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Discovery of the Distant Lunar Sodium Tail and its Enhancement Following the Leonid Meteor Shower of 1998

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Abstract.
Night-time measurements using a bare CCD all-sky imaging system have detected the presence of an extensive region of neutral sodium emission (589.1 nm) in the direction of the anti-solar/lunar points. The emission was observed to occur during the nights of 21–22 August and 18–20 November, 1998 UT, centered on the new Moon period. The Moon is the most likely source of the neutral sodium, making this the first detection of the lunar sodium tail out to a distance of hundreds of lunar radii. The greater brightness of the emission feature on 19 November is attributed to the Leonid meteor shower which peaked on 17 November, 1998, less than two days before new Moon.

1. Introduction

The prediction of possible Leonid "meteor storm level" fluxes for 1998 and 1999 (Yeomans *et al.*, 1996) has mobilized the lunar observing community to search for enhancements to the lunar sodium atmosphere and its extended component. Hunten *et al.* (1991) were the first to offer evidence for such an effect from a sporadic source, and suggested an as yet unknown meteor shower as the cause. Verani *et al.* (1998) presented evidence for an enhancement during the 1996 Leonid meteor shower and initial results for the 1997 Leonids (Hunten *et al.*, 1998) offer evidence that is "mildy supportive of the idea that an enhancement was observed".

As pointed out by Hunten *et al.* (1998), the 16–17 November, 1998 event precluded direct observations of circumlunar locations due to the Moon's proximity to the Sun (new Moon occurred on 19 November). In this study, we describe observations made in the anti-solar/Moon direction that show strong evidence for both a remarkably long lunar Na tail and a Leonid-induced two to three-fold enhancement in its brightness.

2. The Imaging System

The observations were made using an all-sky camera system in which the standard image-intensified CCD was replaced by a 1024 x 1024 pixel back-illuminated, bare CCD (Baumgardner *et al.*, 1993). The all-sky camera system was being used to routinely image gravity wave activity in the mesospheric neutral sodium (589.1 nm, FWHM = 1.9 nm) and atomic oxygen (557.7 nm, FWHM = 1.2 nm) layers near 90 and 96 km, respectively (Smith *et al.*, 1999), using 120 s integrations during the Leonid meteor shower. An off-band image at 644.4 nm (FWHM 1.4 nm) was acquired every 30 minutes.

3. Observations

All-sky observations were made spanning the new Moon periods of August and November, 1998, at the Boston University Station at the McDonald Observatory, in Fort Davis, Texas (30°49′18″N, 104°01′18″W). An unusual Na emission feature was observed on two nights in August and three nights in November. The feature was always situated near the anti-solar point. Its morphology and brightness changed nightly, but its size was approximately 3° x 3° (full-width at half-brightness, FWHM). Figure 1 shows two examples of raw images taken on 19 and 20 November 1998 UT. Despite imaging on other nights, the Na "spot" feature was only seen on the three nights spanning new Moon. Most importantly, the emission was spectral in nature, being only visible at the sodium wavelength (589.1 nm) and not at any of the other wavelengths observed. All-sky images at 769.9 nm (FWHM = 1.4 nm), due to neutral potassium (K) emission, which was first reported in the lunar atmosphere by Potter and Morgan (1988), were also obtained over a 3-hour period on 20 November. Assuming a Na/K brightness ratio of 2.1 (Potter and Morgan, 1988), and using the Na emission feature brightness on 20 November (Table 1), one might expect ~20 Rayleighs (R) due to K emission, but a K emission feature was not detected.

Figure 2 (a–e) shows time-averaged images of the sodium emission region on the nights 21–22 August and 19–20 November, 1998 UT. They were obtained by co-adding and averaging together a number of bias and off-band subtracted images for each night. Spatial distortion inherent in the images was removed by using known star positions. The images were then mapped onto the Earth's surface using a Mercator projection and converted into astronomical coordinates. The un-

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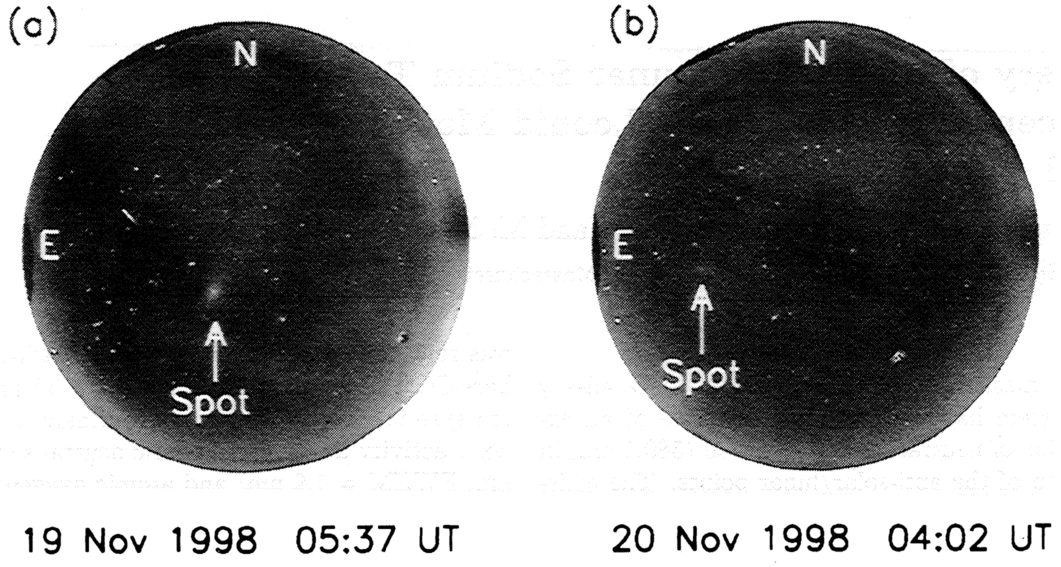

Figure 1. Two examples of raw CCD all-sky images taken in sodium emission on consecutive nights (19 and 20 November, 1998) at the McDonald Observatory. The Na emission feature is marked with an arrow in both images. The constellations of Orion and Taurus are seen in the East in the 19 November image, along with a meteor trail (a). The general glow throughout the two images is due to the mesospheric sodium layer near 90 km altitude. An extensive gravity wave event is visible propagating through the layer in the 20 November image (b).

certainty in the size and position of the emission feature was less than 2%. Spatial and temporal variations in the terrestrial Na emission (see Figure 1b), were minimized by time-averaging. The average zenith brightness of the terrestrial Na emission during August and November was 50 R and 100 R, respectively; and the wave variations were typically 10 R. The time-averaged images were calibrated using standard calibration techniques (Mendillo *et al.*, 1999). Table 1 lists the feature's central brightness during each night.

There were similarities in the feature's morphology and brightness at similar lunar phases during August and November. In the images one night before new Moon (21 August and 18 November) (Panels a and c), the feature was a comet-like streak. On the nights closest to new Moon (22 August and 19 November), the emission feature was brightest and exhibited a more circular or elliptical shape (Panels b and d). At this lunar phase, the Na feature was brighter in November than in August by a factor of nearly five. On the night after new Moon (20 November), the emission region was dimmer, more elongated and fan-shaped (Panel e). The feature was below the detection limit (<4–5 R) on 17 and 22 November (Table 1).

Table 1. Measured parameters of the sodium spot region. The calibration uncertainty is due primarily to the standard deviation of the background noise.

Date 1998 (UT)	Observing Period (UT)	Mid-Observing Time (UT)	R.A. 2000.0 (h m s)	Dec. 2000.0 (° ′ ″)	Size (FWHM) (° × °)	Peak Brightness (R)	Remarks
20 Aug.	–	–	–	–	–	–	no data
21 Aug.	06:45–08:50	07:48	21 29 53	−13 56 22	7.5×2.2	12±4	streak
22 Aug.	04:30–05:22	04:56	21 41 55	−14 08 09	1.6×1.3	19±6	circular
23 Aug.	–	–	–	–	–	–	no data
17 Nov.	03:38–08:28	06:02	–	–	–	–	not det.[a]
18 Nov.	03:31–05:43	04:37	02 59 13	+14 48 24	3.8 × 3.3	22±5	streak
19 Nov.	04:31–09:02	06:47	03 15 09	+16 54 02	3.2 × 2.4	90±4	ellip.
20 Nov.	02:48–04:44	05:32	03 26 01	+17 59 24	3.3 × 1.7	38±4	v. ellip.
21 Nov.	–	–	–	–	–	–	no data
22 Nov.	05:32–09:31	07:30	–	–	–	–	not det.[a]

[a] Not detected.

4. Possible Sources

We have ruled out several possible sources; firstly, the Na spot remained in the same region of the sky from night to night and exhibited a sidereal motion; hence, it could not be related to atmospheric gravity wave activity which was clearly seen in the imaging data during both periods. No bright comets were reported in this region of sky in August or in November, and the spot's narrow spectral emission range would also tend to preclude a direct cometary origin.

The feature was not due to emission from Na atoms in an undetected dust cloud at either the Earth-Sun L_2 Lagrangian point (~0.01AU in the anti-solar direction from the Earth) or the Earth-Moon L_3 Lagrangian point (~400,000 km away in the anti-lunar direction); material residing at the solar L_2 point would exhibit a daily eastward motion of ~1° per day, and material residing at the lunar L_3 point would exhibit a daily eastward motion of ~13° per day. The sodium emission region exhibited an eastward motion of 3–4° per day, in both August and November, which is inconsistent with material at either Lagrangian point.

The feature was also not the gegenschein, a brightening of the zodiacal light at the anti-solar point that is generally believed to be preferential back-scattering of solar radiation by interplanetary zodiacal dust (Weinberg and Sparrow, 1978). The zodiacal light was detected at 589.1 nm and 644.4 nm, but the gegenschein was not. The Na feature was only detected at 589.1 nm

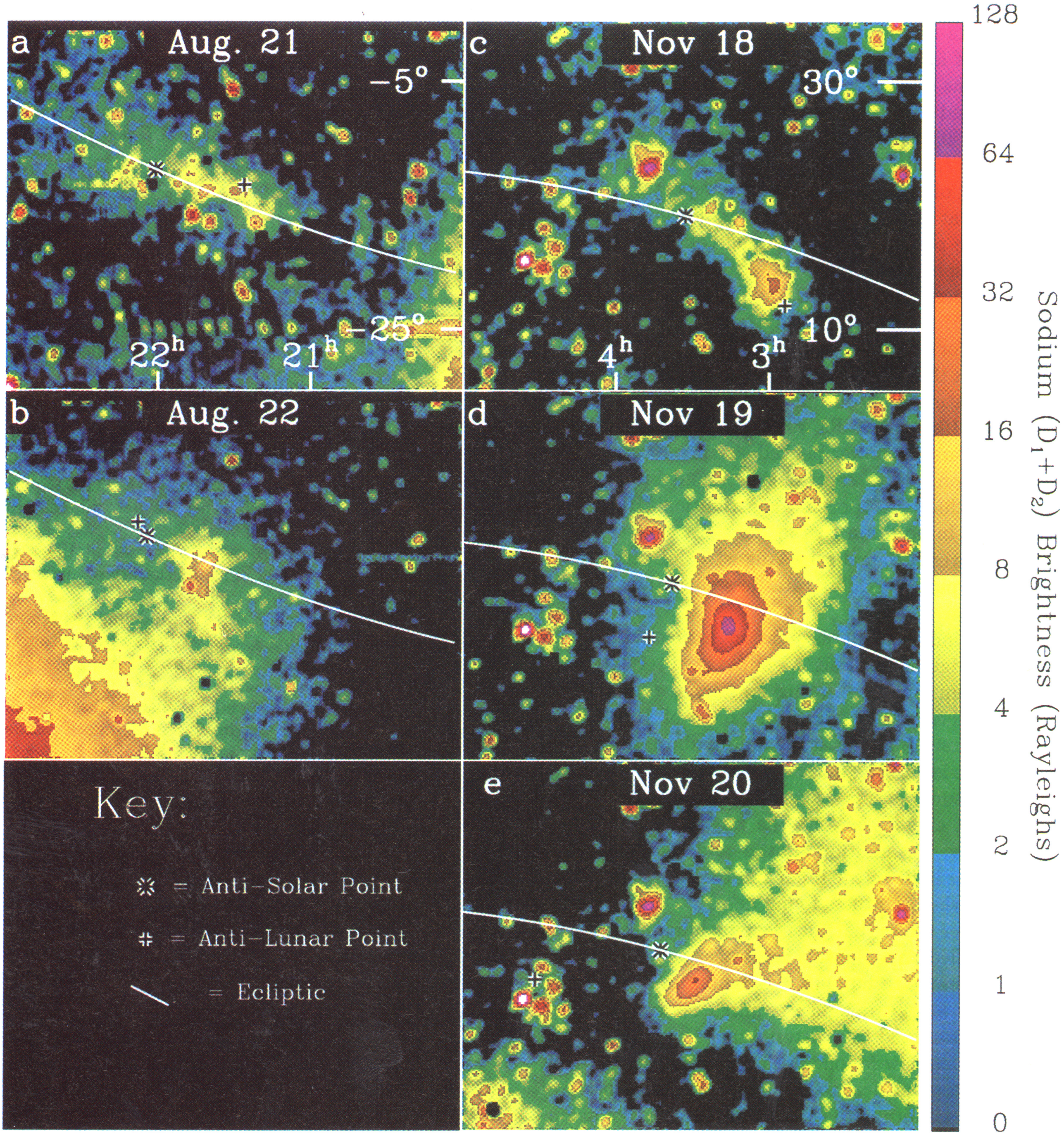

Figure 2. Time-averaged images of the sodium emission region on 21–22 August and 18–20 November, 1998. North is upwards and East is towards the left. The August panels (a, b) span an area from 20h–23h in R.A. (45° right to left) and from -30°–0° in Dec (30° bottom to top). Each November panel (c, d, e) spans a similar area, from 2h–5h in R.A. (right to left) and from +5°–+35° in Dec (bottom to top). New Moon phases occurred at 02:03 UT on 21 August and 04:27 UT on 19 November. The positions of the anti-solar and anti-lunar points at the mid-integration times are also shown on each plot. The 'V'-shaped Hyades cluster is visible to the left of the sodium spot in the November panels. Strong spatial gradients in the terrestrial Na nightglow appear at the lower left in Panel (b) and to the right in Panel (e).

and in addition, the emission feature never appeared precisely on the ecliptic at the anti-solar point. We therefore conclude that it was not associated with the gegenschein.

5. Discussion

The observed behavior of the Na emission feature is consistent with a lunar origin for the sodium. The nightly motion of the emission is due to the combination of Earth's gravity and geometric (line of sight) effects (Wilson *et al.*, 1999). The Earth's umbra was not a significant factor in the brightness of the emission feature because the width of the tail was very large (~few × 10^5 km at the Moon's orbital distance from the Earth (Wilson *et al.*, 1999)) compared to size of the umbra.

The Moon can be compared to a comet in that it exhibits a coma-like atmosphere which produces two tails composed of ions and of neutral species. Detection of energetic ions (e.g. O^+, Si^+, Al^+) of lunar origin have been reported from several spacecraft (Hilchenbach *et al.*, 1991, 1993 (AMPTE); Cladis *et al.*, 1994 (ISEE) and Kirsch *et al.*, 1997 (GEOTAIL and WIND)) in the vicinity of the Earth. Here we report on a neutral species at even greater distances. Earlier modeling studies have portrayed the escaping component of the lunar atmosphere to extend beyond the edge of their simulation results (10 lunar radii (R_L) for Ip, 1991; Flynn and Mendillo, 1995; Smyth and Marconi, 1995; and 15 R_L for Mendillo *et al.*, 1997).

We expect that the measured brightness of the sodium emission feature seen during August, and perhaps, 18 November, 1998 (19±6 R) was close to quiescent level. The 1998 Perseid shower peaked sharply 10 days prior to new Moon, so its contribution would be expected to be less than the sporadic contribution (Hunten *et al.*, 1998). In addition to the Perseids, several minor meteor showers occur during August (McBeath, 1998) but they typically exhibit rates less than the sporadic contribution.

Previous independent observations are consistent with the lunar origin hypothesis; Mendillo *et al.* (1999) measured sodium emission during four lunar eclipses and in two of these, they found an excess of 10–30 R of sodium emission in the Earth's umbra above the terrestrial sodium level. The lunar sodium tail will contribute to the measured excess because it would be sunlit and visible as it extends beyond the Earth's tapering umbral shadow. In addition, Potter and Morgan (1991) set an upper limit to the lunar tail brightness of 200 R, well above the brightness found here.

This paper shows that the escaping lunar atmosphere can be studied on a monthly basis near new Moon with relatively simple techniques. In comparison with other techniques, all-sky imaging requires no tracking and is not compromised by scattered moonlight during the week spanning new Moon. Such a system can therefore contribute a great deal to the long-term monitoring of the time-variability of the lunar atmosphere. For example, transients produced by a solar wind enhancement or a solar flare might create a similar Na tail.

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