A Final Report for

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FINAL REPORT
PLANETARY ASTRONOMY
NASA GRANT NAG5-4647
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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.
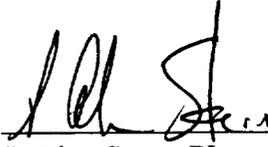
S. Alan Stern, PI   1 July 1998

Attachments

A Spectroscopic Survey of Metallic Species Abundances in the Lunar Atmosphere

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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, but 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.   © 1996 Academic Press, Inc.

INTRODUCTION

The lunar atmosphere was first detected by Apollo *in situ* instruments in the early 1970s. Among these instruments, the Apollo 17 surface mass spectrometer identified both Ar and He, with Ar densities reaching at least 4×10^4 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 2×10^4 cm^{-3} level. In contrast, Apollo surface total pressure measurements indicated that even at night, when equipment outgassing is not a factor, densities exceeding 2×10^5 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 $\sim 10^2$ cm^{-3} for Na and 10^1 cm^{-3} for K. These number densities correspond to characteristic columns of $8 \pm 3 \times 10^8$ cm^{-2} for Na and $1.4 \pm 0.3 \times 10^8$ 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).

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TABLE I
Estimated Lunar Resonant Scattering Intensities

Species	λ_0 (Å)	Surf Abun Ratio	g-factor (sec⁻¹)	Col Abun Est cm⁻²	Brightness Est (kR)
Na I'	5890	1	0.54	4.8 × 10⁹	2.6
K I'	7699	0.3	1.7	6.3 × 10⁸	1.0
Si I	3906	50	0.058	2.5 × 10¹¹	15.
Al I	3962	30	0.037	5.7 × 10⁹	0.21
Ca I	4227	16	0.49	2.3 × 10¹⁰	12.
Fe I	3720	8	0.0061	6.3 × 10¹¹	3.8
	3859	8	0.012	6.3 × 10¹¹	7.6
Ti I	5036	1	0.68	2.5 × 10⁹	1.7
Ba I	5536	0.03	11.	1.2 × 10⁴	0.00013
Li I	6708	0.005	16.	2.9 × 10⁶	0.046
Rb I'	7800	0.0009	-	-	-
Cs I'	8521	0.00004	-	-	-

ᵃ Wavelength of leading line of multiplet.
ᵇ Surface abundance relative to Na (Taylor 1982).
ᶜ Scattering efficiency.
ᵈ Estimated atmospheric column abundance at 40 km (20") above the subsolar limb at quarter Moon based on relative surface abundance. ionization lifetime, and altitude distribution from a Chamberlain exosphere at 1000 K.
ᵉ Estimated emission brightness at 40 km.
ᶠ Species has been observed via ground-based spectroscopy and direct imaging.
ᵍ Atomic data not available.

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 10⁶ 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 II
Lunar Spectroscopic Observational Log

(McDonald 2.7 m)					
Wavelength	Surface Exp (sec)	Off-Limb Exp (sec)	Date	UT Range	Phase Angle
Na 5890 Å	33	600	7/31/94	08:10-08:22	99°
Ca 4227 Å	120	2400	7/31/94	08:26-09:32	100°
Ti 5036 Å	30	780	7/31/94	09:50-10:04	100°
Li 6708 Å	30	2100	7/31/94	10:10-11:07	100°
(McDonald 2.1 m)					
Wavelength	Surface Exp (sec)	Off-Limb Exp (sec)	Date	UT Range	Phase Angle
3705-3985 Å	2700	8335	3/12/95	02:15-07:24	60°
5510-6913 Å	50	4200	3/11/95	01:59-03:47	71°
6900-9675 Å	150	5100	3/11/95	04:35-07:21	70°

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.
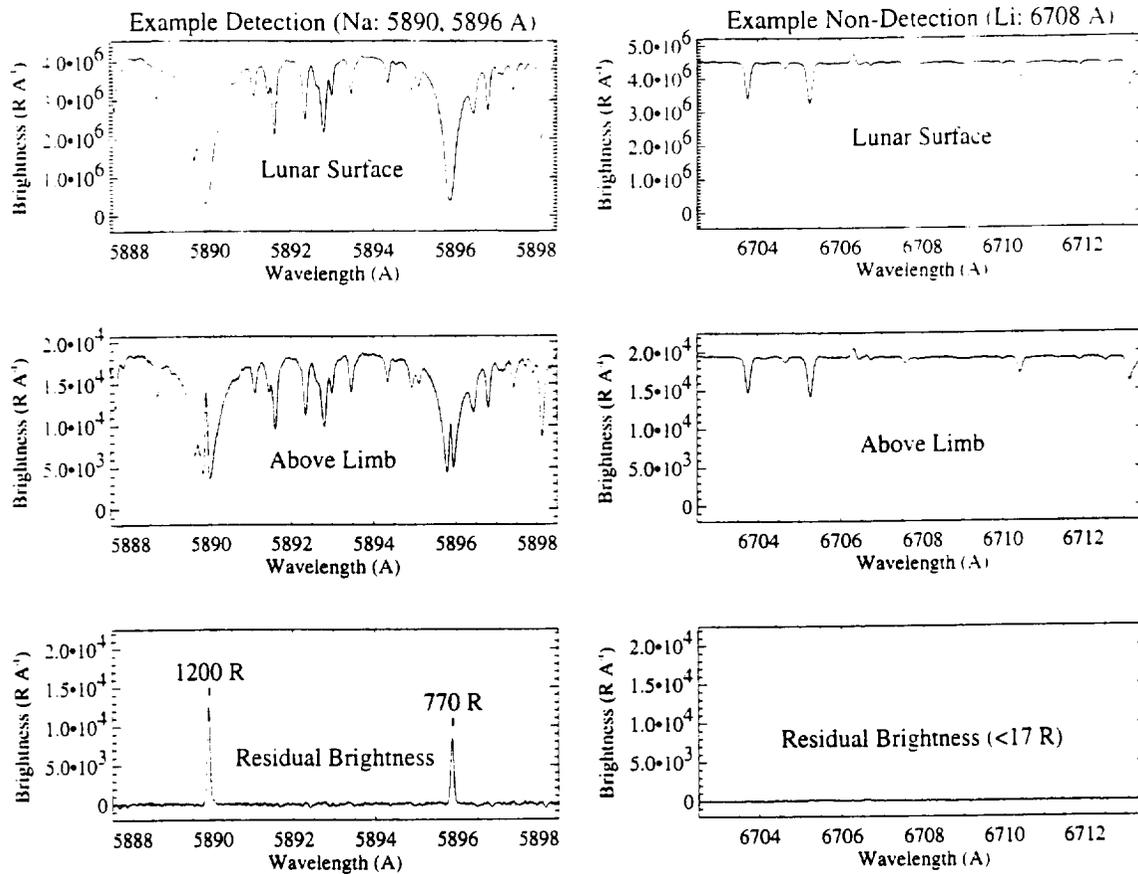
FIG. 1. Spectra taken in July 1994 near the resonant lines of Na (left) and Li (right). Top: Spectra taken of the lunar surface 20" from the apparent subsolar point on the limb. Middle: Spectra taken 20" (40 km) above the apparent subsolar point, showing terrestrial atmospheric scattering of the lunar 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.

surface abundances. Of course, other factors, such as ionization 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 photoioniza-

tion 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

$$4\pi I = 10^{-6}gN. \tag{1}$$

where $4\pi I$ 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
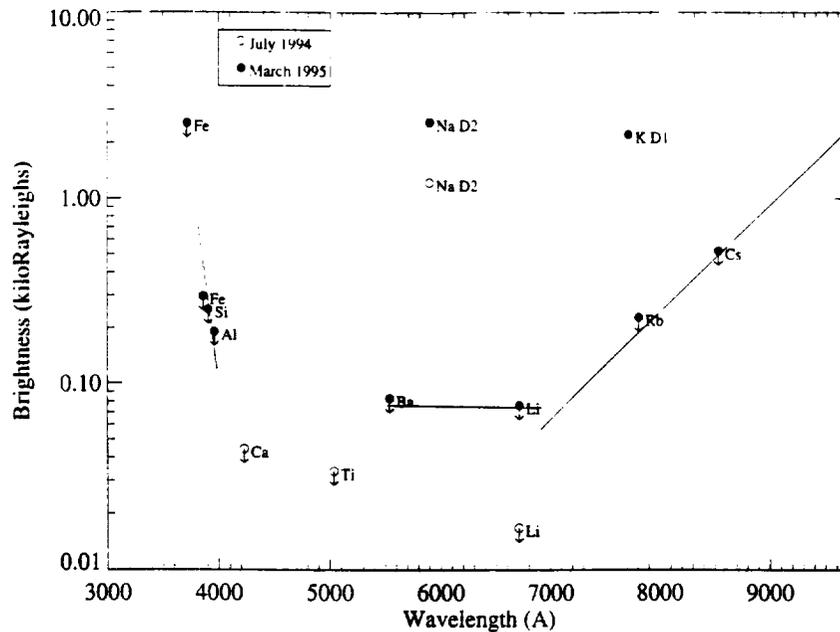
FIG. 2. Na and K detections and 5σ upper limits for other species. Species upper limits are distinguished from detections by downward arrows. Shown as solid lines are the approximate 5σ sensitivity levels for the three wavelength ranges observed in March 1995. The July 1994 observations were more sensitive, but covered narrow bandpasses with widths of only ~10 Å.

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 $R \simeq 60,000$, using an 800 × 800-pixel charge-coupled device (CCD). The spectrograph slit had a projected length of $\simeq 20''$. Order-separating filters were used to prevent order mixing. The resulting spectra encompassed $\simeq 10$ 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 × 1200-pixel CCD. We used three grating positions giving broad spectral ranges of 3705–3985, 5510–6913, and 6900–9675 Å. To prevent overlap of orders, a slit length of 6'' was used.

The observing technique was as follows. Each atmospheric spectrum was taken $\simeq 20''$ above the apparent subsolar 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 $\simeq 20''$ from the apparent subsolar 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 $\simeq 50$–70 mÅ for the July 1994 data and $\simeq 120$–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 $\approx 20\%$, 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 D_1 (5896 Å) and D_2 (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. Emission line intensities of 1.2 kR (D_2) and 0.77 kR (D_1) for July 1994 and 2.6 kR and 1.8 kR (March 1995) were computed by integrating over the lines in wavelength. These intensities are consistent with previous measurements of Na at $\approx 20''$ 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 fall below the values predicted from a simple stoichiometric model (cf. Table I). Figure 3 shows the degree to which the species depart from stoichiometry. Figure 3 also gives the ratio of the observed upper limits on atmospheric abundances relative to their stoichiometrically predicted values. The

TABLE III
Combined Spectroscopic Results

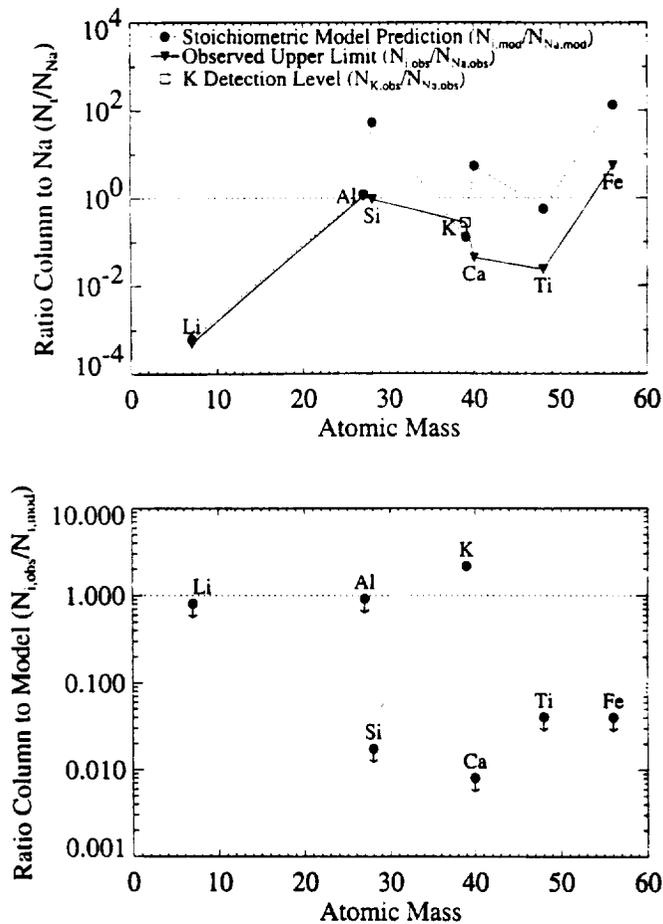| Species	λ_0 (Å)	July 1994 Bright. (kR)	July 1994 Col Abun (cm^{-2})	March 1995 Bright. (kR)	March 1995 Col Abun (cm^{-2})
Na I	5890	1.2	2.2×10^9	2.6	4.8×10^9
K I	7699	-	-	2.2	1.3×10^9
Si I	3906	-	-	<0.25	$< 4.3 \times 10^9$
Al I	3962	-	-	<0.19	$< 5.1 \times 10^9$
Ca I	4227	<0.045	$< 9.2 \times 10^7$	-	-
Fe I	3720	-	-	<2.5	$< 4.1 \times 10^{11}$
	3859	-	-	<0.30	$< 2.5 \times 10^{10}$
Ti I	5036	<0.034	$< 5.0 \times 10^7$	-	-
Ba I	5536	-	-	<0.083	$< 7.5 \times 10^6$
Li I	6708	<0.017	$< 1.1 \times 10^6$	<0.076	$< 4.9 \times 10^6$
Rb I	7800	-	-	<0.23	-
Cs I	8521	-	-	<0.52	-

FIG. 3. Top: Line-of-sight column abundances at 40 km above the limb for Si, Al, Ca, Fe, Ti, and Li relative to Na from both the stoichiometric model (filled circles) and the observations (triangles). The detected value for K is within a factor of 2 of the predicted stoichiometric value. Bottom: Ratios of observed upper limit column abundances to predicted values. A ratio of unity indicates stoichiometric behavior relative to Na. Arrows denote that values are upper limits in the cases of Si, Al, Ca, Fe, Ti, and Li. Note that the K value is within a factor of 2 of unity.

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 sufficiently gardens 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, TiO_2) 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

REFERENCES

ALLEN, C. W. 1973. Astrophysical Quantities. Athlone, London.

CHAMBERLAIN, J. W., AND D. M. HUNTEN 1987. Stability of planetary atmospheres. In Theory of Planetary Atmospheres, pp. 330–415. Academic Press, Boston, MA.

FELDMAN, P. D., AND D. MORRISON 1991. The Apollo 17 ultraviolet spectrometer: Lunar atmosphere measurements revisited. Geophys. Res. Lett. 18, 2105–2108.

FLYNN, B., AND M. MENDILLO 1995. Simulations of the lunar sodium atmosphere. J. Geophys. Res. 100.

HAPKE, B. 1966. An improved theoretical lunar photometric function. Astron. J. 71, 333–339.

JOHNSON, R. E., AND R. BARAGIOLA 1991. Lunar surface: Sputtering and secondary ion mass spectrometry. Geophys. Res. Lett. 18, 2169–2172.

KOZLOWSKI, R., A. SPRAGUE, AND D. HUNTEN 1990. Observation of potassium in the tenuous lunar atmosphere. Geophys. Res. Lett. 17, 2253–2256.

KURUCZ, R. L., I. FURENLID, J. BRAULT, AND L. TESTERMAN 1984. Solar Flux Atlas from 296 to 1300 nm. Harvard University, Cambridge.

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.

MENDILLO. M.. AND J. BAUMGARDNER 1995. Detection of the Moon's extended atmosphere during a total lunar eclipse. *Science.* in press.

MENDILLO. M.. J. BAUMGARDNER. AND B. FLYNN 1991. Imaging observations of the extended sodium atmosphere of the Moon. *Geophys. Res. Lett.* **18.** 2097.

MORGAN. T.. AND S. A. STERN 1991. The lunar atmosphere. *EOS* **72.** 522.

POTTER. A. E. 1995. Chemical sputtering could produce sodium vapor and ice on Mercury. *Geophys. Res. Lett.* **22.** 3289.

POTTER. A. E.. AND T. H. MORGAN 1988a. Discovery of sodium and potassium vapor in the atmosphere of the Moon. *Science* **241,** 675–680.

POTTER. A. E.. AND T. H. MORGAN 1988b. Extended sodium exosphere of the Moon. *Geophys. Res. Lett.* **15,** 1515–1518.

POTTER. A. E.. AND T. H. MORGAN 1994. Variation of lunar sodium emission intensity with phase angle. *Geophys. Res. Lett.* **21,** 2263–2266.

SPRAGUE. A.. R. KOZLOWSKI. D. HUNTEN. W. WELLS. AND F. GROSSE 1992. The sodium and potassium atmosphere of the Moon and its interaction with the surface. *Icarus* **96.** 27–42.

STERN. S. A.. AND B. C. FLYNN 1995. Narrow-field imaging of the lunar sodium exosphere. *Astron. J.* **209.** 835–840.

TAYLOR. S. R. 1982. *Planetary Science: A Lunar Perspective.* Lunar and Planetary Institute. Houston.

TYLER. A.. R. KOZLOWSKI. AND D. HUNTEN 1988. Observations of sodium in the tenuous lunar atmosphere. *Geophys. Res. Lett.* **15,** 1141.

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. © 1997 Academic Press

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 5×10^4 cm^{-3}.

In 1988, ground-based work detected two additional lunar atmospheric species, Na and K (Potter and Morgan 1988a, Tyler *et al.* 1988). This landmark work renewed interest in the lunar atmosphere, in part because it made ground-based observations of this tenuous exosphere possible for the first time. The combined, near surface number density of Na and K in the lunar atmosphere is $<10^2$ cm^{-3}. Various spectroscopic studies (e.g., Potter and Morgan 1988b, Sprague *et al.* 1992, Stern and Flynn 1995) have built a case that much of the lunar Na is created through energetic, nonthermal processes that populate a corona many lunar radii in diameter. These findings were later dramatically confirmed by images of the Na D lines at 5890 Å during a lunar eclipse, which directly revealed Na emission out to a distance of ≈9 lunar radii (R_M; 2.3°) from the lunar center (Mendillo and Baumgardner 1995). Taken together, the four known lunar atmsopheric species, Ar, He, Na, and K, comprise only 5–10% of the total measured gas number density (cf. Morgan and Stern 1991). This fact implies that the composition of most of the lunar atmosphere remains unknown.

A few years ago, Feldman and Morrison (1991) reanalyzed data from the Apollo 17 Ultraviolet Spectrometer (Fastie *et al.* 1973) and convincingly showed that C, N, O, H, CO, and Xe were not detected and cannot provide the "missing mass" of the lunar atmosphere. More recently, Flynn and Stern (1996, hereafter F&S96) reported results from a ground-based search for potentially undiscovered lunar atmsopheric metals that might be created by the same sputtering source process(es) that create Na and K. F&S96 reported constraining upper limits on a host of species, including Ti, Fe, Ca, Li, Rb, Cs, Si, and Al.

In what follows we report the results of the first survey of the 2200–3300 Å mid-UV region of the lunar atmosphere. This search yielded useful
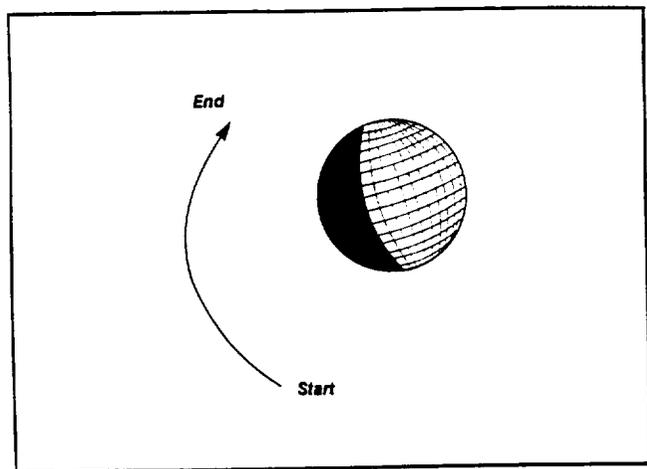
FIG. 1. The geometry of the 1996 October 6.9 lunar atmosphere HST observations. North is up in this illustration. The illuminated portion of the Moon is to the right (west) of the terminator. The trajectory of the FOS aperture around the Moon was created primarily by the changing parallax of the Moon as seen from HST during the observation.

upper limits on Mg. Mg⁺, and the potentially important daughter product of H_2O. the OH radical; new but less constraining upper limits on Al and Si were also obtained.

Observations. The highly extended nature of the lunar Na corona opens the door to Hubble Space Telescope (HST) studies by allowing observations far enough from the surface to overcome the lunar avoidance angle limits of HST.

We obtained data from the HST Faint Object Spectrograph (FOS) and High Resolution Spectrograph (HRS). The FOS observations were centered at UT 1996 October 6.96 (Project GO-6513). The objective of the FOS observation was to obtain a moderate resolution ($R \approx 1000$) survey spectrum of the lunar atmosphere to search for bright mid-UV emissions without bias to the possible composition of the atmosphere. The purpose of the HRS observations. which were taken in the ~120 min prior to the FOS spectrum. was to obtain more sensitive. high-resolution ($R \approx 10,000$) échella spectra in narrow bandpasses around three particular atomic emissions: Si I (2516 Å), Mg I (2852 Å), and Al I (3092 Å). The higher spectral resolution of the HRS increases its sensitivity to faint lines over that of the FOS by reducing the "noise" contributed by scattered lunar surface continuum in the telescope.

Unfortunately, the HRS was misconfigured, causing the wrong échelle orders to be used. As a result. no useful data were obtained. Fortunately. however. the FOS dataset was properly obtained by HST and provides new and useful information.

The FOS observations were made using the FOS's BLUE digicon detector and its G270H grating. which yielded a spectrum over the wavelength range from 2222 to 3301 Å. We used the largest available FOS aperture. which measures 3.66 × 3.7 arcsec². and obtained a total exposure time of 820.0 sec.

Owing to HST bright object avoidance constraints. the FOS aperture was not allowed to approach closer than 0.3° (1.2 R_M) to the lunar limb. Figure 1 shows the path of the FOS aperture in lunar-centered coordinates during the lunar atmosphere observation. which occurred on 6 October 1996.

Results. We inspected the FOS spectrum in various ways in order to search for possible emission features. The upper panel of Fig. 2 shows the accumulated FOS spectrum. in flux units. with a solar spectrum for comparison. Although the Moon itself never entered the FOS field of view. the FOS spectrum consists primarily of scattered moonlight.[1] Superimposed on this scattered light would be any UV emission from species in the lunar atmosphere.

The lower panel of Fig. 2 shows the residual created by subtracting a scaled version of the Upper Atmospheric Research Satellite/Solar Ultraviolet Irradiance Monitor (UARS/SUSIM) solar spectrum from the HST/FOS lunar spectrum (cf. Van Hoosier *et al.* 1988). This subtraction demonstrates that no lunar atmosphere spectral features can be detected by visual inspection of either the FOS raw spectrum or the residual spectrum obtained after removal of the solar spectrum by subtraction.

In Table I we present upper limits derived for atomic Si. Mg. and Al. as well as the OH molecule and the Mg⁻ ion. These upper limits correspond to the brightness of a highly conservative 5σ fluctuation in the local noise level at the location of each of the prospective emission features of interest.

Presented alongside the upper limits given in Table I are model predictions for each neutral atomic species. The predictions for the Si. Mg. and Al neutrals were derived using the stoichiometric atmosphere model recently discussed by F&S 96. They correspond to the predicted brightness of each species at the time-weighted average altitude of the observations (3.1 R_M from the center. 2.1 R_M above the limb) obtained by scaling for the surface abundance. scale height. and atomic resonance fluorescence coefficient ratios relative to Na. In preparing these estimates. we assumed that these species exhibit the same (~1000 K) suprathermal density distribution that sodium does. In computing the model predictions. we corrected for the penetration of the FOS line of sight through the lunar shadow: this factor reduced the model brightnesses by a factor of 2 over a fully sunlit line of sight with the same impact parameter.

The results presented in Table I represent the first spectroscopic constraints on the neutral Mg and singly ionized Mg in the lunar atmosphere. Owing to the short lifetime of ions in the lunar atmosphere. which is open to the solar wind electric field. the nondetection of Mg⁻ by the FOS is not unexpected.[2] However. the nondetection of the Mg neutral was rather unexpected. and allows us to impose a strong constraint. corresponding to a 9:1 or greater depletion relative to the stoichiometric model. Although 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&SS96.

Conclusions and interpretation. A search for resonant scattering mid-UV emissions above the lunar limb detected no spectral features. At the 5σ confidence level. these nondetections correspond to ≈15 R for Si I (Al 2516 Å). ≈19 R for the Mg II doublet (2797 Å). ≈53 R for Mg I (2852 Å). ≈74 R for Al I (3092 Å). and ≈67 R for OH (3085 Å). Of these. the Mg I (2852 Å) constraint provides the most significant new information.

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.

The Mg finding is in agreement with our earlier. ground-based search for a variety of other surface-derived metallic neutrals (cf. F&S96). 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.

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[1] We verified this by its lunar-like color slope at wavelengths longward of 2650 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] But see Hilchenbach *et al.* 1991 for evidence of a possible *in situ* detection.
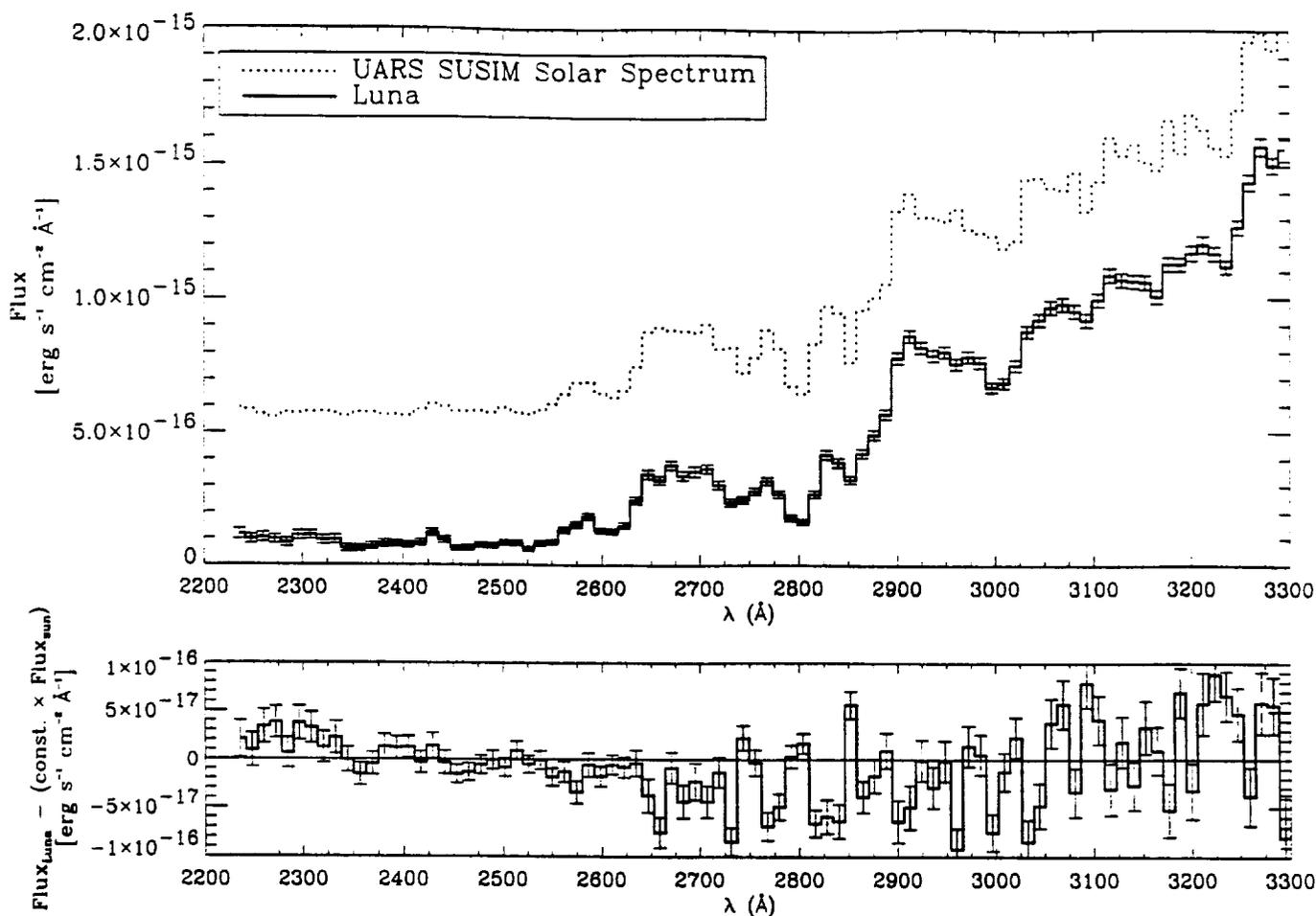
FIG. 2. (*Upper panel*) The flux spectrum obtained by the FOS near the Moon on 1996 October 6.9 (solid line, with error bars), compared to the average of three full-disk solar spectra obtained by the UARS SUSIM instrument on 1996 October 5–7, binned to the FOS resolution (dotted line). The solar spectrum has been scaled by a constant multiplier to fit on the same scale as the lunar spectrum. The FOS spectrum is dominated by scattered moonlight and reveals no obvious atmospheric emissions at wavelengths indicated by the labels (*Lower panel*) The residual spectrum created by subtracting the scaled version of the UARS SUSIM solar spectrum shown in the upper panel from the HST/FOS lunar atmosphere spectrum. Error bars depict only the statistical uncertainty of the HST spectrum, since we have no information on the UARS solar spectrum error budget; quadrature sums of FOS+UARS errors would be larger. The lack of species detection is clear.

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_r, SiO_r, and AlO_r.

In closing, we find it worthwile 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

Species	λ_0	Upper limit brightness (5σ)	Model brightness $(3.1\ R_M)$
Si I	2516 Å	15 R	002 R
Mg II	2797 Å	19 R	N/A
Mg I	2852 Å	53 R	476 R
Al I	3092 Å	74 R	002 R
OH (0–0)	3085 Å	67 R	N/A

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_M 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

Fastie. W. C., P. D. Feldman. R. C. Henry, H. W. Moos, and T. M. Donahue 1973. A search for far-ultraviolet emissions from the lunar atmosphere. *Science* **182**, 710–711.

Feldman. P., and D. Morrison 1991. The Apollo 17 ultraviolet spectrome-

ter: Lunar atmosphere measurements revisited. *Geophys. Res. Lett.* **18**, 2105–2108.

Flynn. B. C., and S. A. Stern 1996. A spectroscopic survey for metallic species in the lunar atmosphere. *Icarus* **124**, 530–536.

Hilchenbach. M., D. Hovestadt B. Klecker. and E. Mobius 1991. Detection of singly ionized energetic lunar pick-up ions upstream of Earth's bow shock. in *Proceedings of Solar Wind 7. Goslar* (E. Marsch and G. Schwenn. Eds.). Pergamon. Elmsford. NY.

Johnson. R. E., and R. Baragiola 1991. Lunar surface: Sputtering and secondary ion mass spectrometry. *Geophys. Res. Lett.* **18**, 2169–2172.

Kozlowski. R. W. H., A. L. Tyler. and D. M. Hunten 1990. An extended potassium component in the lunar exosphere. *Geophys. Res. Lett.* **19**, 642–646.

Mendillo. M., and J. Baumgardner. 1995. Detection of the Moon's extended atmosphere during solar eclipse. *Nature* **377**, 404–406.

Morgan. T. H., and D. E. Shemansky 1991. Limits to the lunar atmosphere. *J. Geophys. Res.* **96**, 1351–1367.

Morgan. T. H., and S. A. Stern 1991. Revived interest in the lunar atmosphere. *Eos* **72**, 225–228.

Na, C. Y., L. M. Trafton. E. S. Barker. and S. A. Stern 1997. A search for new species in Io's extended atmosphere. *Icarus*. submitted.

Potter. A. E., and T. H. Morgan 1988a. Discovery of sodium and potassium vapor in the atmosphere of the Moon. *Science* **241**, 675–680.

Potter. A. E., and T. H. Morgan 1988b. Extended sodium exosphere of the Moon. *Geophys. Res. Lett.* **15**, 1515–1518.

Sprague. A. L., R. W. Kozlowski. D. M. Hunten. W. K. Wells. and F. A. Grosse 1992. The sodium and potassium atmosphere of the Moon and its interaction with the surface. *Icarus* **96**, 27–42.

Sprague. A. L., R. W. Kozlowski. D. M. Hunten. and F. A. Grosse 1993. An upper limit on neutral calcium in Mercury's atmosphere. *Icarus* **104**, 33–37.

Sprague. A. L., D. M. Hunten. and F. A. Grosse 1996. Upper limit for lithium in Mercury's atmosphere. *Icarus* **124**, 345–349.

Stern. S. A., and B. C. Flynn 1995. Narrow-field imaging of the lunar sodium exosphere. *Astron. J.* **109**, 835–841.

Tyler. A. L., R. W. Kozlowski. and D. M. Hunten 1988. Observations of sodium in the tenuous lunar atmosphere. *Geophys. Res. Lett.* **15**, 1141–1144.

Van Hoosier. M. E., J.-D. F. Bartoe. G. E. Bruekner. and D. K. Prinz 1988. The solar ultraviolet spectral monitor. *Astron. Lett. Comm.* **27**, 163–168.