First observations of long-lived meteor trains with resonance lidar and other optical instruments

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Abstract. In November 1998 the earth passed through a maximum in the cometary material responsible for the yearly Leonids meteor shower. The meteor storm event produced numerous examples of long-lived chemiluminescent trails—visible to the naked eye—over New Mexico, where a major observation campaign was centered. One trail was detected for over an hour with a CCD camera employing a narrow sodium filter, and many others were observed for over ten minutes each. For the first time, sodium densities in such trails were measured while also being imaged in sodium light. We have verified one source of long-lived light emissions—a sodium-catalyzed reaction involving ozone—but it is far too weak to explain the visibility of such trails. In addition, we present a new explanation for the cylindrical shell appearance long reported for chemiluminescent trails and show that ozone depletion by chemical processes is a possible explanation for this phenomenon.

Introduction

One of the most fascinating effects of meteor entry into the earth's upper atmosphere is the occasional production of long-lived chemiluminescent trails. The first reports in scientific literature stem from observations of these trails during meteor storms in the last century, particularly during the 1866-68 period when the Leonids meteor shower exhibited one of its 33-year activity peaks. The drawing in Figure 1 reproduces what a visual observer saw over Cardiff, England during Leonid shower activity on November 14, 1866 [*Trowbridge*, 1907; 1911]. The trail was triangulated from Sidmouth and Cardiff and found to have a length of 26-29 km and a mean height of 90 km. The trail was visible to the naked eye for 12 minutes.

Even to this day, the process or processes responsible for this phenomenon have remained uncertain due to difficulty in performing measurements during such a transient phenomenon. Here we report on a comprehensive set of observations made during the 1998 Leonids meteor shower,

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observations that provide the opportunity to quantitatively test the sodium airglow theory for the origin of this spectacular light show [*Chapman*, 1956; *Baggaley*, 1977a; 1981]. A unique aspect of the approach used here was the coupling of the University of Illinois resonance sodium lidar to the 3.5 m telescope at the Air Force Research Laboratory's Starfire Optical Range (SOR). We were thus able to measure–for the first time–the sodium content, temperature, and spatial distribution for long periods of time.

The measurements were conducted as follows. The Leonids shower peaked on the night of November 16/17 in 1998, a night that was very clear over New Mexico. Rooftop observers recorded meteor visual magnitudes and rates and waited for a lingering trail. Once sighted, the telescope operator was given look directions until the trail was visible in his bore-sighted, image intensified camera, at which time he took over the tracking. The laser beam was invaluable initially as a pointer, assisting the rooftop observer. Later, even when the trail was too weak to see in the bore-sighted camera, the sodium resonance backscatter from the trail was used to track it. Other astronomical aspects of the observing scheme are described by *Drummond et al.* [2000].

In conjunction with Los Alamos, Cornell University fielded a CCD-based all-sky camera with a narrow (2 nm) sodium filter. This camera was located at Placitas, NM. A 400 mm lens was used with a CCD camera to make white light observations at SOR. Finally, a powerful copper vapor laser operated by SOR was used to illuminate the trail.

Other results from the campaign are reported by *Chu et al.* [this issue] and *Grime et al.* [this issue].

Data Presentation

Some of the trails' complexity, as well as their beauty, have been recorded with the 400 mm camera, which had a 2 degree field-of-view. The trail seen in Plate 1 had been in existence for about 82 seconds when this frame was obtained. The trail was formed in the 90-100 km height range. The distortion of the trail is due to atmospheric winds that vary with altitude. The double-edged character of the trail has long been thought to be an optical depth effect caused by viewing a cylindrical shell from the side [*Trowbridge*, 1907; 1911; *Hawkins*, 1957]. We return to a discussion of the shell formation below.

Plate 2 shows another trail detected at the SOR using the same CCD camera. Notice the great similarity of this photograph with the sketch in Figure 1. The laser light sources can also be seen in the images. The most intense beam in Plate 2 is from the copper vapor laser. Light from the weaker sodium beam can be seen in both figures. We were able to track a dozen lingering trails over the course of the evening.
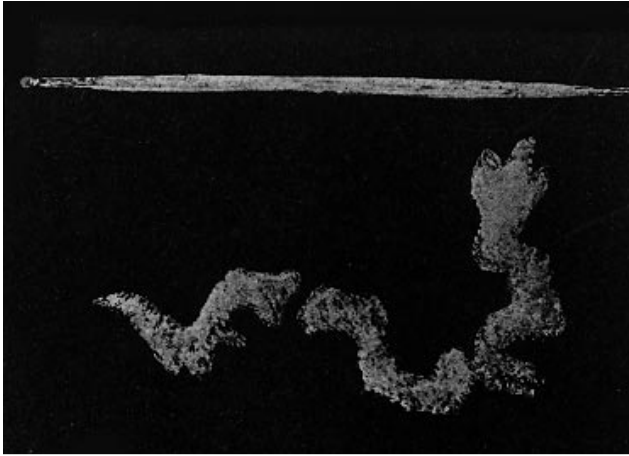
Figure 1. Persistent trail observed over Cardiff, England during the 1866 Leonids. The top portion shows the initial trail while the lower portion shows the trail minutes later after distortion by gravity wave activity. This sketch is one of many made of persistent trails during the 1866-1868 period.

The sodium resonance lidar has the ability to measure the amount of sodium in the upper atmosphere as well as its temperature and mean velocity in each range gate [*Gardner*, 1989]. This measurement is the crucial one which, for the first time, will allow a quantitative estimate of the sodium glow component in the chemiluminescence theory of *Chapman* [1939, 1956] and *Baggaley* [1977a, 1981] outlined be-

low. All of the trails tracked by the system and within the spread of the laser range gates exhibited very strong resonance sodium backscatter. The trail in Plate 2 was at an elevation of 30° and just outside the reach of the largest lidar range gate. However, as shown below, the trail glowed brightly enough in the sodium emission line to be detected for over an hour by the all-sky camera.

An example of the measured sodium profile display from the event shown in Plate 1 is presented in Figure 2. The spike at 92 km had a peak sodium density ten times that of the background sodium layer, which is also apparent in the plot. Two spikes are seen, since the laser was pointed at the place where the trail seemed to cross itself. Such measurements will allow for a quantitative estimate of the sodium glow from both the trail and the background sodium layer airglow intensity. Sodium all-sky camera images of the structure shown in Plate 2 are presented in Figure 3. The length of time the emissions last and the wind-induced distortion of the trail are evident in this presentation as well. Together, these data show convincingly that sodium glow is a component of the lingering trail phenomenon and verify the earlier suggestions by *Chapman* [1956] and *Baggaley* [1977a, 1981] that sodium airglow chemistry plays a role in the lingering trail phenomenon.

We have searched the CCD images for any evidence of Mie (dust) scattering of the stronger CVL beam, without success.

Discussion

In brief, the sodium-based theory for long-lived trails involves a catalytic process in which the sodium released by
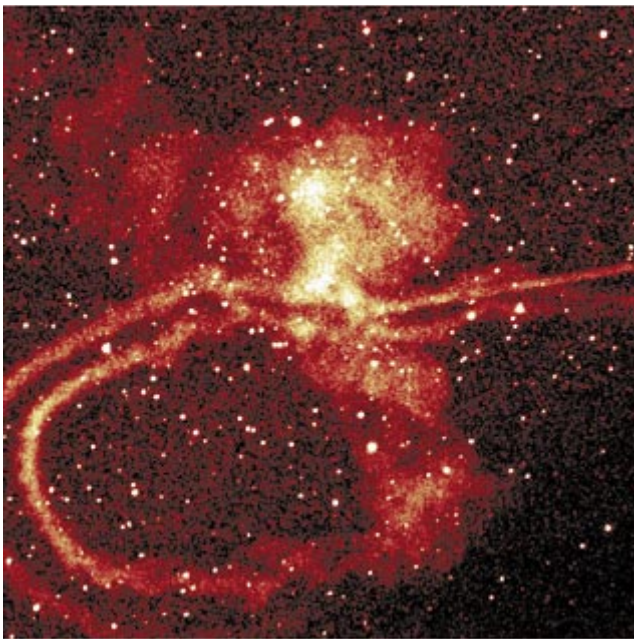

Plate 1. Trail observed from the Starfire Optical Range on Kirtland Air Force Base near Albuquerque, NM. The meteor of magnitude -1.5 appeared at 2:28 MST on November 17, 1998 and remained visible to the naked eye for about 5 minutes. This image of the trail, dubbed the Diamond Ring, was a one-second exposure taken with a Photometrics CCD camera with a 2 degree field-of-view 82 seconds after the meteor's appearance. The sodium laser is faintly seen as the straight shaft of light coming in from the right. The circular appearance is quite similar to that of artificial trails made using tri-methyl aluminum released from rockets.

Plate 2. Another trail, called the Glowworm, observed from the SOR on November 17, 1998. It appeared at 3:06 MST and was magnitude -4.5. The image is a one-second exposure taken 97 seconds after the appearance of the meteor and was visible to the naked eye for more than 20 minutes. The bright beam from the lower left is the 180 Watt copper vapor laser, while the 1 Watt sodium laser is barely visible coming in from the right.
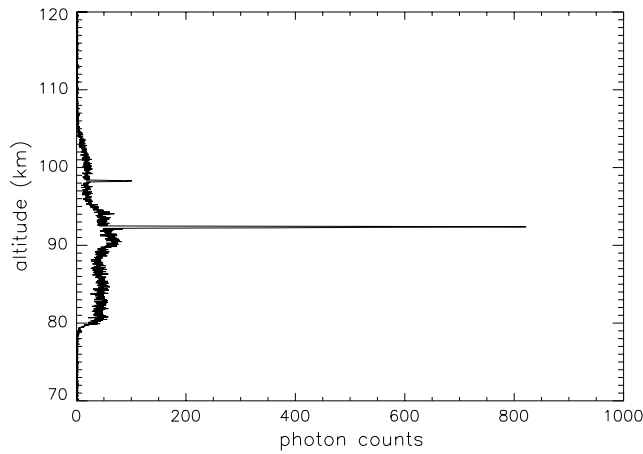
Figure 2. Typical sodium lidar profile for the trail shown in Plate 1. The two spikes correspond to where the laser intercepted the trail at two different heights. The lidar has a range resolution of 24 m and took 15 s time integrations. The signal was so strong that the laser power was reduced to avoid saturation. The natural sodium layer is evident as well from 80 to 105 km.

meteor ablation cycles through a set of reactions, thereby releasing energy stored in the ablation/burning event behind the meteor. The reactions proposed by *Chapman* [1939] and later in the meteor context by *Chapman* [1956] and *Baggaley* [1977a, 1981] are as follows:

$$Na + O_3 \longrightarrow NaO + O_2 \qquad (1)$$

$$NaO + O \longrightarrow Na + O_2 \qquad (2)$$
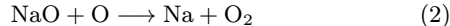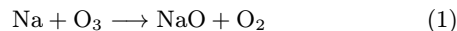
Sodium is thus available to repeatedly pass through this cycle, provided ozone remains available for reaction (1).

Hapgood [1980] made an important advance by observing a lingering trail with a filter (700-900 nm) that did not pass the 589 nm sodium line. He attributed these emissions to the excited infrared states of O_2 expected in these same reactions. A broadband IR imager fielded at the site for measurements of OH emissions detected emissions from the trail shown in Plate 2 and in Figure 3 (G. Swenson, personal communication, 1999). However, since the OH and O_2 bands overlap, it is not possible to tell whether the signal was actually due to OH or from the O_2 lines reported by *Hapgood* [1980].

Some qualitative estimates of the expected airglow are given here, based upon a model under development. Using the lidar-determined sodium density and physical size of the trail determined from the cameras and the sodium lidar profile, the total amount of Na is found to be $\cong 2 \times 10^{16}$ m^{-1} along the trail. Using the reaction rates provided by *Plane and Helmer* [1994] and the recently determined percentage of Na in reaction (2), which goes into the Na(^{2}D) state [*Hecht et al.*, 2000], we find a sodium line emission rate of $\cong 3 \times 10^{13}$ m^{-1}s^{-1}. Such a rate is a factor of 30 below the 30 ergs/cm·s required as a minimum for visibility by the naked eye [*Cook and Hawkins*, 1956]. Baggaley estimated much higher sodium emission values, but used a much larger branching ratio in reaction (2) than was reported by *Hecht et al.* [2000]. The rates we find are in good agreement with the 10-600 Rayleighs determined from our all-sky imager data. We thus conclude that although the

catalytic sodium reaction chain does occur in the lingering trail phenomenon, the 589 nm line is too weak to explain the total light intensity.

If reactions (1) and (2) are a main source of the visible and broadband observations, then the O_2 lines must play an important role, as first suggested by *Hapgood* [1980]. These calculations are underway and will take into account the depletion of ozone implied by (1), as well as other metallic contributions to reactions with ozone and atomic oxygen.

We suggest here—for the first time, as far as we can determine—that the chemical ozone depletion caused by reaction (1) may be responsible for the hollow cylinder effect. Initially, with a trail radius of a few meters, the Na density is the order of 10^{15} m^{-3} which, using the reaction rate of 10^{-15} m^{3}s^{-1} of *Plane and Helmer* [1994], indicates an ozone depletion time constant of about one second. The background O_3 density is only about 10^{14} m^{-3}, so rapid ozone destruction is possible. Eventually, ozone diffusion back toward the center of the expanding cylinder would balance the chemical reactions in such a model. Ozone destruction would reduce the Na emissions even further. *Baggaley* [1977b] suggested that charge exchange between Na and the many metallic ions created in the ablation process might reduce Na emissions at the center of the trail and lead to a hollow cylinder effect. But since the Na light is so weak, this mechanism does not seem feasible for a visible effect.

Zinn et al. [1999] have proposed an alternative model in which an intense UV flash destroys all the ozone in a cylindrical region, thereby yielding an active Na/O_2 airglow zone only at the periphery. More experiments with better spectroscopy will be conducted in future Leonids showers, which should help to resolve the open questions.

Finally, because of the deep contrast between the center and the edges of the structure in Plate 1, the hollow cylinder effect is called into question.
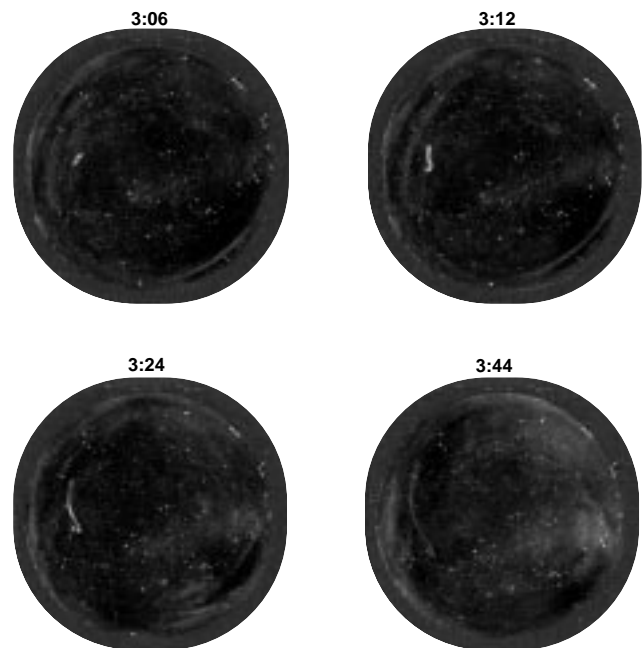

Figure 3. Images of the trail shown in Plate 2 as seen from Placitas, New Mexico, 30 km north of Albuquerque, with a CCD all-sky camera using a sodium filter. The camera took 90 s integrations. The trail was seen by the camera for nearly an hour, long after it was no longer visible to the naked eye.

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