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Lidar Observations of Elevated Temperatures in Bright Chemiluminescent Meteor Trails During the 1998 Leonid Shower

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Abstract. Seven persistent trails associated with bright fireballs were probed with a steerable Na wind/temperature lidar at Starfire Optical Range, NM during the 17/18 Nov peak of the 1998 Leonid meteor shower. These chemiluminescence trails were especially rich in Na. The average Na abundance within the trails was 52% of the background Na layer abundance, which suggests that the corresponding masses of the meteors were from 1 g up to 1 kg. CCD images show that the chemiluminescent emissions (including Na and OH) are confined to the walls of a tube, which expands with time by molecular diffusion. Lidar profiles within the trails show that the temperatures are highest at the edges of the tube where the airglow emissions are brightest. Approximately 3 min after ablation, temperatures at the tube walls are 20–50 K warmer than the tube core and background atmosphere. Neither chemical nor frictional heating provides a satisfactory explanation for the observations.

Introduction

The nights of 16/18 Nov during the 1998 Leonid meteor shower were particularly rich in bright fireballs, some as bright as the full Moon. Many left in their wakes chemiluminescent trails that remained visible for several minutes [*Kelley et al.*, 2000; *Jenniskens*, 1999]. Those long duration trails allowed the pointing of imaging and ranging instruments at the path of several bright fireballs just minutes after the meteors had ablated. Our group observed the shower at the Starfire Optical Range (SOR), NM (35°N, 106.5°W) and used a steerable Na wind/temperature lidar to actively probe the persistent trails for the first time.

Persistent trails are a unique feature of Leonid showers and are otherwise rarely observed. Typically, these trails are associated with meteors of visual magnitude -2 and brighter, corresponding to masses of 1 g up to 1 kg [*Spurny et al.*, 2000]. These meteors are brighter and more massive (by 1–3 orders of magnitude in mass) than those probed by our airborne Fe lidar during the 1998 Leonid Multi-Instrument Campaign experiment over Okinawa, Japan [*Chu et al.*, 2000]. Moreover, the SOR experiment enabled us to detect debris trails sooner after formation and probe single debris trails over extended periods of time.

In this paper we report the general characteristics of the Na ablation trails and the background Na layer during the 1998 Leonid shower and compare them with previous observations of the mesospheric metal layers. We also report measurements of the temperature profiles within the persistent trails.

Experimental Configurations

SOR is located on the Kirtland AFB near Albuquerque, NM. The facility is operated by the Air Force Research Laboratory, Directed Energy Directorate and includes a 3.5-m astronomical telescope. The University of Illinois Na wind/temperature lidar is coupled to this telescope through the coude optics so that the beam can be pointed in any direction above 5° elevation. A 1-m diameter portion of the telescope primary mirror is used to project the laser beam while the remainder is used for collecting the backscattered light and focusing it onto the detector. The beam divergence is approximately 1 mrad. At 100 km range, the beam diameter (full width @ e^{-2}) is 100 m. The lidar operates at 30 pps and the laser output power varies between 1 and 1.5 W. For this Leonid experiment the range resolution was 24 m and the integration period was 15 s. The lidar was operated in the normal scanning mode to measure radial wind, temperature, and Na density profiles at zenith and 10° off-zenith to the north, east, south and west. These data are used to derive profiles of the three wind components of the atmosphere as well as the temperature and Na density profiles.

An observer was positioned outside the telescope dome to look for persistent trails associated with fireballs. When one was spotted, the telescope operator was apprised of the approximate azimuth and elevation angle and the telescope was moved to that position. By using a boresighted video camera mounted on the telescope and the lidar profile data, the telescope operator positioned the lidar beam on the persistent trail. In this way seven persistent trails were tracked and probed with the lidar for as long as 30 min. Visible CCD cameras, allsky airglow imagers, and meteor radar also collected correlative data at SOR during the meteor shower.

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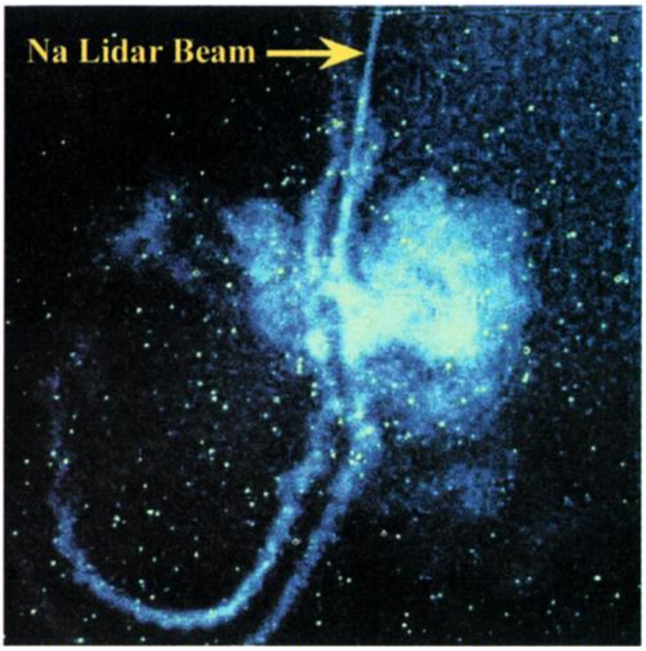

Figure 1. CCD image of the persistent chemiluminescence trail (Diamond Ring) observed at 09:30 UT 17 Nov 98 at the Starfire Optical Range, NM. The straight line near the top center of the image is the Na lidar beam.

Observations

The persistent trails observed on 17/18 Nov at SOR were given descriptive names that characterized their visual appearances in the video and CCD images. Figure 1 is a false color CCD image of the one of these trails (Diamond Ring) observed at 09:30 UT on 17 Nov. The bright trail is chemiluminescence associated with a variety of emissions including Na and OH airglow [*Kelley et al.*, 2000; *Abe et al.*, 1999]. In situ winds began distorting the trail immediately after the initial fireball. Because of the fortunate viewing geometry, the meteor has produced a visual hodograph, which illustrates the rotation of the horizontal wind vector with altitude. In the case of Diamond Ring, the winds from a large amplitude gravity wave have distorted the trail into a spiral, which rotates clockwise with increasing altitude. The faint laser beam can be seen in the top center of Figure 1 probing the trail at the crossover point of the spiral. Figure 2 is the associated Na density profile showing the two trails at 92.2 and 98.4 km. The gravity wave responsible for the wind rotation has a vertical wavelength approximately equal to the separation of the two trails, viz. 6.2 km.

The characteristics of the seven trails observed at SOR are tabulated in Table 1. Following the initial fireballs, the persistent trails left in their wakes were acquired by the lidar in about 2 min. The duration in Table 1 is the elapsed time from ablation until the Na trail was no longer observable by the lidar. In all cases the trails were lost because the chemiluminescence was no longer visible on the video monitor and the Na trail drifted out of the field-of-view of the lidar. Mean characteristics such as abundance, density and altitude were determined using the meteor trail profiles exhibiting the highest abundances. Typically, these profiles were acquired within 2–3 min of the initial fireball. Visual magnitude of the initial fireballs was estimated by the observer (Drummond). The high mean altitude of the Na trails, 94.0±1.6 km, is consistent with the Fe observations reported by *Chu et al.* [2000] (95.67±0.93 km) and is believed to be related to high entry velocity of Leonid meteors (72 km/s).

The abundance of the background Na layer varies seasonally at mid-latitudes in the Northern Hemisphere with maximum values in November averaging 5×10^9 cm^{-2} [*States and Gardner*, 1999]. The mean background Na abundance on 17/18 Nov 1998 was approximately 9×10^9 cm^{-2}. Although the measured Na abundances are higher than normal, the Leonid shower did not have a noticeable impact on the background Na or Fe densities [*Chu et al.*, 2000]. However, the observed persistent trails are especially rich in Na. The average abundance of the trails is nearly 52% of the background Na abundance on 17/18 Nov and comparable to the mean abundance for this time of year. The abundance of one trail, Hairpin, exceeded the 17/18 Nov background by 45%. The peak Na densities in the persistent trails averaged about 2×10^5 cm^{-3} and the maximum was 3.86×10^5 cm^{-3}, nearly 100 times the maximum background Na density. The high abundances and densities of the Na ablation trails are consistent with the assumption that the bright fireballs are associated with meteoroid masses ranging from 1 g up to 1 kg [*Spurny et al.*, 2000].

Wilson et al. [1999] and *Smith et al.* [1999] modeled a substantial enhancement of the lunar Na tail observed during the 1998 Leonid shower. However, these researchers were unable to determine if the enhanced Na was vaporized directly from the meteors impacting the lunar surface or was associated with enhanced sputtering of the lunar regolith by the high-speed meteor particles. *Zinn et al.* [1999] reported bright Na airglow emissions from several persistent trails observed to the north of SOR on 17/18 Nov 1998. *Abe et al.* [1999] recorded the spectra of a persistent trail in Japan and identified strong Na emission lines. These results are consistent with the enhanced Na abundance in lidar meteor profiles. Meanwhile, G. Swenson (private communication) recorded images of several persistent trails using allsky OH imager at SOR.

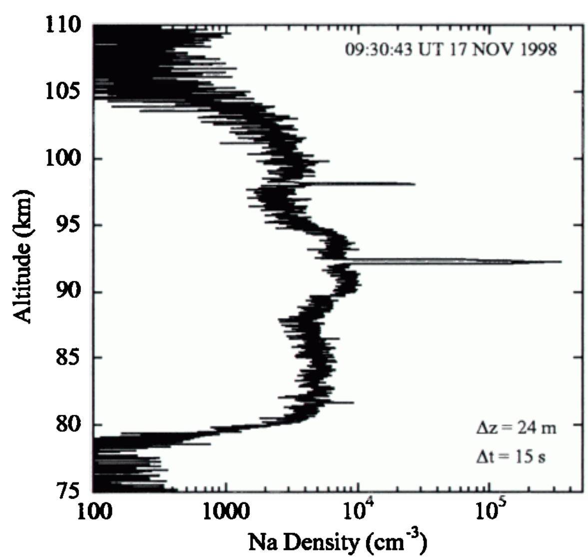

Figure 2. Na meteor trail profile probed by the Na wind/temperature lidar at SOR during 1998 Leonid meteor shower. The vertical resolution is 24 m and the integration period is 15 s.

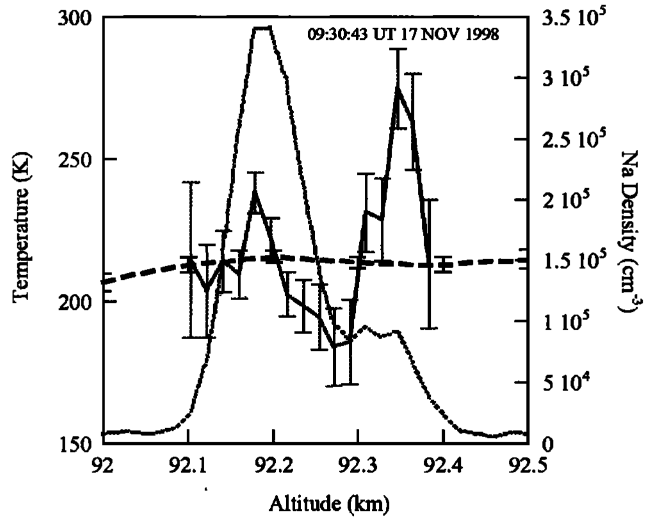

Figure 3. Na density (dotted line, scale on the right) and temperature (solid line, scale on the left) profiles of the lower Diamond Ring ablation trail plotted in Figure 2 at 09:30:43 UT. The background temperature profile (dashed line) was obtained by averaging temperatures between 09:30 UT and 09:32 UT and then applying a 500-m fullwidth Hamming window to smooth out meteor signals. Error bars are plotted for the two temperature profiles.

Plotted in Figure 3 are the expanded Na density and atmospheric temperature profiles within the lower Diamond Ring ablation trail obtained 2 min 53 sec after the fireball. The background temperature profile was obtained by averaging temperature collected during the whole event and then applying a 500 m full width Hamming window to remove meteor signals. While there is some Na structure within the ablation trail, the shape is consistent with the *Kelley et al.* [2000] catalytic model. The temperature profile shows a double-peak structure, exhibiting low temperatures in the center of the Na ablation trail and elevated temperatures on the bottom and top edges. The airglow emissions of the persistent trails observed at SOR appear to be confined to the walls of a tube which increases in diameter with time as molecular diffusion disperses the ablated material [*Kelley et al.*, 2000]. When the tube is viewed from the side, edge-brightening effects give the appearance of a double trail as can be seen in the Diamond Ring image of Figure 1. The double-peak structure of lidar temperature profile indicates that the temperatures are highest at the tube walls where the airglow emissions are largest while the temperature at the tube core is relatively cool. Because the trail diameter is only about 250 m and the laser beam diameter is about 90 m, the lidar must be pointed at the center of the ablation trail to obtain accurate temperature measurements of the airglow tube center and walls. If the lidar is pointed off-center, the temperatures would be characteristic of just the edges of the tube where the airglow is most intense.

Plotted in Figure 4 are the Na density and temperature profiles for the Straightened Diamond Ring trail obtained 3 min 21 sec after meteor ablation. This trail also exhibits cooler temperatures in the center and warmer temperatures on the edges where the airglow emissions are greatest. The core temperature is comparable to the background temperature while the edge temperatures are 20–50 K warmer than the background. *Abe et al.* [1999] also reported that high temperatures (~2200 K) are required to accurately model the intense emission spectra of the persistent trail (12–22 seconds after ablation) they observed during the 1998 Leonid shower.

Discussion

The structure of the enhanced temperature and observed chemiluminescence suggest that chemical heating might be partially responsible for the enhanced temperatures within the ablation trails. The OH and Na airglow emissions result from the reaction of atomic H and Na with O_3 [*Chapman*, 1967; *Baggaley*, 1981].

$$H + O_3 \rightarrow OH^* + O_2, \quad (1)$$

$$Na + O_3 \rightarrow NaO + O_2, \quad (2)$$

$$NaO + O \rightarrow Na^* + O_2. \quad (3)$$

These reactions are exothermic and in the case of OH, play an important role in the thermal balance of the mesopause region [*Mlynczak and Solomon*, 1993; *States and Gardner*, 2000]. The excess energy of the excited species is either dissipated as heat through collisional quenching with other air molecules or is radiated in the form of visible and near infrared photons. Chemical heating of the mesopause region can exceed 10-20 K/d. It is greatest at night, when the O_3 densities are largest, between 85 and 95 km where the OH airglow emissions are brightest. *Kelley et al.* [2000] suggest that the high concentration of Na in the ablation trail consumes the O_3 at the center of the tube (reaction 2) because the Na is catalytically restored by reaction 3. In this way multiple reactions could consume all the ozone provided the initial Na densities are sufficiently large. High concentrations of H released from water and hydrocarbons in the meteor by the high ablation temperatures may also deplete O_3 in the trail core (reaction 1) [*Delsemme*, 1986; *Zolensky et al.*, 1999]. Emissions are confined to the walls of the tube as atmospheric O_3 diffuses inward to react with the high concentrations of H and Na at the edges of the ablation trail. However, the chemical heating rate estimated from reaction (1)–(3) is about two orders of magnitude smaller than observed.

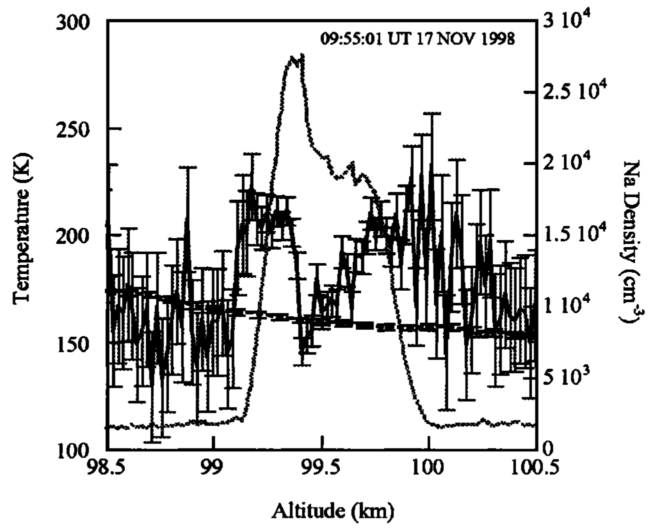

Figure 4. Same as Figure 3 but for the Straightened Diamond Ring ablation trail at 09:55:01 UT. The background temperature profile was obtained with data between 09:55 UT and 10:02 UT.

Table 1. Characteristics of the 1998 Leonid Na Meteor Trails

Event	Ablation Time (UT)	Peak Density Time (UT)	Duration (min)	Altitude (km)	Meteor Abundance ($10^9 cm^{-2}$)	Background Abundance ($10^9 cm^{-2}$)	Meteor Peak Density ($10^3 cm^{-3}$)	Visual Magnitude
Diamond Ring 1	09:27:50	09:30:43	4.8	92.20	4.31	11.0	341	-1.5
Diamond Ring 2	09:27:50	09:29:55	24.0	98.41	7.74	8.77	195	-1.5
Straightened Diamond Ring	09:51:40	09:55:01	10.8	99.41	1.21	7.99	27.6	-1.5
Baby Glowworm	10:17:30	10:19:42	3.0	92.04	0.55	8.65	40.7	0
Sailboat	11:07:00	11:09:23	21.2	88.75	6.15	9.92	285	-2
Hairpin	11:32:48	11:35:53	4.7	89.96	11.3	7.78	386	-1.5
Rope	11:35:52	11:52:50	31.3	97.16	2.33	9.95	114	-1
Mean			14.3	94.0±1.6	4.80	9.15	198	
Std			11.2	4.3±1.1	3.87	1.17	144	

Another source of the elevated temperatures is frictional heating. A simple estimate can be made by invoking kinetic energy conservation. If we assume that a meteoroid, with a mass of 100 g enters the atmosphere with speed of 72 km/s, is completely ablated and expands to a column 200 m in diameter and 100 km in length, and all its kinetic energy is homogeneously distributed to all the molecules within this column, the temperature within the column would be elevated by about 50 K. This is comparable to the value we observed. However, the heating generated by friction should have a temperature structure that is hotter in the center of the trail, inconsistent with the double-peak structure we observed. Thus, the elevated temperatures in the persistent trails remain to be explained.

Conclusions

Although the 1998 Leonids shower was rich in fireballs, the influx of ablated material had no measurable impact on the structure or abundances of the background Na or Fe layers [*Chu et al.*, 2000]. The persistent trails included unusually high densities of Na and emitted brightly at the Na and OH wavelengths. CCD images of the persistent trails show that the chemiluminescent emissions are confined to the walls of a tube, which expands with time under the influence of molecular diffusion. Temperature profiles within the persistent trails exhibit low temperatures in the center and elevated temperatures on the bottom and top edges where the airglow emissions are brightest. Approximately 3 min after ablation, temperatures at the tube walls are 20–50 K warmer than the tube core and background atmosphere. Neither chemical nor frictional heating can provide a satisfactory explanation of this temperature structure. Unfortunately, the 1998 SOR Leonid observations did not include spectroscopy so that it is not possible to obtain quantitative estimates of the airglow emission intensities and the concomitant atmospheric heating effects.

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