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High-resolution optical spectroscopy of 2001 Leonid meteors with a cooled CCD camera

By

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Abstract: A brief overview is given of the high resolution spectra of Leonid meteors obtained by cooled CCD slitless spectrographs during the 2001 Leonid Multi-Instrument Aircraft Campaign. All meteors are dust grains that were ejected by comet 55P/Tempel-Tuttle in 1767. Different parts of the spectrum provide information about physical conditions in the meteor air plasma, elemental abundances of meteoric matter, and the fate of the ablated organic matter.

1. INTRODUCTION

Cooled CCD cameras are a recent development in the field of meteor spectroscopy. They offer significant advances over more traditional photographic techniques (Ceplecha 1968, Bronshten 1983, Borovicka 1993). They extend the spectral sensitivity to above the 600 nm cut-off of most photographic film used in past spectroscopic surveys. In particular, they are sensitive to the strong air plasma emissions from N_2, O and N in the range 700–880 nm. They also offer much higher sensitivity and linearity over a large dynamic range, thus enabling similar high-resolution spectroscopy for relatively faint meteors of magnitude +1 to −2 than normally obtained for fireballs of magnitude −6 to −10. This makes it possible to derive quantitative spectroscopic information on elemental abundances and the fate of ablated organic matter from optically thin plasma emissions.

The first application of a cooled CCD meteor spectrograph was during the 1998 Leonid Multi-Instrument Aircraft Campaign (Jenniskens et al. 1999), with a specially designed instrument to search for weak emissions of C, C2 and CN. The high altitude observations minimize absorptions from water vapor in the near infrared part of the spectrum, thus not hampering the interpretation of the meteor atom line and molecular band emissions. At the time, only seven meteor spectra were obtained, because Leonid shower rates remained relatively low (Jenniskens et al. 2000). Additional 2–3 spectra each were obtained during routine operations at annual Perseid and Geminid showers. No data were obtained during the 1999 Leonid meteor storm due to a technical problem with the framegrabber card that could not be repaired in the field. We eagerly anticipated a second opportunity during the 2001 Leonid meteor storm. The results

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exceeded our expectations. Some 23 meteor spectra were recorded during a flight from Alabama to California at the time of the encounter with the dust ejected by comet 55P/Tempel-Tuttle in 1767. This paper gives an impression of some of the first results from this data.

Fig. 1: NASA Ames Astrobiology Academy student Emily Schaller operated the cooled CCD spectrograph during the 2001 Leonid MAC mission. The instrument was mounted on tripod and stored during takeoff and landing.

2. THE INSTRUMENT

The instrument is described in some detail elsewhere (Jenniskens et al. 2003a). The instrument is shown in Figure 1. In brief, a Pixelvision camera with two-stage thermoelectrically cooled 1024 $\times$ 1024 pixel back illuminated SI003AB CCD with 24 $\times$ 24 micron pixel size (24.5 $\times$ 24.5 mm image region) was used in unintensified mode to keep as high spectral resolution as possible. To limit the readout time (dead time) to less than 1 second, we recorded with 4x binning in the direction perpendicular to the dispersion direction. The imaging optics was an AF-S Nikkor f2.8/300D IF-ED 300 mm telephoto lens, providing a field of view of 5 $\times$ 5°. In front of the lens is mounted an 11 x 11 cm plane transmission grating #35-54-20-660 by Richardson Grating Laboratory, with Aluminum coating on a 12 mm BK7 substrate. We measured a dispersion of 540 l/mm and blaze wavelength of 698 nm (34°). This provides a full 2^{nd} order spectrum out to about 925 nm. The spectral response curve of the instrument is shown in Figure 2. What part of the spectrum is recorded depends on the angle between the position of the meteor on the sky and the viewing direction of the camera. The effect of vigneting is discussed in Jenniskens et al. (2003a). Integration times were 0.8 s. With aircraft motion, this resulted in a limiting star magnitude of about +11. The limiting magnitude for meteors is about +6 because of their higher angular velocity, while spectra are recorded for meteors brighter than +4. Good signal-to-noise data are obtained for meteors that are a factor of 100 less intense than traditional results from photographic techniques, meteoroids small enough to be in the rarefied flow regime.

3. RESULTS

A total of 23 spectra were recorded over a period of about five hours from an altitude of 37,000 ft (Jenniskens & Russell 2003). The camera was pointed in a forward (northwestern) direction, with the grating positioned at various directions over the course of the mission (Figure 1). Simultaneous imaging of the sky with intensified cameras provided zero-order images of the meteors even for spectra recorded in 2^{nd} (and 3^{rd}) order. This was a one-plane

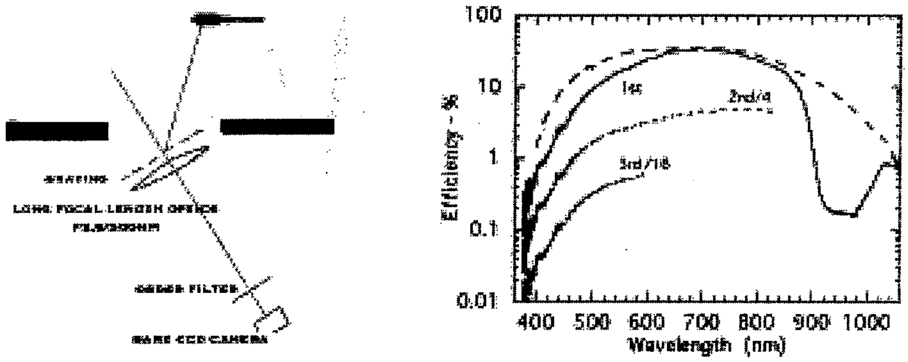

Fig. 2: Instrument layout (left) and spectral response curves for the 1st, 2nd and 3rd order part of the spectrum (right).

mission and no stereoscopic information is available, unless the meteor was photographed at one of our ground stations in Arizona.

3.1 Air plasma emissions

All spectra pertain to wavelength regions longward of 550 nm, possibly because of the higher probability of catching Leonids far from the viewing direction near the horizon. Typical examples of "normal" Leonid spectra in the 700–860 nm range are shown in Figures 3. The top first order spectrum shows diffuse emission from the N_2 first positive bands and strong atomic emission lines of oxygen and nitrogen. The meteor has a brief end flare. The meteor moves from top right to bottom left. The onset of the emission is the start of the exposure. The strongest lines and molecular bands are identified. The bottom spectrum is part of the same wavelength range in 2nd order. This is a magnification of the left part of the top figure. The extracted spectrum is shown in Figure 4. Most emission "lines" are in fact rotational and vibrational structure in the $\Delta v = +2$ first positive band of molecular nitrogen. Superposed are emission lines from atomic nitrogen and some meteoric metal atoms, including 3rd order lines of iron (466–512 nm). Background star images have been removed. The wavelength scale runs left to right, the meteor moved from bottom to top, increasing in brightness. The end of the exposure terminates the spectrum.

The presence of both nitrogen atoms and first positive band emission of molecular nitrogen is a sensitive thermometer for air plasmas in Local Thermodynamic Equilibrium (LTE). At chemical equilibrium, the ratio of atoms and molecules is determined by the dissociation equilibrium. By comparing our observations with LTE air plasma models, we can also use the measured ratios of oxygen lines relative to the molecular N_2 emission as a measure of temperature. From the full sample of available spectra, we measured the magnitude dependence reproduced in Figure 5 (From: Jenniskens et al. 2003b). Note that the temperatures are in a narrow range and there is no clear dependence with meteor mass over this magnitude range.

The close agreement with the LTE results is surprising. If the emission is due to collisional excitation of compounds, one would not necessary expect there to be such equilibrium (Bronshten 1983). Indeed, there are significant discrepancies between observed line ratios and the values calculated for LTE models. The relative N_2 band intensity for different Du is also not what is expected for an LTE emission (Laux 1993). These discrepancies can provide important clues to the exact excitation mechanism in future modeling.

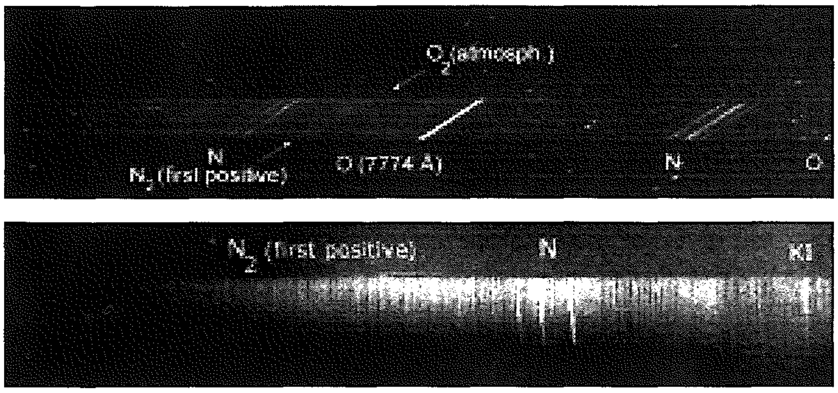

Fig. 3: Top: spectrum of the 10:44:58 UT Leonid meteor between 703 and 843 nm in first order. Bottom: spectrum of the 09:42:25 UT Leonid in the range 699–768 nm in second order.

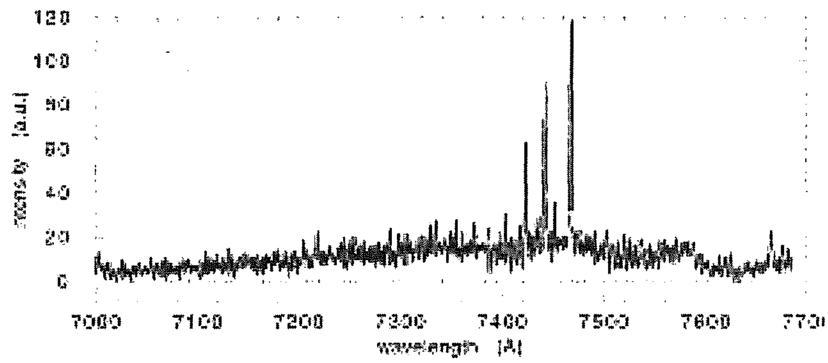

Fig. 4: Extraction of the bottom 09:42:25 UT spectrum. Most of the shown structure is due to structure in the $\Delta v = +2$ first positive band of N_2.

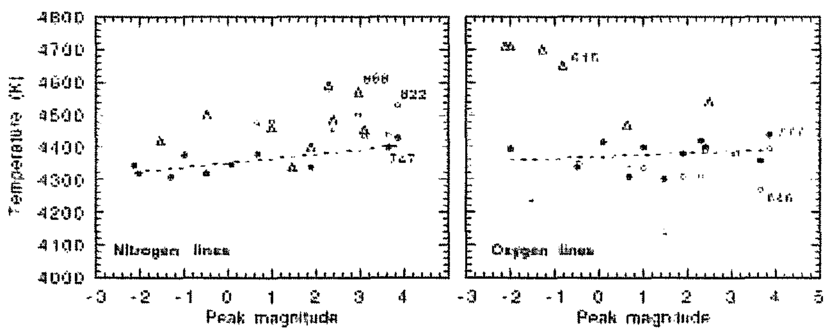

Fig. 5: Magnitude dependency of temperatures derived from various line intensities relative to that of molecular nitrogen. Symbols refer to the wavelength (nm) for the various lines used (From: Jenniskens et al. 2003b).

3.2 Metal atom abundances and ablation process

There is much color variation from one Leonid to the next. Most of that color variation is due to varying amounts of emissions from the air plasma and the metal atom ablation products. A typical spectrum rich in metal atom lines is shown in Figure 6. Now, strong metal atom emissions in the near-UV 3rd order part of the spectrum, such as the strong Ca^+ (Ca II) lines, are superimposed on the 2nd order spectrum. Most lines are from iron, but other elements are also identified: Mg, Ca, Mn, Si, Al, and Na, and also Ti, Cr, V, Ni, and K. This spectrum has proven valuable for calculating the elemental composition of Leonid meteors (ongoing work). Metal atom line intensity ratios do not change along the path, until the peak of the flare. Most volatile compounds, including iron, are in found to be in solar abundances. However, magnesium and especially calcium and aluminum are underabundant. It could be that this signifies a true under abundance in the cometary matter, or that those elements are not fully ablated and left in some residue.

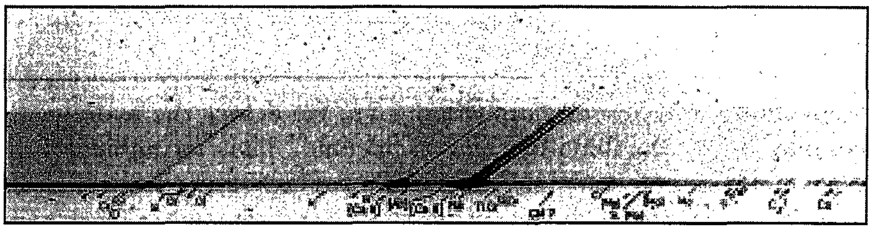

Fig. 6: Spectrum of the 09:05:58 UT Leonid meteor. The exposure starts at top and includes the end flare of the meteor at the bottom. Line identifications between brackets refer to 3rd order lines.

Indeed, at the end of the trajectory atom line ratios start to deviate significantly. First iron, then Mg and Na, and then Ca and Al are lost. This sequence is consistent with the loss of minerals during flash heating of meteoritic material (Alexander, 2002).

3.3 Fate of ablated organic matter

The search for organic compounds has proven unsuccessful. Our best chance of probing the fate of organic matter in the rarefied high-Mach number flow of small meteoroids is to look for the production of the CN radical. This radical is most easily detected because of a strong $B \rightarrow X$ transition of low energy potential with a band head at 388 nm. Early work by Ceplecha (1971) identified CN in the -12 magnitude flare of a cometary meteoroid, but the identification is in doubt by the many iron lines in the region. Our first efforts at detecting CN during the 1999 Leonid Multi-Instrument Aircraft Campaign focused on slitless spectroscopy of meteors in first order, using an UV sensitive intensified CCD camera (Abe et al. 2000, Rairden et al. 2000). The best result set an upper limit of 1 CN molecule per 3 Fe atoms, only about a factor of 2 less than expected if all nitrogen would be released in the form of CN radicals (Rairden et al., 2000).

The new data in hand resolve the individual iron lines in this region. The band head of the CN molecule is found to be in between strong iron lines. Our results put a strong lower limit to the presence of CN molecules in the meteor plasma, with less than one CN per 30 Fe atoms (Jenniskens et al. 2003a).

We do, however, see some evidence of the loss of functional groups from organic matter in the meteoroid. Hydrogen is released from the -8 magnitude 10:52:32 UT Leonid during

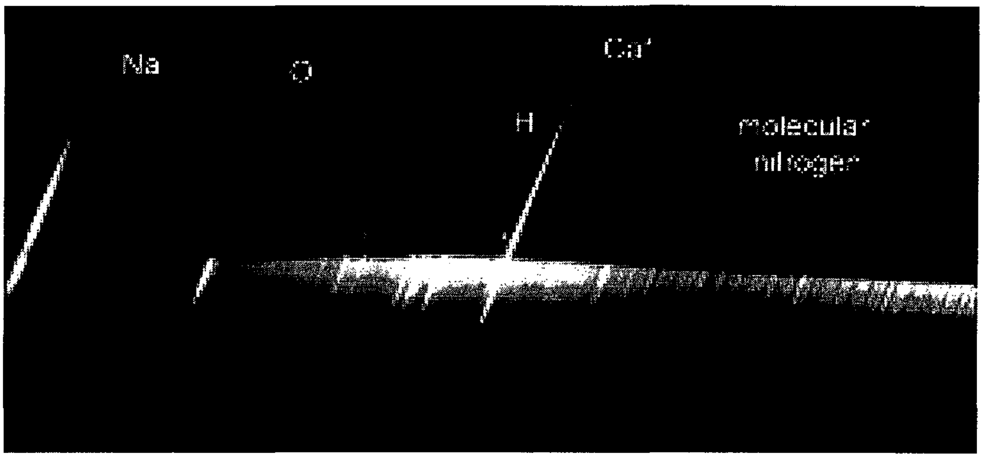

Fig. 7: Loss of hydrogen in the -8 magnitude 10:52:32 UT Leonid fireball following a catastrophic fragmentation. The spectrum is expanded by a factor of 2 in the vertical direction.

catastrophic fragmentation in an end flare (Figure 7). We detect the hydrogen line next to a strong line that may be a recombination line of calcium. That recombination line may well have confused past analysis of less high-resolution data. Once created, the hydrogen alpha line is visible until the meteor fades. The analysis of these data demands a clear understanding of the excitation conditions of this high-energy transition and is ongoing.

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