the photoionization loss rates for each species. We then used published oscillator strengths (Allen 1973) and solar spectra (Kurucz et al. 1984) to compute the resonant scattering efficiencies \( g \) for each species. The predicted brightnesses are then given by

\[
4\pi l = 10^{-6}gN.
\]

where \( 4\pi l \) is in Rayleighs and \( N \) is the predicted line-of-sight column abundance.

The results of such calculations are shown in Table I. Note that the column abundances and brightnesses predicted by this model for K agree with existing K observations (cf. Potter and Morgan 1988a, Kozlowski et al. 1990). Note also that the predicted brightnesses for Si, Ca, Fe, and Ti are brighter than or are comparable to that of Na, and should therefore be easily detectable if the stoichiometric assumption is valid. The predicted values for Li and Al are less easily detectable, and, because of its low

FIG. 1. Spectra taken in July 1994 near the resonant lines of Na (left) and Li (right). Top: Spectra taken of the lunar surface 20° from the apparent subsolar point on the limb. Middle: Spectra taken 20° (40 km) above the apparent subsolar point, showing terrestrial atmospheric scattering of the lunar surface continuum and, in the case of Na, lunar atmospheric emission features. Bottom: Difference of top and middle panels showing strong Na emission features at 5890 and 5896 Å and nondetection of Li. The signal-to-noise ratio for the D_2 line (5890 Å) is approximately 100. The 5σ upper limit for Li is indicated.
expected brightness, a detection of Ba would require super-stoichiometry relative to Na. For completeness, we also targeted other alkalis, Rb and Cs, but the lack of atomic data precluded brightness predictions for these species.

**OBSERVATIONS**

The observations analyzed in this paper are summarized in Table II. Our July 1994 observations targeted only Na, Ca, Ti, and Li, and were taken with the McDonald Observatory 2.7-m coudé spectrograph at $R = 60,000$, using an 800 $\times$ 800-pixel charge-coupled device (CCD). The spectrograph slit had a projected length of $\approx 20''$. Order-separating filters were used to prevent order mixing. The resulting spectra encompassed $\approx 10$ $\text{Å}$ centered on the strongest resonant scattering emission lines of our four target species.

The March 1995 observations were obtained by using the McDonald 2.1-m cassegrain echelle spectrograph. This instrument is cross-dispersed to separate orders and uses an 800 $\times$ 1200-pixel CCD. We used three grating positions giving broad spectral ranges of 3705–3985, 5510–6913, and 6900–9675 $\text{Å}$. To prevent overlap of orders, a slit length of 6$''$ was used.

The observing technique was as follows. Each atmospheric spectrum was taken $\approx 20''$ above the apparent sub-solar point of the Moon’s limb, with the slit oriented approximately parallel to the lunar limb. To obtain a brightness calibration, spectra were also taken of the lunar surface with the slit pointed $\approx 20''$ from the apparent sub-solar limb and oriented in the same way as the atmospheric spectra. All data were taken near quarter Moon.

**DATA REDUCTION AND ANALYSIS**

Each spectrum we obtained was corrected for vignetting, bias, and pixel-to-pixel gain differences by using white-lamp and dark images. Wavelength calibrations were obtained by means of both a Th–Ar lamp and a solar spectrum (Kurucz et al. 1984). The Th–Ar spectra also provided a calibration of the spectral resolution, which was $\approx 50$–70 mÅ for the July 1994 data and $\approx 120$–180 mÅ for the March 1995 data. Spectral line tilt and curvature were corrected through subpixel shifts of each row in the wavelength dimension to allow for coaddition along the slit. Individual atmospheric or surface spectra for each species were coadded to further increase the signal-to-noise ratio. In some cases, small, subpixel shifts in wavelength were required to match the positions of solar absorption features precisely.

We obtained absolute calibration of our surface spectra by computing the surface brightness of the Moon at the continuum level for the appropriate observing geometry. We assumed a V-band surface reflectivity of 10%; phase factors were computed by using Hapke’s lunar photometric theory (Hapke 1966). The assumed V-band reflectivity was
adjusted at other wavelengths by using the lunar spectral reflectivity of McCord and Johnson (1970). We estimate that this calibration method introduces an absolute uncertainty of ≈20%, which is due mainly to uncertainties in the precise albedo of the surface regions measured for calibration. Uncertainties of this magnitude are not significant in the context of the results that follow.

Calibrated spectra taken of the lunar surface and atmosphere at the Na D1 (5896 Å) and D2 (5890 Å) lines in July 1994 are shown in the left of Fig. 1. The top panel shows a spectrum of the surface; the middle panel is a 10-min exposure of the lunar atmosphere; note the prominent Na emission features superimposed on the scattered lunar spectrum. The bottom panel shows the residual intensity resulting from scaling and subtracting the surface spectrum from the atmospheric spectrum. These intensities are consistent with previous measurements of Na at ≈20° made above the apparent subsolar point on the Moon’s limb (e.g., Potter and Morgan 1988a, Sprague et al. 1992), and their difference may be indicative of the level of variability seen in atmospheric Na brightness.

An example upper limit measurement is shown in the right panels of Fig. 1. No emission feature is evident in the residual spectrum. In the case of such nondetections, we computed upper limits on emission line brightnesses as follows. First, the 1σ standard deviation of each residual spectrum was computed. Then we integrated over an artificial emission line (gaussian) with a 5σ amplitude and a full width at half maximum corresponding to the measured spectral resolution in the neighborhood of each line to arrive at the 5σ upper limits shown in Fig. 2.

The upper limits for our stoichiometrically modeled species correspond to line-of-sight column abundances shown in Table III. When compared with the predicted column abundances in Table I, we find that the observed upper limits for most species listed fall significantly below the stoichiometric model predictions, whereas our detected brightness for K is within a factor of 2 of the predicted value. The implications of this result are discussed below.

**DISCUSSION**

Our targeted search for resonant scattering emissions above the lunar limb has produced the first constraining upper limits on the abundances of six atomic species that were predicted to be potentially abundant in the lunar atmosphere. Upper limits were also obtained for three additional species of interest. The measured upper limits on emission brightnesses for these species depart from stoichiometry. Figure 3 gives the ratio of the observed upper limits on atmospheric abundances relative to their stoichiometrically predicted values. The

<table>
<thead>
<tr>
<th>TABLE III Combined Spectroscopic Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>Na I</td>
</tr>
<tr>
<td>K I</td>
</tr>
<tr>
<td>Si I</td>
</tr>
<tr>
<td>Al I</td>
</tr>
<tr>
<td>Ca I</td>
</tr>
<tr>
<td>Fe I</td>
</tr>
<tr>
<td>Ti I</td>
</tr>
<tr>
<td>Ba I</td>
</tr>
<tr>
<td>Li I</td>
</tr>
<tr>
<td>Rb I</td>
</tr>
<tr>
<td>Cs I</td>
</tr>
</tbody>
</table>
upper limits for all of these species except Al and Li are more than an order of magnitude below the stoichiometric prediction. These strongly substoichiometric abundances are in clear contrast to the case of atmospheric K, for which the observed 5:1 to 11:1 abundance ratio is consistent with the 7:1 ratio predicted by stoichiometry. We note that detections or upper limits obtained during each observing run were normalized to Na values obtained during the same run, to provide a calibration scale and minimize uncertainties due to temporal variations.

The presence of the volatile species Na and K in the lunar atmosphere, coupled with the absence of atmospheric counterparts of other abundant lunar surface constituents, such as Si, Al, Ca, Fe, Ti, and Li, indicate to us that the production mechanisms, whatever they are and even if they are in competition with one another (Sprague et al. 1992), apparently preferentially favor Na and K over other atoms. The lack of stoichiometry we have documented also appears to indicate that the surface layer may not have reached radiation-exposure equilibrium. This could occur, for example, if meteoritic bombardment sufficientlygardens the lunar surface to result in a reduced effective surface age (Johnson and Baragiola 1991). In this case solar wind sputtering yields would not approach stoichiometry and volatile species would dominate atmospheric metal abundances. Alternatively, the lack of other abundant surface atoms in the atmosphere may indicate that chemical sputtering (Potter 1995), which favors high-vapor-pressure species like Na and K, may be significant or that the other metal species we searched for may be preferentially injected as molecular oxide fragments (e.g., CaO, TiO, TiO₂) rather than atoms, in which case we would not have detected them. Finally we note that the apparent lack of stoichiometry in the atmosphere may also be influenced by recycling of Na and K through the surface, which would enhance the steady-state abundances of Na and K in the atmosphere (Kozlowski et al. 1990, Sprague et al. 1992).

ACKNOWLEDGMENTS

We are grateful to our colleagues Bob Johnson, Tom Morgan, and Larry Trafton for helpful discussions. We thank Bill Cochran and David Doss for assistance with the observing equipment at McDonald Observatory. Ann Sprague and an anonymous reviewer provided many helpful comments. This research was supported by the NASA Planetary Astronomy Program.

REFERENCES


McCord, T., and T. Johnson 1970. Lunar spectral reflectivity (0.30 to 2.50 microns) and implications for remote mineralogical analysis. Science 169, 855–858.
NOTE

An HST Search for Magnesium in the Lunar Atmosphere

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In October 1996 we used the Hubble Space Telescope's Faint Object Spectrograph to make the first-ever mid-ultraviolet spectroscopic search for emissions from the lunar atmosphere. This spectrum revealed no emission lines, despite the fact that strong resonance emission transitions from the Al, Si, and Mg neutrals and from Mg$^+$ occur in the bandpass. We derive 5σ upper limits on the atmospheric abundances of each of these species and on OH (0-0) emission. The most constraining upper limit we obtained was for Mg, which we find to be depleted by a factor of at least 9 relative to model predictions using the known abundance of Mg in the lunar regolith. These findings reinforce the negative findings of our previous, ground-based search for neutral atoms in the lunar atmosphere (B. C. Flynn and S. A. Stern, 1996, Icarus 124, 530-536) and suggest that Na and K may be rather unique in their ability to readily sputter from the surface as atomic neutrals. Other species may sputter away as ions or in molecular fragments.

Introduction. During the Apollo program, surface-based cold cathode gauges measured nighttime lunar atmosphere number densities as high as $10^6$ cm$^{-3}$, but detected only He and Ar as identifiable species, with a combined peak number density near $5 \times 10^4$ cm$^{-3}$.
The purpose of comparison. Although the Moon itself never entered the FOS field of search was not allowed to approach closer than 0.3 ° (1.2 aperture, which measures 3.66 × 3.7 arcsec:, and obtained a total exposure length by scattered lunar surface continuum in the telescope.

\[3\text{ particular atomic emissions: Si I (2516 Å). Mg I (2852 Å), and Al I (3092 Å).} \]

\[2222 \text{ to } 3301 \text{ Å. We used the} \]

\[\text{predictions for each neutral atomic species. The predictions for the Si, Mg, and Al neutrals were derived using the stoichiometric atmosphere model established in F&S 96. The Si and Al constraints derived from the FOS spectrum are not constraining relative to the stoichiometric model, they are consistent with the significantly more constraining ground-based results published in F&S 96.} \]

\[\text{Conclusions and interpretation. A search for resonant scattering mid-UV emissions above the lunar limb detected no spectral features. At the} \]

\[5 \text{ confidence level, these nondetections correspond to } \approx 15 R \text{ for Si I (385 Å), } \approx 19 R \text{ for the Mg II doublet (2797 Å), } \approx 53 R \text{ for Mg I (2852 Å), } \approx 74 R \text{ for Al I (3092 Ä), and } \approx 67 R \text{ for OH (3085 Å).} \]

\[\text{Of these, the Mg I (2852 Ä) constraint provides the most significant new information.} \]

\[\text{We have found that the Mg neutral is depleted in the lunar atmosphere by a factor of at least 9 at an altitude of 1.2 R_m, relative to stoichiometric sputtering predictions using Na as the reference species. This of course does not eliminate the possibility of a low-energy and therefore low-altitude Mg population, but the conclusion that stoichiometric sputtering is not the source process remains valid, regardless of this possibility.} \]

\[\text{The Mg finding is in agreement with our earlier, ground-based search for a variety of other surface-derived metallic neutrals (cf. F&S 96). The absence of so many stoichiometrically predicted atmospheric metal species strongly indicates that whatever the production mechanism is that generates Na and K, it preferentially favors Na and K neutrals over other atomic neutrals.} \]

\[1 \text{ We verified this by its lunar-like color slope at wavelengths longward of } 2650 \text{ Å; the blue upturn in our data at shorter wavelengths has been seen in other FOS observations, and is most likely an instrumental artifact.} \]

\[2 \text{ But see Hilchenbach et al. 1991 for evidence of a possible in situ detection.} \]
Because of the well-established nonthermal nature of the lunar atmosphere's Na and K, it has been natural to suspect that a sputtering process, perhaps stoichiometric, could be responsible for generating metal species in the lunar atmosphere. The upper limits presented here and in F&S96 show that this is not the case.

This situation could occur for any of a number of reasons. One possibility is that meteoritic bombardment (Morgan and Shemuansky 1991) might sufficiently garden the lunar surface, reducing the effective surface age (Johnson and Baragiola 1991) and therefore resulting in a nonstoichiometric sputtering process. In this case solar wind sputtering yields would not approach stoichiometry and more volatile species such as Na and K would dominate atmospheric metal abundances. A second possibility is that atmospheric recycling through photodesorption of loosely bound Na and K produces an anomalously high abundance of these two species (cf. Sprague et al. 1992; cf. also Kozlowski et al. 1990 with regard to K).

Yet another possibility concerns the nature of the chemical fragments released by the source process, whether it is sputtering or something else.

Given (i) that all of the species we have searched for here and in F&S96 are significantly depleted from stoichiometric sputtering predictions, and (ii) that both solar photon and solar proton sputtering are sufficiently energetic to break chemical bonds and to even ionize some species as they are removed from the lunar surface layer, the depletions we have found may also imply that Na and K are being preferentially injected into the lunar atmosphere as atomic neutrals, while other species may be injected as atomic ions, or perhaps more likely as molecular fragments, such as MgO, SiO, and AlO.

In closing, we find it worthwhile to note that Na/K exospheres of Mercury and Io have also been thought to be generated in large measure by charged particle sputtering. However, like the Moon's, Mercury's atmosphere has been found to be significantly depleted in both Ca (Sprague et al. 1993) and Li (Sprague et al. 1996), and Io's extended atmosphere has been found to be significantly depleted in a wide variety of metallic atomic species (Na et al. 1997). This suggests to us that "missing" neutrals in the atmospheres of Mercury and Io may be absent for the same reasons as in the case of the Moon and heightens our interest in determining the...
TABLE I
Comparison of FOS Upper Limits to Model Predictions

<table>
<thead>
<tr>
<th>Species</th>
<th>$\lambda$ (Å)</th>
<th>Upper limit brightness ($5\sigma$)</th>
<th>Model brightness ($3.1 R_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si I</td>
<td>2516</td>
<td>15 $R$</td>
<td>002 $R$</td>
</tr>
<tr>
<td>Mg II</td>
<td>2797</td>
<td>19 $R$</td>
<td>N/A</td>
</tr>
<tr>
<td>Mg I</td>
<td>2852</td>
<td>53 $R$</td>
<td>476 $R$</td>
</tr>
<tr>
<td>Al I</td>
<td>3092</td>
<td>74 $R$</td>
<td>002 $R$</td>
</tr>
<tr>
<td>OH (0–0)</td>
<td>3085</td>
<td>67 $R$</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Note. The observed upper limits are for a spectral binning equal to the 25 Å resolution of the filled FOS slit with the G270H grating. Model-predicted brightnesses (cf. F&S96 for model details) were computed for an impact parameter of 3.1 $R_\odot$ from the lunar center for the shadow geometry of our observations. The stoichiometric model does not meaningfully predict the brightness of either OH or Mg.

reason for the lack of so many species once suspected to exist in all three of these atmospheres.

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REFERENCES


