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Radial Velocity Observations of the Extended Lunar Sodium Tail

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Radial velocity observations of the extended lunar sodium tail

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[1] We report the first velocity resolved sodium 5889.950 Å line profile observations of the lunar sodium tail observed in the anti-lunar direction near new Moon. These observations were made on 29 March 2006, 27 April 2006 and 28 April 2006 from Pine Bluff (WI) observatory with a double etalon Fabry-Perot spectrometer at a resolving power of ~80,000. The observations were made within 2–14 hours from new Moon, pointing near the anti-lunar point. The average observed radial velocity of the lunar sodium tail in the vicinity of the anti-lunar point for the three nights reported was 12.4 km s^{-1} (from geocentric zero). The average Doppler width of a single Gaussian fit to the emission line was 7.6 km s^{-1}. In some cases the line profile appears asymmetric, with excess lunar sodium emission at higher velocity (~18 km s^{-1} from geocentric zero) that is not accounted for by our single Gaussian fit to the emission.

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1. Introduction

[2] An extended tail of lunar sodium atoms over 400,000 km long was discovered by a team from Boston University (BU) in 1999 with an all sky imaging device [see *Smith et al.*, 1999, 2001]. The observations presented here are the first of the extended sodium tail's radial velocity structure, observed in the anti-lunar direction near the time of new Moon (i.e., looking down tail as it moves beyond the Earth, along the Sun–Moon–Earth line).

[3] The Moon is known to possess a rarefied atmosphere of helium, argon, sodium, potassium, and other trace species. These gasses are released from the lunar surface by several mechanisms, including photon, ion and chemical sputtering, thermal desorption, and meteoric impact vaporization; the relative importance of each of these processes remains somewhat uncertain. Refer to *Stern* [1999] and *Wilson et al.* [2006] for further details.

[4] Sodium atoms emit two well known "D-lines" at 5895.924 Å (D_1) and 5889.950 Å (D_2). This sodium D-line emission (excited by solar resonant scattering) has been used since the late 1980s to observe remotely the morphology and dynamics of the lunar sodium atmosphere, starting with the detection of sodium in the Moon's atmosphere by *Potter and Morgan* [1988a] and *Tyler et al.* [1988]. *Potter and Morgan* [1988a] observed sodium D_2 emission out to a distance of 40 km above the bright limb of the Moon, and estimated a sodium zenith column density of ~8 × 10^8 atoms cm^{-2} (with a surface density of ~70 atoms cm^{-3}). Additional observations by *Potter and Morgan* [1988b], and those of *Tyler et al.* [1988], extended this detection out to 1200 km above the subsolar point. Refer to the review by *Stern* [1999] for further discussion.

[5] *Mendillo et al.* [1991] obtained the first imaging observations (D_1 + D_2) of the extended lunar sodium atmosphere, observing emission out to ~5 lunar radii (R_m) on the dayside, and out to 15–20 R_m in a "tail-like" structure on the nightside. *Mendillo et al.* [1991] qualitatively describe the morphology of the lunar sodium atmosphere much like that of a comet, "with a bright (sodium) coma centered on the Moon and an extended (sodium) tail extending away in the antisunward direction".

[6] Employing a wide-angle imaging system, *Wilson et al.* [2003] observed the full coma of the lunar sodium exosphere (during the 16 July 2000 lunar eclipse) out to ~20 R_m, and used these observations to constrain the high-end speed distribution of lunar sodium exosphere source processes. The model-data comparisons by *Wilson et al.* [2003] indicate that ≤20% of the escaping sodium atoms are ejected from the lunar surface with speeds greater than the lunar escape velocity (2.4 km s^{-1}) and therefore, solar radiation pressure is largely responsible for most of the sodium escape into the Moon's outer exosphere and sodium tail.

[7] Sodium D-line emission has also been used to study the Earth's daytime and twilight mesosphere (at an altitude of ~90 km) through resonant scattering emission, and deep into the night through photochemical reactions [see, e.g., *Chamberlain and Hunten*, 1987]. On several evenings in August and November 1998, a team from BU was making mesospheric sodium observations, using an all sky imaging system with a sodium filter [see *Baumgardner et al.*, 1993], when they detected a bright sodium emission feature approximately 3 degrees in diameter in the night sky [*Smith et al.*, 1999]. This feature was detected close to the time of new Moon and located near the anti-solar/lunar point; it also exhibited an eastward drift of ~3–4° per day [*Smith et al.*, 1999]. On nights before new Moon (21 August 1998 and 18 November 1998) the feature had the appearance of a "comet-like streak" and on nights closest to new Moon (22 August 1998 and 19 November 1998), the "emission feature was brightest and exhibited a more circular or elliptical shape" [*Smith et al.*, 1999]. *Smith et al.* [1999] concluded that this emission feature (or "spot") was consistent with a lunar origin, and that it was in fact an extension of the lunar sodium tail [see, e.g., *Mendillo et al.*, 1991] observed past the Earth out to hundreds of R_m.

[8] In a companion modeling paper, *Wilson et al.* [1999] showed that the location and morphology of the lunar sodium spot can be explained by steady-state models of

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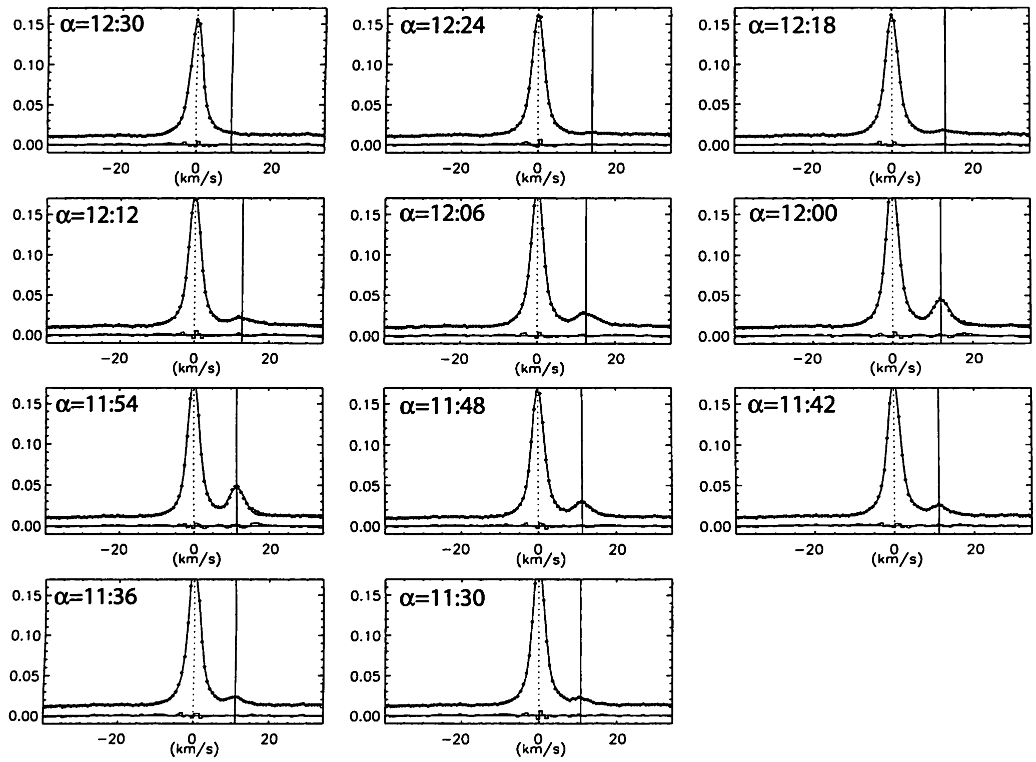

Figure 1. Velocity resolved spectra of the lunar sodium tail observed in the anti-lunar direction (new Moon, 29 March 2006). Right ascension α (hours:minutes) decreases by 6^m (1.5°) intervals from the upper left to lower right. Terrestrial sodium emission is indicated by a vertical dashed line; lunar sodium is indicated by a vertical solid line. The velocity scales (abscissa) are referenced to the geocentric rest frame. The intensity scales (ordinate) are in arbitrary units (but consistent between spectra). Refer to Table 1 for calibrated terrestrial and lunar sodium intensities and lunar sodium Doppler widths and shifts.

the Moon's sodium atmosphere, and that the observations are consistent with the lunar sodium tail as seen in the anti-lunar direction at a distance of over 400,000 km and 2 days from its origin at the Moon. Note, the November BU all-sky observations were taken two days after the peak of the Leonid meteor shower and these observations indicate that the lunar sodium spot was enhanced by as much as a factor of five during the meteor storm, presumably due to micro-meteor impacts on the Moon which led to an increase in the lunar sodium escape flux [*Wilson et al.*, 1999]. Subsequent observations indicate that this feature is a regular occurrence in the night sky near the time of new Moon, with a maximum brightness (D_1 + D_2) between 15– 90 Rayleighs (R) [*Smith et al.*, 2001]. Due to the broadband nature (~19 Å FWHM) of the BU imager, no velocity resolved spectral information was obtained.

2. Instrumentation

[9] The velocity resolved line profile observations presented here were carried out with a large aperture (15 cm), double etalon, Fabry-Perot annular summing spectrometer located at the Pine Bluff Observatory (PBO), University of Wisconsin–Madison (43.07°N, 270.33°E). The PBO Fabry-Perot is coupled to a siderostat with a circular 1.5° field-of-view on the sky, and is capable of sampling a 75 km s^{-1} spectral interval with ~3.5 km s^{-1} spectral resolution at 5890 Å. Broadband etalon coatings and a pressure control system allow the 75 km s^{-1} spectral window to be set anywhere between 4500 and 9000 Å. Refer to *Mierkiewicz et al.* [2006] for further details.

3. Observations

[10] We report the first velocity resolved sodium 5889.950 Å (D_2) line profile observations of the lunar sodium tail observed in the anti-lunar direction near new Moon. Our observations were obtained from PBO on the nights of 29 March 2006, 27 April 2006, and 28 April 2006. The PBO Fabry-Perot was tuned to 5889.950 Å, and the bandpass was set to place the terrestrial sodium emission near the center of the 75 km s^{-1} spectral window.

[11] The first observation on 29 March 2006 (~3 hours before new Moon) was taken near the anti-solar point at right ascension (α) 12^h 30^m (187.5°) and declination (δ) −3.3° (7:00 UTC); the integration time was 300 s. Ten subsequent 300 s observations were made, stepping the Fabry-Perot's 1.5° field-of-view 6^m 15° west after each integration, while holding δ fixed.

[12] Figure 1 shows eleven sodium D_2 spectra obtained with the PBO Fabry-Perot 29 March 2006. Terrestrial sodium emission in each of the spectra is indicated by a vertical dashed line; lunar sodium is indicated by a vertical solid line. In Figure 2 the terrestrial components have been removed in order to highlight the lunar sodium emission. Individual spectra are plotted sequentially as a function of decreasing α; dotted lines separate each 1.5° step on the sky. The intensity, Doppler width, and Doppler shift (from

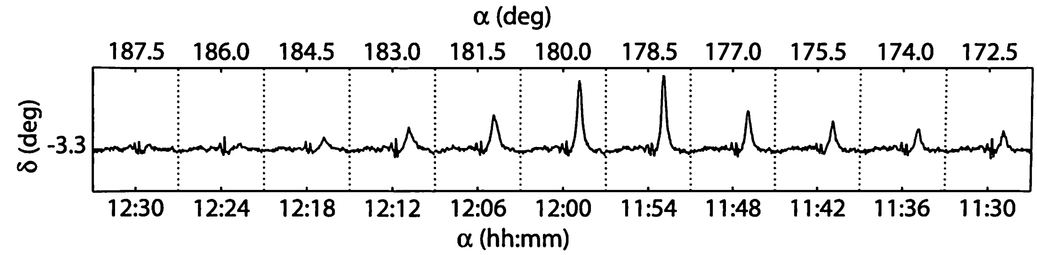

Figure 2. The terrestrial emission in Figure 1 has been removed in order to highlight the lunar sodium emission. Individual spectra are plotted as a function of decreasing α; dotted lines separate each 6^m (1.5°) step west in α of the PBO Fabry-Perot's 1.5° field-of-view. A peak in the lunar sodium emission is apparent near $\alpha = 11^h\ 54^m$, $\delta = -3.3°$.

geocentric zero) for each of the lunar sodium spectra obtained on 29 March 2006 are listed in Table 1.

[13] Individual spectra were reduced with a three component Gaussian model: two linked Gaussians were used to fit the terrestrial sodium emission and third Gaussian component was used to fit the lunar sodium emission. The weighted mean (i.e., centroid) of the two component terrestrial fit was used to set the geocentric rest frame. Intensity calibration is based on the surface brightness of NGC 7000 ("North American Nebula"; coordinates $\alpha_{2000} = 20.97^h$, $\delta_{2000} = 44.59°$). The NGC 7000 hydrogen Balmer α surface brightness is ~650 R over the PBO Fabry-Perot's 1.5° field-of-view [*Mierkiewicz et al.*, 2006]. Based on our calibration at Balmer α, sodium D_2 line intensities were determined assuming an average transmission for the PBO site, and a filter transmission correction of T(5890 Å)/T(6563 Å) ~0.8. We estimate a 30% uncertainty in our sodium D_2 intensity calibration.

[14] Lunar sodium line profile observations were repeated on the nights of 27 April 2006 and 28 April 2006, ~14 hour before and ~9 hours after new Moon (19:44 UTC, 27 April 2006). The spatial variation of the emission was mapped using a grid of observations with steps of 6^m in α and 1.5° in δ; refer to Figure 3 and Figure 4. The intensities, Doppler widths, and Doppler shifts for nine spectra near the peak lunar emission (indicated by the gray regions in Figures 3 and 4) are included in Table 1.

[15] The lunar sodium Doppler widths reported in Table 1 are not corrected for instrumental broadening. Based on our work with this instrument at Balmer α [see *Mierkiewicz et al.*, 2006], we estimate the width of the instrumental function to be ~3.5 km s^{-1} at 5890 Å. Assuming purely Gaussian line shapes, an estimate for the deconvolved Doppler width of the lunar sodium emission can be determined by $w_a = (w_m^2 - w_{IP}^2)^{1/2}$, where w_a, w_m, and w_{IP} are the actual, measured, and instrumental Doppler widths respectively.

4. Discussion

[16] The peak observed lunar sodium D_2 intensities were: ~7 R for 29 March 2006 (near $\alpha = 11^h\ 54^m$, $\delta = -3.3°$), ~6 R for 27 April 2006 (near $\alpha = 13^h\ 44^m$, $\delta = -12.0°$), ~9.8 R for 28 April 2006 (near $\alpha = 14^h\ 02^m$, $\delta = -13.5°$). The average terrestrial sodium D_2 intensity during the course of our observations was ~30 R in March, and ~34 R in April. In the ~24 hour period between the 27 April and 28 April observations, the peak position of the lunar sodium emission shifted 1.5° south and 18^m (4.5°) east, consistent with the 3–4° eastward drift observed by *Smith et al.* [1999]. The position of the anti-lunar spot moved 5.2° south and 46^m east in this same time period.

[17] *Smith et al.*'s [1999, 2001] lunar sodium $D_1 + D_2$ intensities range from 15–90 R, with a quiescent peak intensity of 19 ± 6 R. Scaling our intensities to represent combined $D_1 + D_2$ emission (by assuming a D-line intensity ratio of $I(D_2)/I(D_1) = 2$), our observations fall on the low end of the *Smith et al.* [1999] quiescent peak intensity.

[18] On 29 March 2006 the average radial velocity of the lunar sodium tail observed in the vicinity of the anti-lunar

Table 1. Terrestrial (I_T) and Lunar (I_L) Sodium D_2 Intensities, and Lunar Sodium Doppler Shifts (Δv) and Widths (Δw)[a]

Time, UTC	α, hh:mm	δ, °	I_T, R[b]	I_L, R[b]	Δv, km s^{-1}	Δw,[c] km s^{-1}
29 March 2006 (New Moon: 10:15 UTC 29 March 2006)						
7:00	12:30	−3.3	26	0.37	9.4	4.0
7:07	12:24	−3.3	28	0.58	14.0	6.9
7:14	12:18	−3.3	27	1.3	13.4	6.9
7:20	12:12	−3.3	29	2.8	12.8	7.6
7:29	12:06	−3.3	31	4.3	12.6	7.0
7:37	12:00	−3.3	33	6.8	12.1	5.3
7:44	11:54	−3.3	31	6.9	11.5	4.9
7:51	11:48	−3.3	29	3.9	11.4	5.5
8:01	11:42	−3.3	30	2.7	11.2	5.4
8:11	11:36	−3.3	32	2.0	11.1	5.1
8:19	11:30	−3.3	33	1.7	10.8	5.3
27 April 2006 (New Moon: 19:44 UTC 27 April 2006)						
6:32	13:50	−12.0	28	2.5	15.3	14.0
6:39	13:44	−12.0	29	5.9	14.3	9.2
6:46	13:38	−12.0	31	4.7	12.8	7.4
5:43	13:50	−13.5	30	3.5	12.0	8.1
5:49	13:44	−13.5	29	4.2	11.7	6.6
5:55	13:38	−13.5	28	3.7	11.4	5.6
6:26	13:50	−15.0	30	2.5	11.4	8.6
6:20	13:44	−15.0	31	2.7	11.1	6.3
6:14	13:38	−15.0	31	3.1	10.8	5.8
28 April 2006 (New Moon: 19:44 UTC 27 April 2006)						
5:06	14:08	−12.0	34	2.7	13.1	13.4
5:00	14:02	−12.0	36	4.0	15.1	13.0
4:58	13:56	−12.0	36	3.9	13.7	9.7
4:10	14:08	−13.5	43	3.4	13.0	9.3
4:16	14:02	−13.5	40	9.8	14.8	9.5
4:22	13:56	−13.5	40	5.8	13.0	8.7
2:57	14:08	−15.0	38	4.1	12.0	5.9
3:03	14:02	−15.0	38	5.0	12.4	6.6
3:09	13:56	−15.0	34	1.4	11.7	5.9

[a]Single Gaussian fit to the lunar sodium emission.
[b]1R = $10^6/4\pi$ photons cm^{-2} s^{-1} str^{-1}; the uncertainty in the PBO sodium intensity is 30%.
[c]Not corrected for instrumental broadening.

point was 11.8 ± 1.2 km s^{-1}; the average (single Gaussian) Doppler width was 5.8 ± 1.1 km s^{-1}. On 27 April 2006 and 28 April 2006, the average radial velocities of lunar sodium tail were 12.3 ± 1.6 km s^{-1} and 13.2 ± 1.1 km s^{-1} respectively; the average (single Gaussian) Doppler widths were 8 ± 2.4 km s^{-1} (27 April) and 9.1 ± 2.6 km s^{-1} (28 April). In some cases the line profile appears asymmetric (see e.g., α = 12:00 and α = 11:54 in Figure 1), with excess lunar sodium emission at higher velocity (~18 km s^{-1} from geocentric zero) that is not accounted for by our single Gaussian fit to the emission.

[19] The 29 March 2006 observations were obtained 2–3 hours before new Moon, whereas the 27 April 2006 and 28 April 2006 observations were obtained approximately 14 hours before and 9 hours after new Moon respectively. In the context of this limited data set, the observed velocity distribution near new Moon appears to be narrower and more sharply peaked than observations obtained −14 and +9 hours from new Moon. The projection of the lunar tail along the line of sight may be in part responsible for the larger distribution of observed speeds ~12 hours off new Moon compared to the observations of 29 March 2006 which were near new Moon.

[20] If we assume a constant acceleration of 2.7 × 10^{-5} km s^{-2} from radiation pressure due to the flux at the center of the solar Fraunhofer D_2 line [see e.g., *Mendillo et al.*, 1991], it will take 4.2 days (and 2.7 × 10^6 km) for escaping lunar sodium atoms (with an initial velocity of 2.4 km s^{-1}) to reach our observed average velocity of 12.4 km s^{-1}. *Wilson et al.* [1999] have reported that the emitting sodium atoms have traveled a distance of over 400,000 km from the Moon in 2 days. This discrepancy may be due in part to our assumption of constant acceleration by radiation pressure since our measured mean velocity of the sodium atoms is a significant fraction of the half-width-at-half-maximum of the solar Fraunhofer D_2 line (19 km s^{-1}). Furthermore, the geometry at new moon may mean that the Earth's gravitational focusing of the lunar sodium tail may be contributing to the observed velocity.

[21] In summary, the average observed radial velocity of the lunar sodium tail observed in the vicinity of the anti-lunar point for the three nights reported here was 12.4 km s^{-1}. The average Doppler width of a single Gaussian fit to the emission line for all nights was 7.6 km s^{-1}.

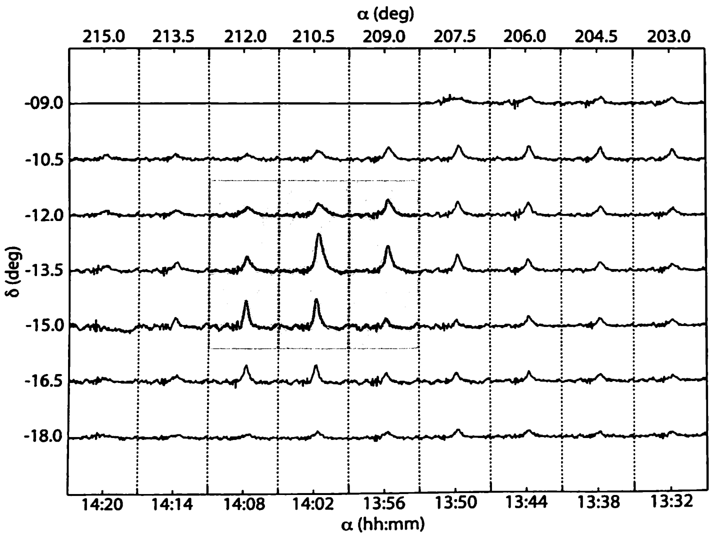

Figure 4. A map of the lunar sodium tail observed in the anti-lunar direction (~12 hours after new Moon, 28 April 2006). Refer to Figure 3's caption for further details.

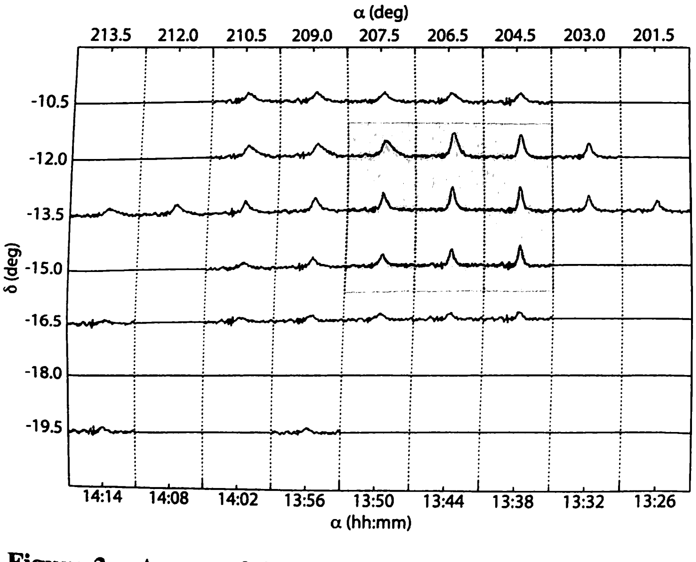

Figure 3. A map of the lunar sodium tail observed in the anti-lunar direction (~12 hours before new Moon, 27 April 2006). The ordinate is in degrees of declination, the abscissa in hours and minutes (and decimal degrees) of right ascension. The terrestrial emission has been removed for clarity. Each grid point (delineated by dotted lines) represents one pointing of the PBO Fabry-Perot's 1.5° field of view. Refer to Table 1 for terrestrial and lunar sodium intensities, and lunar sodium Doppler widths and shifts for the nine spectra highlighted by the gray box.

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