FeO "ORANGE ARC" EMISSION DETECTED IN OPTICAL SPECTRUM OF LEONID PERSISTENT TRAIN

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Abstract. We report the detection of a broad continuum emission dominating the visual spectrum of a Leonid persistent train. A comparison with laboratory spectra of FeO "orange arc" emission at 1 mbar shows a general agreement of the band position and shape. The detection of FeO confirms the classical mechanism of metal atom catalyzed recombination of ozone and oxygen atoms as the driving force behind optical emission from persistent trains. Sodium and iron atoms are now confirmed catalysts.

Keywords: Airglow, FeO, Leonids 1999, mesosphere, meteors, persistent train

1. Introduction

Bright fireballs of fast meteors leave persistent trains that are visible for many minutes because of a luminous mechanism that is poorly understood. The persistent trains are significant, because they display the wind direction and velocity at altitude and probe the interaction of meteoroids with the atmosphere. A better understanding of the luminous mechanism is needed to make full use of the unique opportunity of probing the physical conditions in the meteor's path many minutes after the meteor (Jenniskens *et al.*, 2000). The first optical spectra of long lasting persistent trains were obtained by eye and with slit-less spectrographs and, consequently, were of low resolution. Visual

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inspection of persistent trains show two bright lines in the green and yellow, tentatively identified with MgI at 517.3 and 518.4 nm and NaI at 589.0 and 589.6 nm (Trowbridge, 1907). Rajchl *et al.* (1995), Borovicka *et al.* (1996), and Abe *et al.* (2000) have published photographically recorded slit less spectra. Borovicka *et al.* (1996) studied two Perseid spectra (370-640 nm) taken between 5 and 25 seconds after the meteor. They reassigned the green line to OIII rather than to MgI. In contrast, they also assigned a near-UV line at 372 nm to OII and a red line at 630 nm to OI, without explaining the range of excitation conditions. The line identifications are somewhat uncertain because of poor 25-nm resolution and no zero order detection.

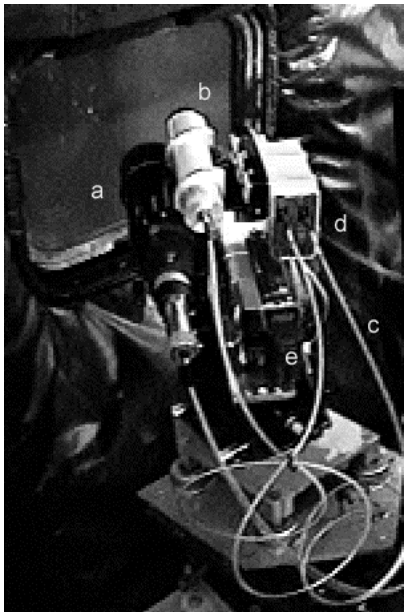

Figure 1. Instrument on optical bench behind aircraft window. (a) F5 / 400 mm telescope for visual and near-IR emission, (b) F3 / 150 mm telescope for near-UV and visual emission, (c) Optical fiber, (d) Miniature spectrometer, (e) Intensified camera for pointing.

To better understand the luminous mechanism of persistent trains at times when the trains become diffuse and faint, modern slit spectroscopy is called for. Slit spectroscopy can shed light on the assignment of the green line, while CCD detectors can extend the spectral range beyond the typical photographic range.

In 1999, fiber-optic coupled slit spectrographs were deployed at Weybourne Atmospheric Observatory in Norfolk (UK) and from aircraft during the Leonid MAC mission. While clouds prevented all but a single 10-second observation from Weybourne, several trains were observed

during the airborne Leonid MAC campaign. We report here the first slit-spectra of a persistent train. All spectra were taken minutes after the meteor appeared and should characterize the mechanism of the persistent glow.

2. Instrumental techniques

The airborne instrument consisted of a compact mount of two optical telescopes: a Celestron Firstscope f5.0/400 mm for low 2.1 nm resolution at 200 - 850 nm wavelengths (Figure 1- "a") and an OptoSigma UV achromat lens 47.0 mm, f = 149.4 mm ("b") for high 0.3 nm resolution at 300-440 nm wavelengths. The telescopes are connected with a 2-meter 600-micron fused-silica patch fiber with SMA905 connectors and 74-UV collimating lenses ("c") to a dual channel Ocean Optics miniature fiber optics spectrograph SD2000 ("d"). The near-UV telescope is connected to a 2400 l/mm holographic grating with UV Detector Upgrade and detector collection lens and a fixed 25-micron slit installed (master). The VIS-NIR telescope was connected to a 600 l/mm blazed grating (400 nm) with a fixed 50 micron slit (slave). The whole assembly can be rotated and pointed to a persistent train. A co-aligned f2.8/100mm Mullard XX1332 intensified camera (Figure 1e) is used for training the telescopes at the persistent train. Its field of view is about 19 x 15 degrees and star limiting magnitude about +8.2. The camera is connected to a video headset display (I-goggles) that is worn by the operator, who also handles the data storage on a Sony Notebook laptop computer and carries an external trigger to start the exposure. Several persistent trains were observed with this instrument at its lowest resolution.

3. Results

The train left by the 3:30:33 UT meteor on November 18, 1999 (Figure 2), provided both successful pointing and data gathering in a timely manner. We obtained six 30s exposures for the train starting at 4m59s, 6m00s, 6m52s, 13m29s, 14m8s, and 15m03s after the first appearance of this meteor. The train was observed low in a southern direction towards the coast of Tunisia. Individual spectra are too noisy for analysis. The combined spectrum is reproduced in Figure 3, yet without correction for spectral response of the instrument. The spectra show the forbidden green line at 557.7 nm of OI, Na emission at 589.5 nm, and a broad

continuum emission that stretches from about 500 to 700 nm. There is also a spectral feature at about 633 nm. The continuum emission is not observed in the background airglow spectrum taken earlier that night (lower part of Figure 3). The 589.5 Na emission is weaker in the background airglow also, but the 557.7-nm OI line is not.

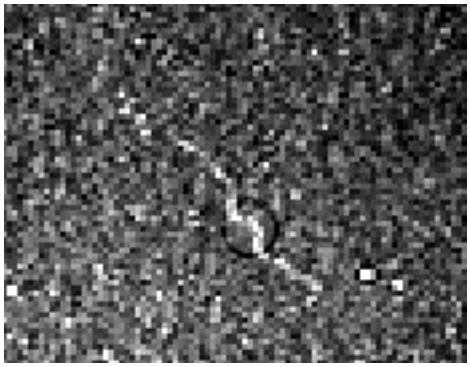

Figure 2. Persistent train of 3:30:33 UT meteor targeted in this work. The dark circle indicates the field of view (0.1° diameter) and the approximate position of measurement.

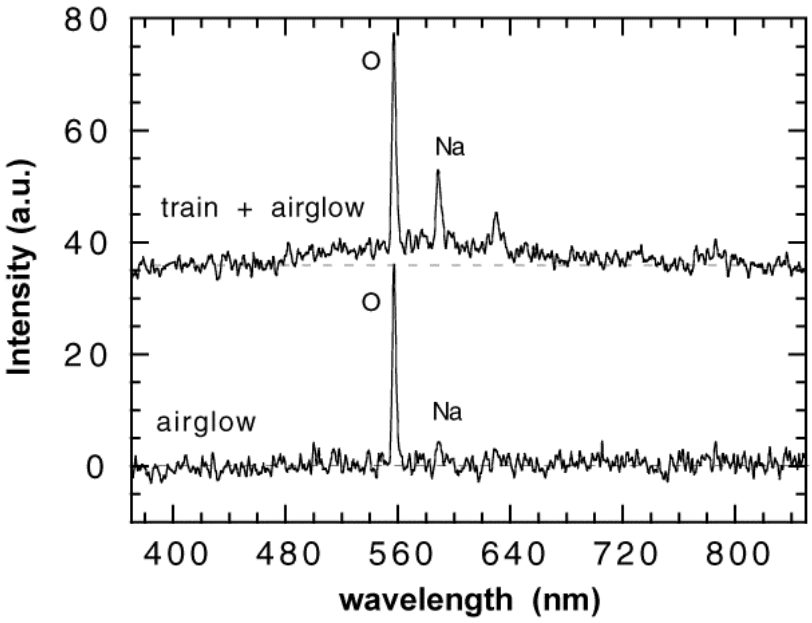

Figure 3. Persistent train spectrum of the 3:30:33 UT meteor and background airglow emission observed with the same instrument.

Figure 4 shows the result after subtraction of the airglow spectrum and correction for the wavelength dependent sensitivity of the system. Note that the sensitivity of the visible channel falls off gradually below 450 and above 700 nm. After background subtraction, a residual 557.7-nm OI emission feature remains plus residual sodium and the broad continuum emission. OH Meinel bands may be present at 610-640 nm (6,1) and 680-700 nm (7,2).

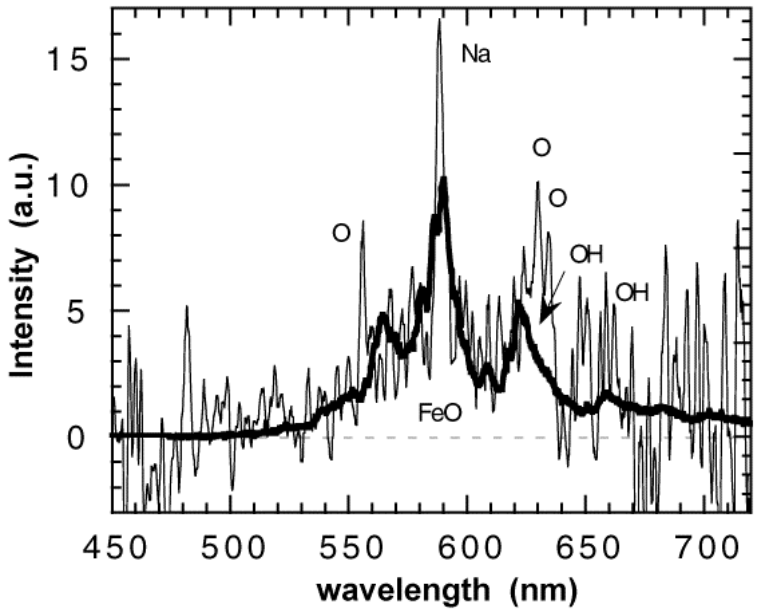

Figure 4. Persistent train spectrum of the 3:30:33 UT meteor after subtraction of airglow background and normalization for the instrument's spectral response. Also shown is an overlay of a laboratory spectrum of the FeO "orange arc" emission bands (thick line).

The spectroscopic observations confirm that the most intense emission arises from the Na D-line, almost certainly through the Chapman airglow mechanism:

$$Na + O_3 \rightarrow NaO + O_2 \quad (1)$$

$$NaO + O \rightarrow Na(3^2P, 3^2S) + O_2 \quad (2)$$

where the branching ratio of reaction 2 to produce the Na(3^2P) state, that then emits an orange photon at 589 nm, is ~10% (Clemesha *et al.*, 1995).

The broad continuum points to a molecular emission band, which probably arises from:

$$Fe + O_3 \rightarrow FeO(^5\Delta \text{ etc.}) + O_2 \quad (3)$$

$$FeO + O \rightarrow Fe + O_2 \quad (4)$$

where the exothermic reaction 3 produces FeO in excited electronic states, leading to emission in the “orange arc” bands between 570 and 630 nm with more than 2 % efficiency (West and Broida, 1975; Helmer and Plane, 1994). Figure 4 compares the observations with our laboratory spectrum of FeO emission. This spectrum was obtained in a fast flow tube operating at 1 mbarr of N_2 and 298K. Fe atoms were generated by the pulsed laser ablation of a pure iron rod using a Nd:YAG laser at 532 nm (energy ≈ 20 mJ pulse^{-1}), and mixed downstream with O_3 (concentration ≈10^{12} cm^{-3}). Further downstream, corresponding to a flow time of 8 ms, the chemiluminescence spectrum was recorded using a 0.5 m f/6.9 Czerny -Turner spectrometer connected to a 1024 x 256 pixel charge coupled device (CCD) detector. The resolution of the instrument with the slits set to 200 μm was approximately 2.2 nm, corresponding to a sampling ratio of 9 pixels per full width at half maximum (FWHM).

The "orange arc" bands of FeO between 500 and 700 nm match the width and shape of the continuum emission in the meteor train very well, particularly the peak around 590 nm and a significant contribution to the 633 nm feature. However, the feature at 553 nm does not appear to be well matched within the noise of the observations. One should bear in mind that our laboratory spectrum was taken at a much higher pressure than encountered in the upper mesosphere and lower thermosphere. Thus, the relative heights and shapes of the three dominant FeO peaks may be somewhat different at low pressure when quenching is absent.

5. Discussion

It is clear from Figure 2 that significant background emission may have been picked up by our spectrometer. The natural airglow emissions are much like the train emissions. Could the broad band be due to artificial

light from coastal villages of Tunisia? Such contamination was not present earlier in the night, when ARIA was farther to the East. Indeed, the difference-spectrum (Figure 4) is not unlike that of airglow emission spectra monitored at Kitt Peak and Mount Hopkins Observatories, for example, which also show a broad emission feature centered at 590 nm (e.g., Massey and Foltz, 2000). This broad emission feature was assigned to high-pressure sodium (HPS) lamps of nearby cities. Upon further inspection, we find that the feature does not increase in intensity with other artificial emissions. Also the shape of the airglow band is somewhat broader and slightly shifted from the HPS emission in the light polluted skies over Silicon Valley (Figure 5).

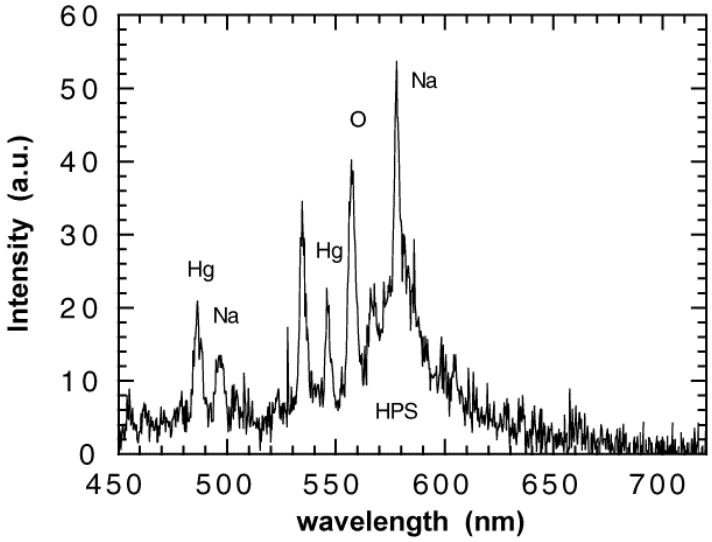

Figure 5. High-pressure sodium (HPS) and other artificial emissions measured with the same instrument in the light-polluted Silicon Valley, California.

Support for the assignment of the key chemical mechanisms of Equations 1-4 comes from the low-resolution slit less spectrum of a bright persistent train reported by Borovicka and Jenniskens (2000). The train itself is visible as excess emission in zero order, while the first order spectrum clearly identifies the train as the source of the spectral feature. This spectrum has a nearly identically shaped broad band as in Figure 4. The NaI emission associated with this train was not observed,

possibly because of the lower spectral resolution. The broad band is slightly shifted to higher wavelengths, but the slit less technique can cause wavelength errors of at least ± 20 nm. Borovicka and Jenniskens found the band to be centered on 610 nm, which led to a tentatively assigned to NO_2. Indeed, a complex series of visible NO_2 bands has been observed due to chemi-luminescence from the radiative recombination reaction of NO and O. In the past, a pseudo continuum of the sum of many overlapping bands of this radiative reaction was proposed as the source for the continuum in the airglow (Hertzberg, 1966, p. 507). However, the peak in the NO_2 pseudo continuum is at about 400 nm, with a secondary maximum at, amongst others, 660 nm. Also, it is not clear how to sustain the NO_2 emission in the persistent trains. We conclude that the assignment to FeO emission is the more likely.

The presence of the two red 630.0 and 636.4 nm "auroral" lines of atomic O in the spectrum is surprising. These lines are produced from $O(^1D)$ with a radiative lifetime of over 100s. However, the excited state is rapidly quenched by N_2 and O_2 collisional de-excitation in the lower thermosphere and upper mesosphere. Typically, $O(^1D)$ emission is observed by satellites only in the altitude range 210-270 km where the pressure, and hence the quenching rate, is very low. Unless the highly unlikely scenario that an aurora was in progress simultaneously that could be seen from the Mediterranean looking in a south/south-western direction, OI line emission cannot be entirely responsible for the large 630 nm peak. FeO emission can significantly contribute to this peak, as well as the OH Meinel bands. Indeed, the peak is much broader than due to an atomic emission (see, the width of the 558 nm green line).

Unlike the spectra obtained by Abe *et al.* (2000), there is no strong MgI emission in our spectra. The possible feature around 520 nm, if real, is probably due to $N(^2D\text{-}^4S)$ emission at 519.9 nm. A $Mg(^3S\text{-}^3P)$ line at 520 nm would be hard to explain because $Mg(^3S)$ is excited by over 5 eV. The only obvious mechanism for exciting Mg to this level is via dissociative recombination of molecular ions with electrons:

$$Mg^+ + O_3 \rightarrow MgO^+ + O_3 \qquad (5)$$

$$Mg^+ + O_2 (+ M, \text{third body}) \rightarrow MgO_2^+ \qquad (6)$$

$$Mg^+ + N_2 (+ M) \rightarrow MgN_2^+ \qquad (7)$$

$$MgX^+ + e^- \rightarrow Mg^* + X \qquad (8)$$

where MgX^+ represents the molecular ions formed in reactions 5–7 (Rowe *et al.*, 1981). Abe *et al.* reported MgI in the spectrum from a bright Leonid fireball at about 10 nm resolution (380–600 nm) wherein this assignment was confirmed by the presence of several other MgI lines at 457, 470, and 553 nm. However, they also identified atomic lines of CaI (443 nm) and FeI (418, 486 and 537 nm), although with less good agreement between theory and observation. Possibly, these emissions are of relatively short duration. The train spectra were obtained shortly after the meteor had extinguished, at a time when the train was still spatially confined on the sky and measured gas temperatures were relatively high. It is possible that the MgI emission is part of a phenomenon called the meteoric afterglow (Borovicka and Jenniskens, 2000), but less important when the train has had time to cool.

In summary, the optical spectrum discussed here confirms the classical mechanism for train luminosity. We find that FeO rather than FeI contributes to the train luminosity. Future work under better observing conditions and with improved instruments are expected to increase the number of metal atom catalysts beyond Na and Fe, and may reveal other chemical processes in the meteor path.

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