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Optical spectral characteristics of sprites

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Abstract. A TV slit spectrograph was used to obtain the first optical spectra of sprites. Twenty-five events were observed over a thunderstorm on the border of Nebraska and Colorado on the night of 22 June, 1995 between 0700 and 0900 UT. For 10 of these events optical spectra were measured in the wavelength range from 540 to 840 nm. After correcting for the spectrograph response function, digitized spectrograph video images are used to measure the wavelengths of and ratios between the emissions. All emissions are found to be of the first positive bands of N_2. There is no evidence of the Meinel bands of N_2^+ indicating that the mechanism responsible for sprites produces little or no ionization at 70 km altitude.

Introduction

Large transient optical phenomena in the middle atmosphere associated with lightning discharges in thunderstorms have been studied with great intensity in the last several years [*Vaughan and Vonnegut*, 1989; *Franz et al.*, 1990; *Vaughan et al.*, 1992; *Sentman and Wescott*, 1993; *Lyons*, 1994; *Sentman et al.*, 1995; *Wescott et al.*, 1995; *Winckler*, 1995]. Two phenomena have been distinguished: red sprites [*Sentman et al.*, 1995] and blue jets [*Wescott et al.*, 1995]

The sprites have a duration of less than 17 ms, and in their vertical totality span the distance from cloud tops (on the order of 15 km) to altitudes of 90 km. The duration of a blue jet is on the order of 200 ms, with propagation upward to 40 km at speeds of 100 km/s. As measured by a color video camera, sprites are primarily red, with lower blue sections [*Sentman et al.*, 1995], and jets are blue [*Wescott et al.*, 1995]. More precise emission information has not previously been obtained. Additional measurements of these optical phenomena includes the relative location of the events with respect to lightning activity in the storm [*Sentman et al.*, 1995; *Wescott et al.*, 1995; *Boccippio et al.*, 1995], the duration of emissions [*Wescott et al.*, 1994; *Winckler*, 1995], and the relationship between sprites and ELF/VLF emissions [*Boccippio et al.*, 1995].

Many questions remain to be answered about sprites and jets: their source mechanisms [*Taranenko and Roussel-Dupre*, 1995; *Milikh et al.*, 1995; *Pasko et al.*, 1995], possible effects in the mesosphere and stratosphere (e.g. chemical), and possible roles sprites or jets may play in the global electric circuit [*Wilson*, 1956]. These physical processes, as well as questions pertaining to optical detection during daylight and total optical energy [*Sentman et al.*, 1995], can be addressed if the spectral emissions present in the sprites are identified.

For these reasons we performed measurements of optical spectra of sprites during an observing campaign at the High Altitude Laboratory, operated by the University of Denver on Mt. Evans, CO (Lon 105° 38' Lat 39° 35' Alt 4.30 km). Measurements were made over the optical bandpass from 540 to 840 nm.

Instrumentation

To measure the emissions from a phenomenon of such brief duration, we employed an intensified CCD (ICCD) TV slit spectrograph system which is used for auroral studies [*Hallinan et al.*, 1985]. The light enters via a 135 mm f/1.2 Vivitar lens focused onto a 3.0 cm variable width slit. The light is collimated with a 305 mm concave mirror, and is dispersed by a 600 lines/mm transmission grating. The first order spectrum is focused onto an image intensifier (VARO) by a 105 mm f/0.87 Delfte lens. The image from the intensifier is reduced to fit onto a 7.9 × 6.0 mm Pulnix CCD chip via a set of transfer lenses. The effective image area of the CCD chip before reduction is 20.2 × 15.4 mm which corresponds to a spectral range of ≈ 300 nm, and a field of view along the slit of 12.5 degrees. To maximize the likelihood of detection, the slit was oriented parallel to the horizon. The resulting video image has spectral information from left to right, and image information (along the slit) from top to bottom. To verify that the signal in the spectrograph was indeed from a sprite, as well as to assist in aiming the system, a similar ICCD camera with a field of view of 15° × 10° was bore sighted with the spectrograph.

Both cameras were operated at TV frame rates of 60 fields per second (30 frames per second) and recorded to videotape via SONY 3/4" U-Matic tape recorders. Timing was obtained from a GPS receiver and the vertical synchronization of the two cameras was slaved for consistent timing of each TV frame. Universal time was recorded on each frame in the SMPTE format `hh:mm:ss;ff` where `ff` is the frame number (00 - 29).

To prepare the data for analysis the video images were digitized using a Truevision TARGA+ image capture

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board. The spectra of Hg, Ar, and Xe lamps were recorded at the beginning and end of each night of observation allowing for a consistent wavelength calibration. The prominent lines from the lamps were used to set the wavelength scale via the standard first order dispersion formula, $\lambda = d \sin\theta$, where λ is the wavelength of the light, d is the line spacing of the grating (1.67×10^{-6} m), and θ is the angle of the light emerging from the grating with respect to the normal of the grating. In the specific examples shown in this paper the spectral range is 540 nm (18.14°) to 840 nm (29.41°).

Observations

The Mt. Evans Observatory, located at 14,125 feet, allows clear viewing conditions above the local and intervening cloud cover. On the night of June 22, 1995, storms over the border between Colorado and Nebraska were observed, as illustrated in a radar/lightning strike map in Figure 1. The Mt. Evans Observatory is marked by a square and the approximate location of the sprite is marked by a solid circle. The distance to the sprites was approximately 500 km.

During the period from 0700 to 0900 UT there were more than 25 sprite events recorded. Ten of these events occurred within the field of view of the spectrograph and spectra were recorded. One example of a visual observation of a sprite and the corresponding spectrum is shown in Figure 2. The dashed line across the scene camera represents the elevation and the horizontal field of view of the slit on the spectrograph. Note that spatial features along the slit are imaged in the spectrograph, specifically the gap between the two bright sprites in the scene camera.

Analysis and Results

To improve the signal to noise ratio of the spectral data, the video scan lines near the peak intensity of the spectrum were averaged for a single frame. This averaged spectrum was normalized with the response function of the spectrograph which was obtained prior to the observing campaign, using a calibration lamp and reflecting screen of known spectral characteristics. Figure 3 shows the corrected spectrum for the event shown in Figure 2 at 07:24:20;15 UT. The slit was set such that the spectral resolution was about 10 nm. The wavelengths for the P_{11} heads of the first positive band system of N_2 (N_2 1P) are indicated above the spectrum, and show good correspondence to the measured bands. Further, the vertical lines under the spectrum show the intensities of each band as calculated for auroral electron precipitation [*Vallance Jones*, 1974] and show good agreement with the measured spectrum, except for the 3-1 band, which is significantly reduced in the spectrum.

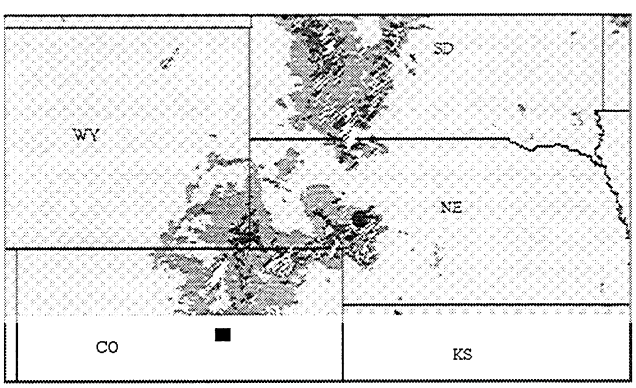

Figure 1. National Lightning Detection Network Data. Denver University's High Altitude Lab is indicated with a black square. The approximate location of the sprite is indicated with a black circle. The dark grey patches are precipitation as measured by radar, and the white patches associated with the precipitation are measured lightning strokes. The blank lower region is where weather data were not available

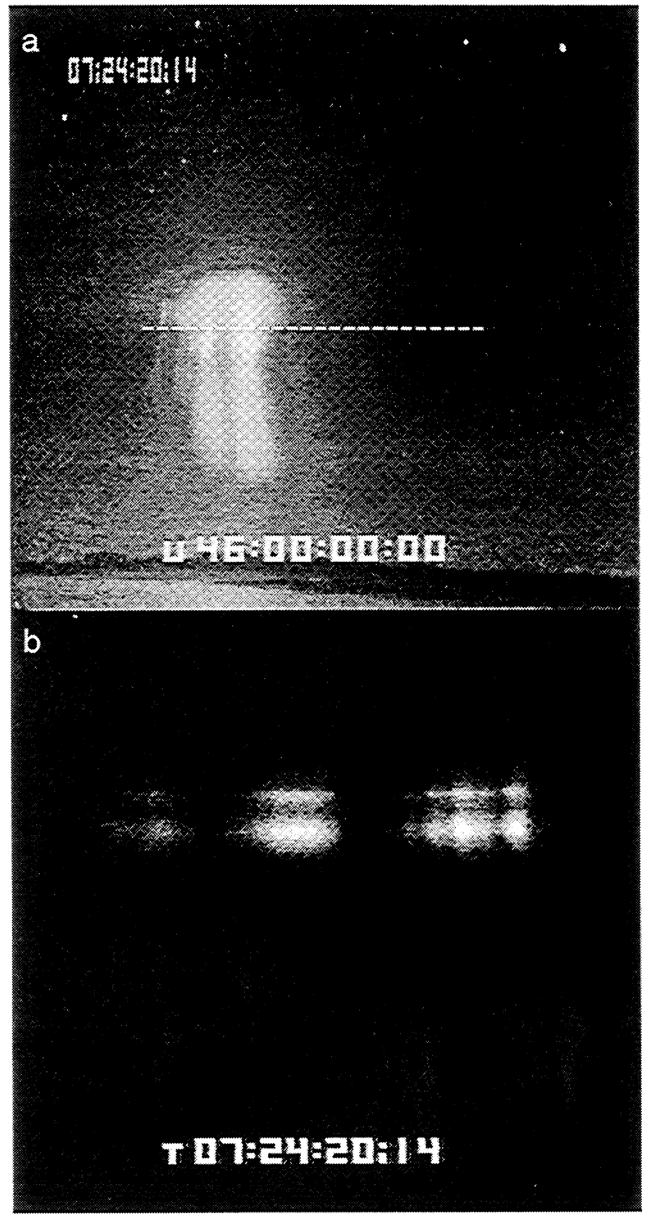

Figure 2. Raw digitized video images of (a) the scene camera and (b) the spectrograph. Note the spectrograph image is rotated, in that the slit direction is vertical.

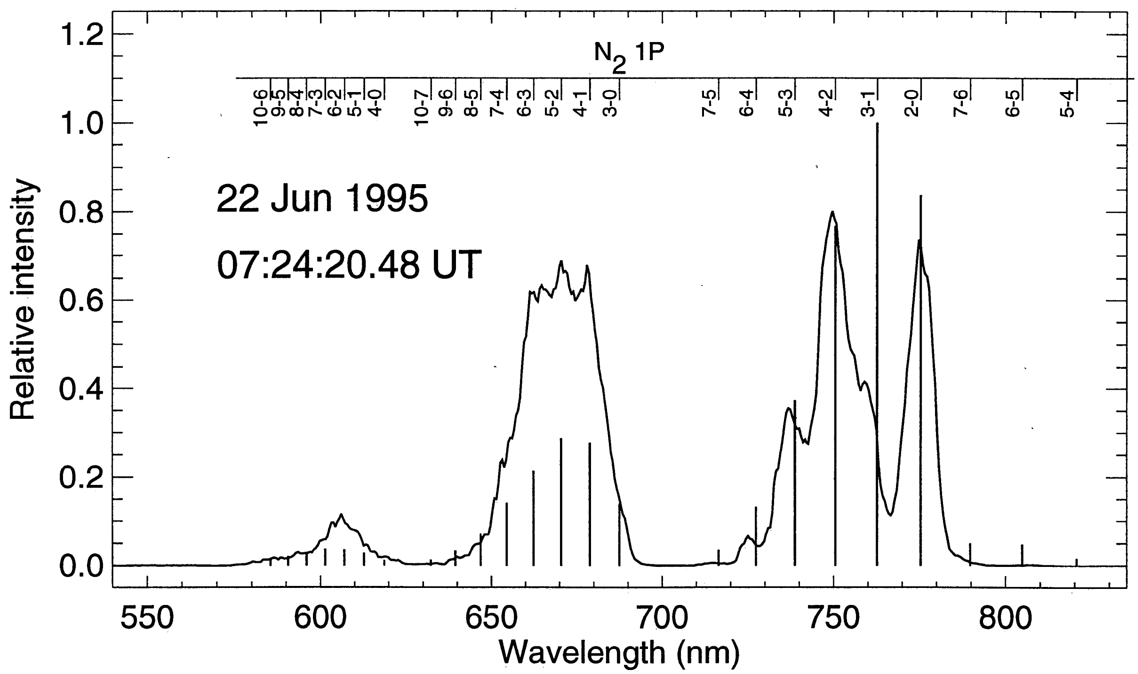

Figure 3. Reduced spectrum from 07:24:20;14 UT. The wavelengths for the band heads for different transitions of the first positive bands of N_2 are marked at top. The vertical lines show the auroral intensities of these transitions (see text for details).

A second spectrum is shown in Figure 4 for an event on the same night at 07:04:39;29 UT. A narrower slit setting in this example improved the spectral resolution to about 6 nm. However, the sprite event was less intense, and the signal to noise ratio is reduced. Again the predominant emissions are seen to be N_2 1P and the intensities are in good agreement with auroral intensities. No other emissions are seen above the apparent noise level (the feature at 575 nm is due to a bright scintillation in the intensifier).

Discussion

Since N_2 is the most abundant species in the 40-90 km altitude range, it is not surprising that its emissions are present in the spectrum. The detailed spectral profile of the first positive system is virtually identical to that of the pinkish/red lower border of some auroral curtains. The similarity to auroral spectra suggests that the physical process responsible for sprites is primarily electron impact excitation, as has been theoretically predicted

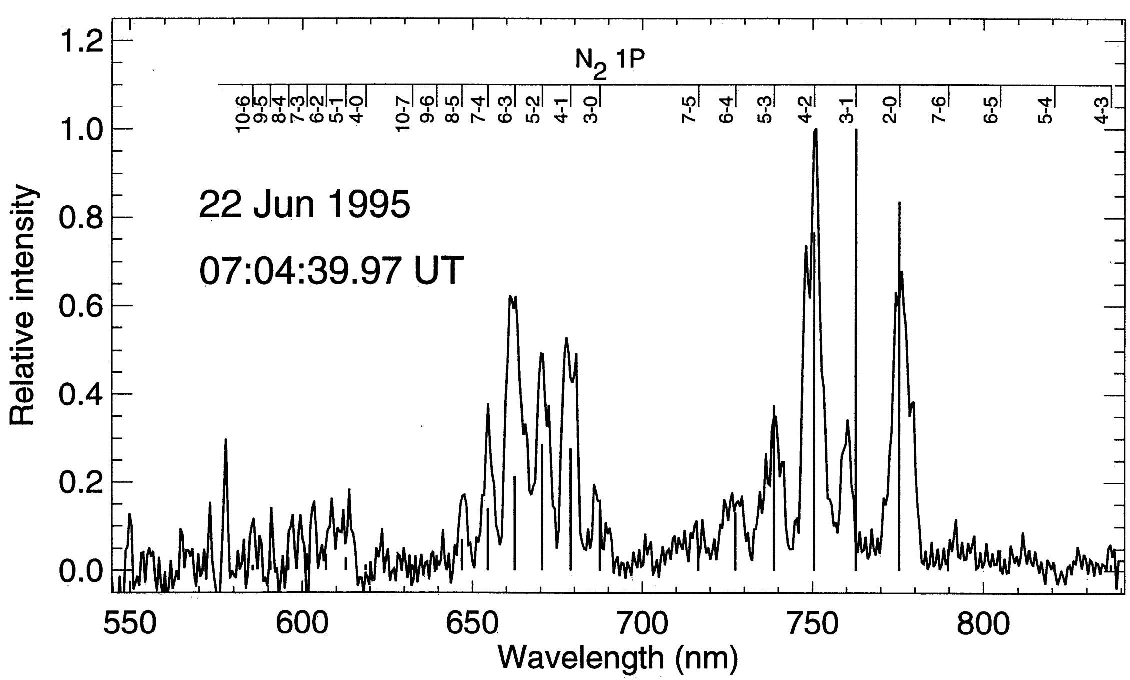

Figure 4. Reduced spectrum from 07:04:39;29 UT. The format is the same as that in Figure 3.

by the runaway electron model [*Taranenko and Roussel-Dupre*, 1995], the quasi-electrostatic electron heating model [*Pasko et al.*, 1995], and the radio wave heating model [*Milikh et al.*, 1995]. The reduced 3-1 band is due to absorption by the 0-0 transitions in the O_2 atmospheric bands – a similar absorption is seen in auroral spectra [C. S. Deehr, personal communication, 1995].

By visual inspection, the spectra show no significant signals from the Meinel bands of N_2^+, which are excited primarily by electron impact ionization of N_2. The threshold energy to excite N_2 1P is 7.35 eV, so the mechanism that creates sprites produces a significant population of electrons above this energy. The threshold energy to excite the Meinel bands of N_2^+ is 16.73 eV. The lack of significant Meinel band emissions may indicate that the source mechanism for sprites does not create a significant electron population above this energy. The rather broad spectral resolution used for most of the measurements (e. g. Figure 3) may result in the Meinel bands being heavily blended with the 1P spectrum. We note however, that the two strongest Meinel bands, the 4-1 and the 2-0 bands are separated from the nearest strong 1P bands by $\approx$ 21 and $\approx$ 10 nm respectively. These Meinel bands should be resolved, given the spectral resolution of 10 nm, if there is sufficient signal.

Sentman et al. [1995] report that, as observed with an enhanced color TV system, many sprite events showed a significant amount of blue signal in the lower altitude portion of the sprite, especially those with tendril like structures similar to those seen in Figure 2. For nitrogen there are two likely candidates for blue emissions, the second positive of N_2 and the first negative of N_2^+. Emissions from the second positive band system of N_2, with a threshold energy of 11.0 eV, would not be present in the wavelength range of the spectrograph. The spectra taken so far have been near the brightest portions of the sprites, near 70 km where the color TV system shows almost exclusively red, which is verified by the spectra. The events showing blue tendrils indicate that the electron distribution becomes harder at lower altitude perhaps becoming more 'lightning-like'.

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