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Sprite Spectra; N_2 1 PG band identification

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Abstract. Imagery and spectra of high altitude luminous flashes, otherwise known as sprites, occurring in the stratosphere/mesosphere above electrically active cumulonimbus clouds were acquired on July 16, 1995 from an observation site near Ft. Collins, Colorado. The spectra, resolved from ~4500-8000 Å included four spectral features in the 6000-7600 Å region which have been identified as N_2 1PG system with Δv=2,3, and 4 from the v=2,4,5,6 vibrational levels of the $B^3\pi_g$ state. The spectra were lacking in other features such as the N_2^+ Meinel or the N_2^+ 1st neg system indicating that the electron energy causing the excitation is quite low.

Introduction

Direct evidence for coupling from lightning events to the upper atmosphere is found in the optical observation and recording of cloud-ionosphere (CI) discharges or sprites from thunderstorm regions [Franz et al., 1990; Winckler et al., 1993; Sentman and Wescott, 1993; Lyons, 1994; Sentman et al., 1995]. The images of these CI discharges were obtained by ground and aircraft-based, low light level television systems. Morphologically there are probably several distinct types of upward luminous phenomena associated with thunderstorms, the most common of which are the so-called red sprites [Sentman et al., 1995] which have been observed by red sensitive low light level television cameras from the ground and from aircraft. A second class of phenomena, "blue jets", which do not propagate beyond the stratosphere [Wescott et al., 1995] have also been identified. There are however no published spectral measurement of these type of events. Spectral measurements are exceedingly important because they can provide a remote sensing characterization of the physical and chemical processes resulting in the emission. In this paper we are reporting one of the first sets of spectral observations of upward discharge phenomena.

Observations

The instrument used in our observation is illustrated schematically in Figure 1 from a top view. It consisted of two channel bore sighted intensified CCD video camera system. The optics of the spectrometer channel is a copy of the transmission grating spectrometers used in the shuttle borne aurora and airglow investigations e.g. Mende et al., [1993]. The spectrograph consisted of an objective lens L1 (f=85 mm F/1.4) which projected the image of the scene on a plate which had a 25 mm long vertically oriented open slit. The slit was widened for the sprite observations and the slit width was approximately 0.3 mm producing an equivalent spectral resolution of about 9 nm. The light from the lens was collimated by L2, a 50 mm F/1.2 lens and diffracted by a transmission grating mounted on the back side of the prism. The prism grating combination (Grism) split the light into divergent beams into a horizontal fan according to wavelength. In Figure 1 three different monochromatic wavelength regions are illustrated as being focused at different part of the detector as λ_1, λ_2 and λ_3. An imaging lens L3 (50 mm F/1.2), focused parallel light rays on the intensifier photo cathode, therefore a given wavelength of light, appeared along a vertical line on the image intensifier photo cathode. The prism was used mainly to steer the light beam back to the center so that the center wavelength of the first order spectra appeared in the center of the image. Note, that the system is an imaging spectrometer and the distribution of luminosity of the image in the direction parallel to the vertical slit is preserved providing true vertical intensity profiles of the observed phenomena. The second optical channel the imaging camera was a simple low light level intensified CCD camera with a 50 mm F/1.4 photographic lens producing an approximately 20x15 degree field of view image on a 25 mm image intensifier. Both cameras had second generation image intensifiers with extended red S-20 photo cathodes. The image intensifiers were fiber optically coupled to the CCD-s. Both video cameras were scanned at standard video rates at 30 frames per second. The video signals were recorded on VHS video tape with suitable time codes marked on each video frame. The spectral responses of both channels were determined through calibration using light sources of known spectral profile. The imager sensitivity peaked at 490 nm dropping off uniformly and quite rapidly towards the blue/UV region to reach 25% sensitivity at about 400 nm. Towards the red it dropped off more gradually reaching the 25% sensitivity point at around 800 nm. The spectrometer had a similar S-20 detector but the grating blaze favored the red region putting the overall sensitivity peak at around 630 nm. The response dropped off quite symmetrically in either direction reaching 25% of peak sensitivity at 450 and 760 nm.

Both instruments were mounted on an azimuth and elevation mount. The bore sighting of the camera and spectrograph were pre calibrated using star images. This allowed the precise determination of the spatial position of the spectrograph slit in the imaging camera field of view and accurate real time pointing of the spectrometer through the imaging camera. This technique also permitted the recording of the two

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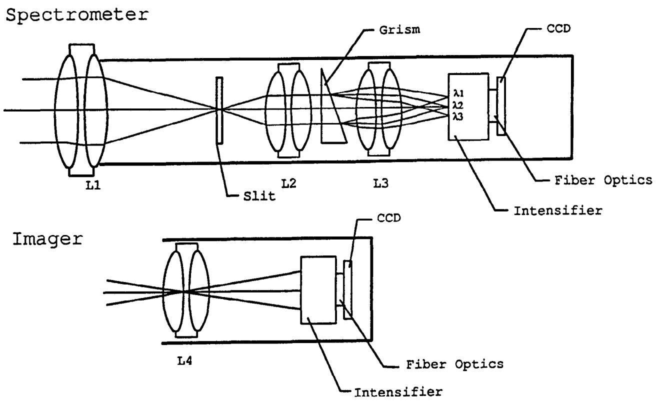

Figure 1. Instrument block diagram of the boresighted imager and spectrograph for Sprite Observations.

dimensional image of the sprite simultaneously with the sprite spectra.

The system was operated at the Yucca Ridge Field Station, operated by ASTeR, Inc. 20 km northeast of Ft. Collins, Colorado. This site provides for nearly unobstructed viewing of sprites and related phenomena to distances as great as 1000 km over the U. S. High Plains (approximately from northwest clockwise through directly south). Several sprite events were detected. On July 16, 1995 conditions were favorable for the observation of sprites although the storms were at some distance from Yucca Ridge. A sprite occurred at 05:16:48.534 UT and a sequence of video frames depicting the sprite is shown on Figure 2. To minimize unwanted backgrounds and nonuniformities a common background frame taken prior to each sprite set was subtracted from each image presented here. The onset of the sprite luminosity was coincident with the start of the underlying cloud illumination and continued for 3 video frames (33 msec each). The first two frames were the brightest with rapid decay in the third frame. The data shows an apparent motion of the luminosity in the westerly direction (towards the left). The far left feature for example on the third frame is actually brighter on the third frame than on the first two.

The storm under surveillance was located near Rapid City, SD, on an azimuth of roughly 25 degrees, and spanned a range from about 400 to 450 km. The radar derived precipitation area associated with the cell was approximately 25,000 km^2. Given the storm's size, and the presence of positive cloud to ground (CG) lightning flashes, it met the criteria found by Lyons [1995] for mesoscale convective systems over the US High Plains to begin generating sprites.

The sprite morphology was typical of the many observed during the campaign. It exhibited a curtain of smaller vertical striations (8-10) with the brightest portion near the top of the structure with less intense tendrils extending downward. From the star field present in the raw images the angular extent of the sprite could be measured accurately. The horizontal extent was 6.5 degrees, and at the estimated range of 450 km (based on the location of the parent positive CG) this implies a horizontal dimension of 51 km. The upper portion of the sprite extended to about 9.2 degree elevation, and locating the sprite within 25 km of the parent positive CG implies the highest extent to be 90 km. The bottom end of the same sprite was at 74 km. No indication of vertical propagation could be obtained from our low-light level video system operating at 16.7 ms field rate.

The spectral slit was vertical and located very close to the brightest event near the center of the image. On Figure 3 we present the spectrum which was observed simultaneously with the imager of Figure 2. Figure 3 is a spectrum in which the left edge of the image represents the 850 nm infrared region and the right edge corresponds to the blue cut off of the instrument at approximately at 430 nm. In the entire spectral range there were only four features. It is important to note that outside of these features there were no other discernible enhancements in the entire spectral range covered by the instrument. The region, which contained some discernible signal, was digitized. In Figure 3 a white frame marks this region. A spectral plot (Figure 4) was produced by summing vertically across the luminous features of Figure 3 and plotting the results along a horizontal (wavelength) axis. To facilitate wavelength calibration we have superimposed the spectra of a neon calibration light source taken while the instrument was still in position at the field site. Using the features of the neon gas a wavelength scale was determined and added to the figure. The wavelength scale permits the recognition of the major features of the sprite spectra.

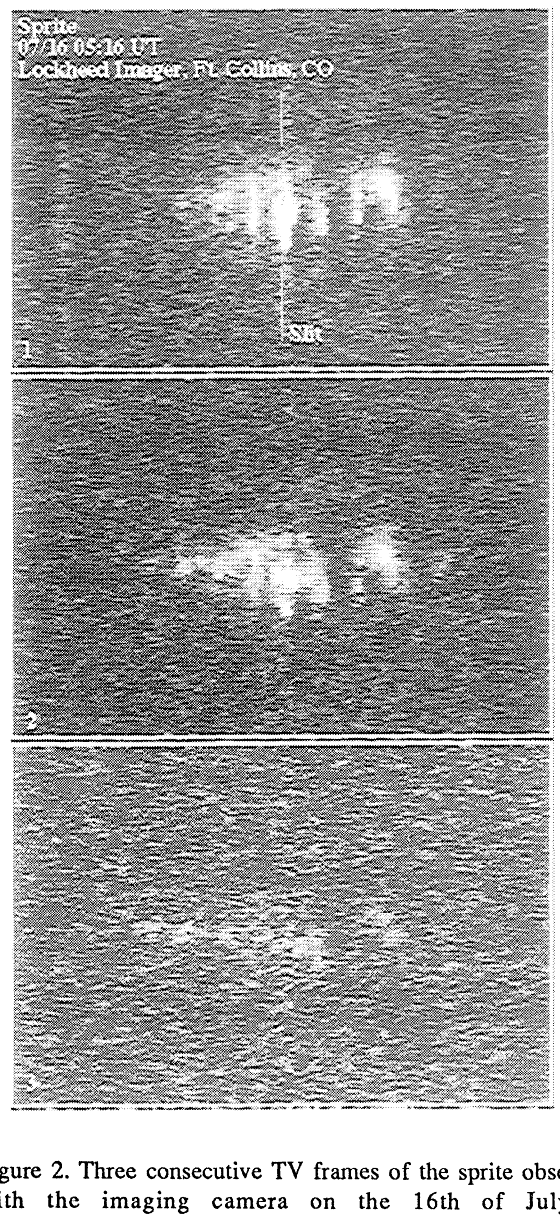

Figure 2. Three consecutive TV frames of the sprite observed with the imaging camera on the 16th of July at 05:16:48.534 UT.

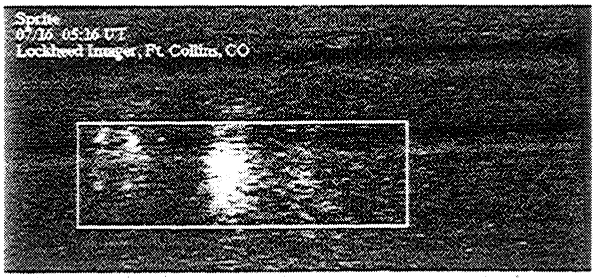

Figure 3. Spectral image or spectrogram of the Sprite event occurring at 05:16 UT. The image covers the wavelength range from 850 nm (left) to 430 nm (right). White frame shows area of detectable signal selected for display on Figure 4.

Discussion

The processes leading to emissions in the atmosphere by energetic electrons accelerated by electric fields in thunderstorms should be greatly similar to auroral light production. Auroras however do not generally penetrate to 90 km and light in sprites is generally produced at this altitude or lower. Although the atmospheric composition is not drastically different at these lower altitudes increased collision frequencies will quench long lifetime auroral emissions. Thus we expect to see only the fast, permitted transitions. The theory of optical excitation of the atmosphere above thunderstorms and the generation of sprites by quasi electrostatic fields has been discussed by Taranenko et al., [1993] and by Pasko et al., [1995] respectively. Taranenko et al. [1993] have predicted that the N_2 1PG system is the brightest emission feature to occur in lightning stimulated upper atmospheric emissions.

The N_2 1PG system was been positively identified in our sprite spectrum and is shown in Figure 4. Between 760 and 770 the (3,1) component of N_2 1PG is strongly attenuated due to absorption by O_2 at 762 nm at slant path. It should be noted that the instrumental spectral response was not applied to the data presented in Figure 4. The N_2 1PG system is a well investigated emission associated with electron bombardment of the atmosphere by auroral electrons is largely the result of secondary electron impact on atmospheric N_2 as described by Vallance Jones [1974] and Strickland [1976]. Chutjian et al.

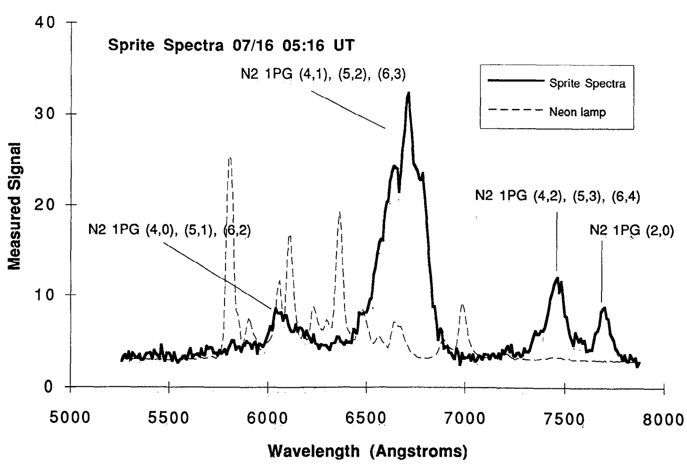

Figure 4. Spectral scan of the image shown in Figure 3. The thick trace represents the spectra of the sprite while the thin trace shows the spectra of a calibration neon light.

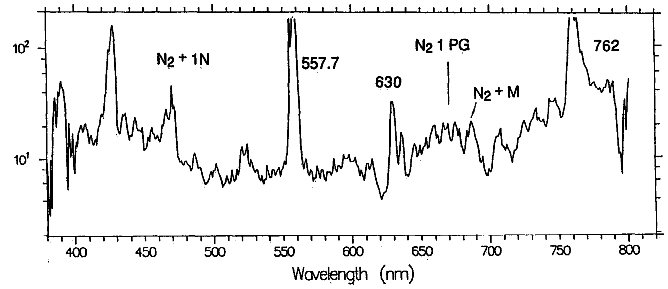

Figure 5. Auroral spectrum taken from the space shuttle. The spectrum was taken with a similar transmission grating image intensified instrument system.

shown the peak of excitation to be near 10 eV with a fast drop off to higher energy with the cross section decreasing by a factor of 15 at 100 eV. In the aurora, it is the large population of secondary electrons produced by primary (keV) electrons which produces the N_2 1PG emission. It is well established that the lifetime is 6-8 μs [Nicholls, 1969], and that with known quenching rates, the emission is not visible below ~50 km as a result of the collisional frequency with known quenching species [Vallance Jones, 1974].

In the case of the sprite spectra, the N_2 1PG system was the only emission detected. In the spectral range of the instrument (430 - 850 nm) no other features were detected above instrument noise background. If electrons with energies higher than 20 eV had been produced by the sprite, then N_2^+ emissions would have been present. For example in aurora where higher energy electrons are available several N_2^+ emissions features are significant. Some of these emissions have very short lifetimes and would not be quenched significantly at sprite altitudes down to 50-60 km. In auroral spectra at about 690 nm there is a strong contribution of the N_2^+ (3,0) Meinel band (See for example spectra presented by Vallance Jones [1974 page 83]). This feature is missing from the spectra presented in Figure 4. The absence of this feature indicates that the electrons in the sprite had insufficient energy to efficiently ionize the nitrogen. Several other features were also missing from the sprite spectra which are characteristic of normal auroral spectra. The same type of instrument was flown on the space shuttle and several auroral spectra had been taken for example on mission STS-45. We have included one of these spectra for comparison as Figure 5. These spectra give us direct one to one comparison between the Sprite spectra and the auroral spectra as observed by the same instrument type. If the sprite had contained hard electrons of several keV then we would expect some of the auroral fast transitions to take place. The shuttle based instrument detected strong 427.8 and 470.9 N_2^+ emissions. Although 427.8 nm emissions was just outside of the wavelength range of the ground based instrument one would have expected to see N_2^+ first negative at 470.9 nm which, when observed in aurora is stronger than the N_2 1PG bands in the 650 and 680 nm range. In Figure 5, apart form the well known auroral features such as 427.8, 557.7, 630 and 636.4 and the 762 airglow band, we can distinguish four peaks between 650 and 700 nm. The three on the left are the N_2 1PG (4,1),(5,2) and (6,3) components. The fourth peak is a combination of the N_2 1PG (3,0) and the N_2^+ Meinel (3,0) where most of the intensity is produced by the ionized Meinel contribution in aurora suggesting the absence of such emission in the sprite. Note that the O_2 atmospheric (0,0) band at 762 nm is a strong emission band in the topside auroral spectra whereas it is a dark absorption feature in the ground based sprite spectra. The relatively poor signal to noise ratio of our measured spectra coupled with the decreasing sensitivity of the instrument and the larger scattering of the slant range atmosphere in the blue spectral region probably accounts for the absence of the N_2 2nd positive bands in our spectra. Our observations therefore could be consistent with the intensity ratio of 7 between the two bands as predicted by Taranenko et al. [1993] There remain a number of controversial issues regarding the details of N_2 1PG excitation in sprites. Just as in auroras these emissions can be produced from possible interactions with other N_2 states or $N(^4S)$ [see Partridge et al. 1988 and Vallance Jones, 1974]. These issues may be enlightened regarding the excitation in sprites through spectral observations in the UV and IR, but the likeliest conclusion is that the electrons in the sprite discharge have energies <100 eV.

Conclusions

During these experiments several sprite images were recorded with the wide field imaging camera. These sprites were quite similar in appearance to the one described above. Most of the observed sprites exhibited multiple columns or channels similar to the image presented in Figure 2. It should be also noted that there appeared to be a spatial drift of the Sprite phenomena. Most sprites observed by our instrument showed that after the first bright frame the images in the weaker frames were seen to be substantially displaced spatially. Assuming that the range was 450 km the event shown on Figure 2 appears to be displace by a distance of about 50 km in 1 or 2 TV frames. Thus the speed of propagation of this phenomena was of the order of about 1500 km/sec in the plane normal to the viewing direction.

A bore sighted imaging camera and imaging spectrograph observed sprite events and recorded their spectra. The spectra contains N_2 first positive bands without any discernible contribution from other emissions. The observed spectrum is consistent with predictions of Taranenko et al. [1993] regarding the relative intensity of optical emissions created in this altitude regime. The absence of other emissions in the sensitivity range of the instrument and the spectral profile of the N_2 first positive emissions suggest that the efficiency of hard electron production in the observed Sprite was low. This observation therefore does not support the attempt of Chang and Price [1995] in explaining the observations of energetic electrons above thunderstorms [Fishman et al., 1994]. Our spectral observations confirm the previous reports that the sprites appear red in color.

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