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Modeling an enhancement of the lunar sodium tail during the Leonid meteor shower of 1998

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Abstract.
A region of non-terrestrial sodium emission seen in the sky on the nights of November 18-20, 1998, has been interpreted as the Moon's distant sodium tail, possibly enhanced by micrometeor impact vaporization of the lunar regolith by the Leonid meteor shower. We show that the location and morphology of the spot can be explained by standard steady-state models of the Moon's sodium atmosphere. Moreover, using a new time-dependent simulation of the lunar atmosphere, we find that the Na escape rate from the Moon increased to 2 or 3 times its normal level during the most intense period of the 1998 Leonid meteor shower on November 16th and 17th.

1. Introduction

The Leonid meteor showers of 1998 and 1999 have been highly anticipated due to the possibility of a "storm" event, during which the rate of visible meteors increases briefly by orders of magnitude. During these events, which can occur once or twice every 33 years (the period of the associated comet Tempel-Tuttle), the total meteoric mass flux at the Earth can be an order of magnitude larger than the background sporadic meteor rate, and two to three orders of magnitude larger than peak fluxes of familiar major showers like the Perseids and Geminids (Hunten *et al.*, 1998). This makes the Leonid meteor shower one of the best opportunities for testing the micrometeor impact vaporization source of the lunar sodium (Na) atmosphere (Hunten *et al.*, 1991; Ip, 1991; Morgan and Shemansky, 1991; Cintala, 1992; Smyth and Marconi, 1995).

Although the nearly-new Moon was essentially unobservable during the Leonid meteor shower of November 17, 1998, it appears that its Na atmosphere was nonetheless observed on the following three nights, around the time of new Moon, in all-sky images looking in the opposite direction (Smith *et al.*, 1999). Figure 1 (a-c) shows the peculiar emission feature seen by an all-sky imager, and observing times are given in Table 1. The feature appeared as a linear "streak" on the 18th, and grew brighter and more circular on the 19th. On the 20th, the last day it was seen, it grew dimmer and smaller. Observations before (on the 17th) and after (on the 22nd) these nights detected no Na emission above the background terrestrial airglow.

2. Modeling

Here we present the first time-dependent model of the lunar Na atmosphere to characterize its escaping component, and to search for enhancements in the escape rate due to the Leonid meteor shower. In this numerical Monte-Carlo model, simulated Na atoms are released from the lunar surface in random directions and with specified speed distributions. We compute trajectories numerically using adaptive step-size fourth-order Runge-Kutta integration, and include the effects of radiation pressure (which depends on the heliocentric radial velocity and distance) and the gravity of the Moon, Earth, and Sun. The model includes the motions of the Moon around the Earth and the Earth around the Sun. Na atoms are removed by photoionization ($\tau = 47$ hours at 1 A.U.; Huebner, 1992; also see Combi *et al.*, 1997; and Cremonese *et al.*, 1997) and by impact with the Moon and Earth. (Na atoms may be re-released after impact with the surface, but we assume for simplicity that all atoms "stick" to the surface.)

We use ejection speeds of 2.1-2.4 km/s from the lunar surface, sufficient to produce an escaping atmosphere component with the help of radiation pressure. Ip (1991) adopted essentially the same speed distribution in simulations of the lunar exosphere, and the lunar atmosphere models of Flynn and Mendillo (1995) and Smyth and Marconi (1995) used similar speeds in the high speed "tail" of the total velocity distribution that characterized the lunar atmosphere/corona within 12 R_M of the Moon. Na atoms ejected at lower speeds (more numerous than those considered here) cannot readily escape from the Moon and so cannot contribute to the lunar tail.

Table 1. Observations (from Smith *et al.*, 1999)

Date (1998)	Time (UT)	No. of images	Lunar phase
Nov. 18	3:31-5:43	38	-1 day
Nov. 19	4:31-9:02	73	New
Nov. 20	2:48-4:44	44	+1 day

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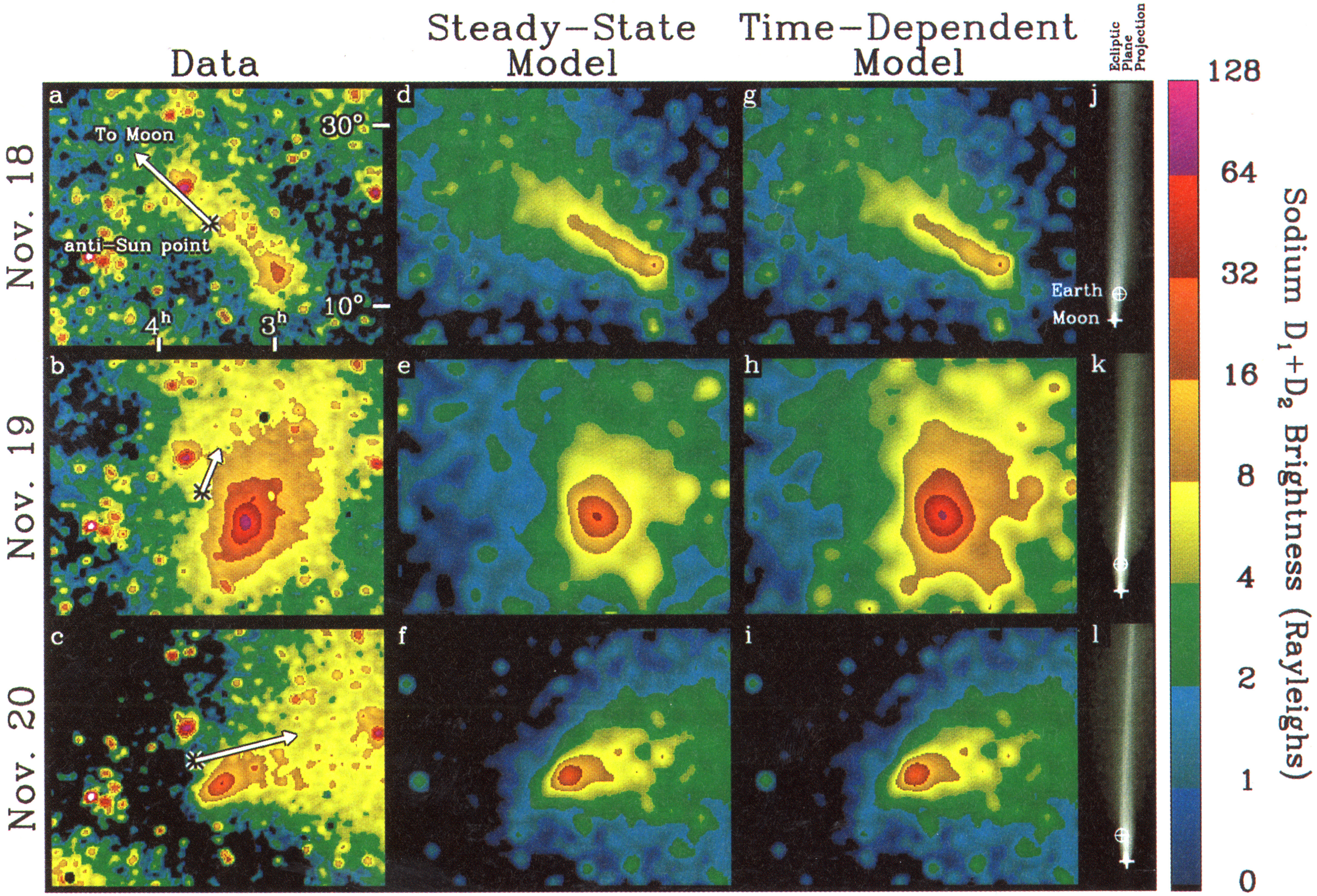

Figure 1. (a-c) Data images of the distant lunar Na tail on November 18-20, looking in the direction opposite from the sun. The image from the 20th (c) suffers from flat-fielding problems in the lower-left and upper-right corners, so brightness levels there are not accurate. (d-f) Model images for a constant Na source of 7 × 10^{21} atoms/s at 2.0-2.4 km/s ejection speeds. (g-i) Model images for a variable source rate at the Moon, with the peak production rate occurring at 1:30 U.T. on November 17. In panels (a) through (i), the field of view extends from 2 hours to 5 hours in Right Ascension (R.A.), and from 5^o N to 35^o N declination. (j-l) View of the modeled Na tail from north of the ecliptic plane. Perturbations by the Earth's gravity result in a slight kink in the right edge of the tail near the Earth in panel (j) (Nov. 18), and a gradual curve in the entire tail in panel (l) (Nov. 20).

A model of the Moon's nominal "background" escaping atmosphere matches the locations and morphologies of the observed Na spot. Figure 1 (d-f) shows model images for a constant Na ejection rate of 7×10^{21} atoms/s for an isotropic, global source. The model ejection rate determines the brightness of the lunar tail, while the ejection speeds determine the morphology. The ejection rate is nearly the same rate found from models by Ip (1991) for similar velocity distributions, and is smaller than the total production rates found from the models of Flynn and Mendillo (1995) and Smyth and Marconi (1995) for broader velocity distributions. The model brightnesses are similar to those in the data on November 18 (Figure 1a, d) and November 20 (Figure1c, f), but are only ~50% as bright as the data on November 19 (Figure 1b, e). It takes approximately 2 days for Na atoms to travel from the Moon to the Earth (near new Moon phase), so the November 19 data suggests that there was an increase in the escape rate from the Moon on or before early November 17. (Previous models of the lunar atmosphere used a shorter photoionization lifetime of ~14 hours; using this lifetime in our model, we require a ~7-fold increase in the escape rates to obtain the same observed lunar tail brightnesses.)

We next consider a time-dependent model which includes an enhancement in the lunar Na production rate, above the constant background source level, at around the peak time of the Leonid meteor shower. Collected worldwide observations indicate the major component of the 1998 Leonid meteor shower occurred on the Earth between ~18 hours UT on November 16 and ~12 hours UT on November 17, with the peak Zenith Hourly Rate of 250 occurring at approximately 1:30 UT on November 17 (Jenniskens, 1999). Given the coincidence of the peaks in the observed Leonid meteor rates and the lunar Na production rate as determined from the model, we use the meteor observations to fix the time and duration of the peak Na production rate in our model, rather than search for the peak production time which best matches the data.

It is reasonable to expect that impact rates on the Moon on Nov. 16-17 paralleled those on the Earth, and therefore that the Na production peak and meteor peak are correlated. At geocentric speeds of 72 km/s, Leonid meteoroids travel one lunar orbital radius in less than two hours, so this is the maximum time delay between terrestrial and lunar encounters of enhancements in the Leonid meteor stream. Although visible meteor rates do not necessarily correspond to meteoroid mass fluxes (see Hunten *et al.*, 1991; 1998), we assume here that Na production rates during the peak of the 1998 Leonids were proportional to observed meteor rates, and reserve for future work any modeling based on more accurate assessments of Leonid mass fluxes.

The time-dependent model is consistent with the location, shape, brightness, and evolution of the observed lunar Na tail. The model images of the Na tail, as seen from the Earth, are shown in Figure 1(g-i). Views of the Na tail projected onto the ecliptic plane are given in Figure 1(j-l) to give a different perspective of the geometry. The model includes a temporary source of Na from the surface (in addition to the background source) which peaks at 2:00 UT November 17. The peak production rate for the temporary source which best matches the data is $\sim 1.7 \pm .5 \times 10^{22}$ Na atoms/s, for a total peak production rate of $2.4 \pm .5 \times 10^{22}$ Na atoms/s. The total simulated Na production profile is shown in Figure 2. The model produces a "streak" of emission on November 18, similar to the observed emission region. This streak is an oblique view of the tail, part of which has been perturbed by the Earth's gravity. The brighter spot on November 19 results from the population of Na atoms ejected two days earlier during the peak of the Leonids. The spot is more circular on this night because the Earth is closer to the central axis of the tail, as seen in the ecliptic projection in Figure 1(k). By November 20, as the Earth moves out of the lunar tail, the emission region grows dimmer and smaller. The model predicts maximum brightnesses of <4 Rayleighs on November 17 and 22, below the level of noise in the data, and is therefore consistent with the non-detection on those nights (Smith *et al.*, 1999).

3. Discussion

The modeling results presented here clearly demonstrate that the Na emission feature seen on November 18-20, 1998, was the lunar Na tail seen at over 400,000 km and 2 days from its origin at the Moon. Thus, the escaping lunar Na atmosphere can be usefully monitored on a monthly basis with surprisingly simple techniques. Observations using an all-sky camera (described in Smith *et al.*, 1999) require no tracking, and are not compromised by scattered moonlight in the sky or in the optics during nights near new Moon. Observations of this type can also contribute to long-term monitoring of the lunar atmosphere to test other transient sources. Future meteor showers, solar flares (an enhanced photodesorption source), and coronal mass ejections (an enhanced solar wind ion sputtering source) will provide additional tests of the various atmospheric production mechanisms on the Moon.

Our time-dependent model of the lunar Na atmosphere indicates that we observed a factor of 2 to 3 increase in the escape of atmospheric Na from the Moon during the peak of the Leonid meteor shower. The changes in the lunar atmosphere itself are not as easily quantified, as the lunar Na tail represents a narrow range of surface ejection speeds (>2.1 km/s) which do not reflect the entire atmosphere. The higher escape rate on November 16-17 was probably due to a combination of increased production and a higher average temperature. Cremonese and Verani (1997) and Verani *et al.* (1998) detected an increase in the scale height of the lunar Na atmosphere 4 days before the Leonid shower of 1996, suggesting that an increase in temper-

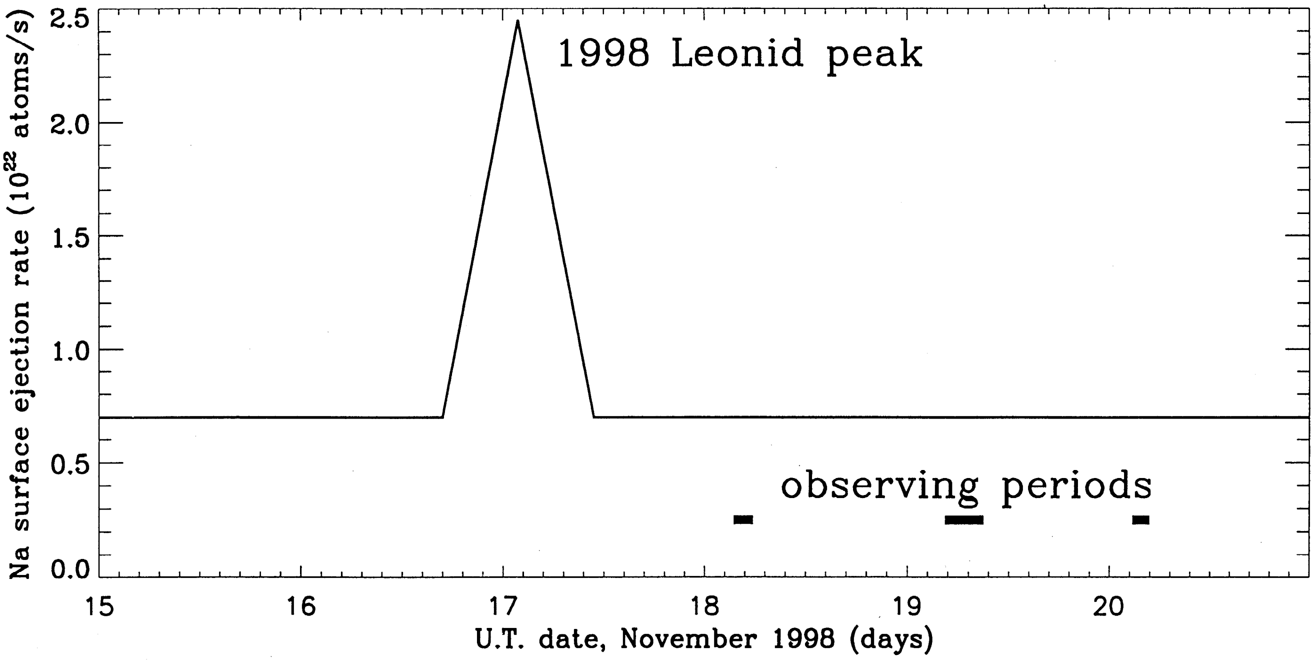

Figure 2. Time-dependent model Na production rate at the lunar surface (v = 2.1-2.4 km/s) for November 15-21. The narrow peak corresponds to the observed Leonid meteor rate profile, while the constant component comes from a combination of solar-induced and sporadic meteor sources.

ature could play a role. In future work, we will address month-to-month changes in the lunar Na tail, and more thoroughly compare the atmospheric model used here with observations and modeling of the lunar atmosphere at quarter and full Moon phases. Future modeling will address both the escaping and gravitationally bound atmosphere components simultaneously.

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