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The optical spectrum of aircraft St. Elmo's fire

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Abstract. On February 26, 1995, during a NASA sponsored mission to Peru to study red sprites and blue jets, the instrumented Westwind 2 jet aircraft encountered spectacular St. Elmo's fire from the wing pods, tail and nose while flying through a cloud at an altitude of 13.83 km (45,376 ft). The phenomenon was captured on low light level monochromatic and color television systems aboard the aircraft, and its spectrum was recorded on a low light level TV spectrograph with response from 395.0 to 750.0 nm. The cameras and spectrograph also recorded scattered intra-cloud lightning and a possible lightning discharge near, or to, the aircraft. The spectrum of St. Elmo's fire was primarily the second (2nd) positive bands of N_2. The data were consistent with a population of electrons having relatively low energy (<18 eV).

Introduction

The University of Alaska has used a Westwind 2 corporate jet aircraft to make NASA sponsored optical measurements of upper atmospheric phenomena, sprites and blue jets [*Sentman et al.*, 1995; *Wescott et al.*, 1995]. In February, 1995, we flew missions out of Lima, Peru to the vicinity of large thunderstorms over the eastern slopes of the Andes Mountains and over the Amazon basin. On the night of 26 February, 1995, while passing through an electrified storm region at an altitude of 13.83 km (about 45,376 ft), we experienced a spectacular show of St. Elmo's fire, a blue glow often observed around the masts of sailing ships and named after the patron saint of sailors. The St. Elmo's fire was punctuated by a possible direct lightning strike to the aircraft. The displays lasted for nearly a minute, and were captured on both monochrome and color low light level television systems, as well as in the television slit spectrograph. Here, the observations are described.

Instrumentation

The monochrome low light level television camera is a Dage-MTI VE-1000 silicon intensified target (SIT) system. It was equipped with a Kinoptic 5.7 mm f/1.8 TEGEA wide angle lens giving a 92° H x 69° V field of view. The color camera is a low light level Ikegami HL-51S system with 2,000,000 ISO equivalent and sensitivity of approximately 2 kR. The camera has three separate SIT subsystems with red, green and blue response that maximize at approximately 600 nm, 530 nm, and 450 nm, respectively. These cameras are the same systems that have previously been used in our research [*Sentman et al.*, 1995; *Wescott et al.*, 1995].

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The television slit spectrograph has previously been described by *Stenbaek-Nielsen et al.*, [1993]. Briefly, the viewing scene is focused with a 100 mm f/2.0 lens onto a horizontal slit with adjustable width. The light from the slit is collimated and passed through a Bausch and Lomb plane transmission grating with 600 lines/mm, a blaze angle of 28.7° and wavelength of 500 nm. The resulting spectrum is imaged on the photo cathode of an intensified silicon intensified target (ISIT) television camera with a 50 mm f/0.95 lens and recorded on a Sony VO-5600 3/4 inch video tape recorder. The slit represents about a 5° field of view horizontally. The spectral resolution depends on the width of the slit; during the Peru flights the slit was set rather wide to increase the amount of light, providing resolution of about 5 nm. We calibrated the wavelength scale of the spectra by using neon and mercury lamps, narrow band interference filters at 670.8 nm and 553.5 nm, and airglow lines at 557.7 and 630.0 nm. The spectral response was measured by observing a barium oxide screen illuminated with a calibrated standard lamp and a set of standard 10 nm interference filters at 400, 450, 500...750 nm. Because the gain of the TV system recording the spectra was adjustable, only a relative amplitude scale is used. The spectral transmission of the actual aircraft window was also measured using the same calibration filters.

Data

The display of the St. Elmo's fire was visually witnessed to emanate from both wings and from the nose of the aircraft.

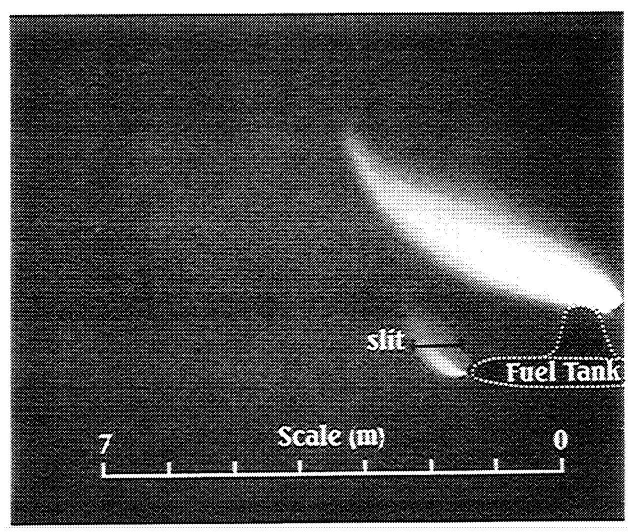

Figure 1. Monochromatic TV frame (91° x 68° FOV) of small St. Elmo's fire from the front of the right wing tip fuel tank, and a larger glow from the front and rear tips of the winglet (vertical fin). The fuel pod and winglet have been outlined in a dotted line. The size and location of the spectrometer slit and the distance scale in the vertical plane containing the fuel tank are indicated.

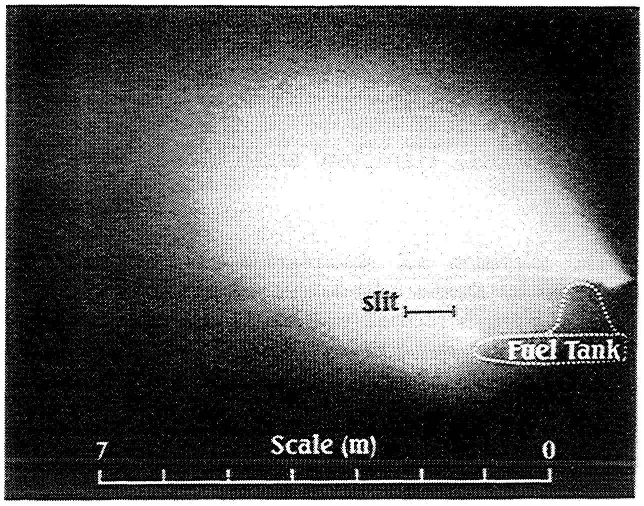

Figure 2. Monochromatic TV frame of the maximum extent of St. Elmo's fire.

In the scenes recorded by the television systems viewing out the right side of the aircraft, the emissions began as small glows from the front of the paraboloidal wingtip fuel pods and the top-front and rear corners of the vertical fins on the pods. See Figure 1. The emissions then grew forward, into the 420 knot (216 m/s) wind produced by the forward aircraft motion. Since the scale size of the glow was about 5 m, the residence time of any particular parcel of air within the glow was about 20 ms. Initially, the St. Elmo's fire was out of the field of view of the spectrograph, but as the coronas grew in size and intensity they extended forward and upward, eventually into the field of view of the spectrograph (Figure 2). When viewed by the color camera, the corona was pure blue in color.

Figure 3 is the spectrum of the St. Elmo's fire shown in Figure 2. The data have been corrected for the response of the spectrograph system and the transmission of the aircraft window. See Table 1 for a list of molecular electronic transitions discussed in this paper and their spectroscopic designations. The N_2 2P band heads [*Vallance-Jones*, 1974] within the range of the spectrograph are shown as vertical

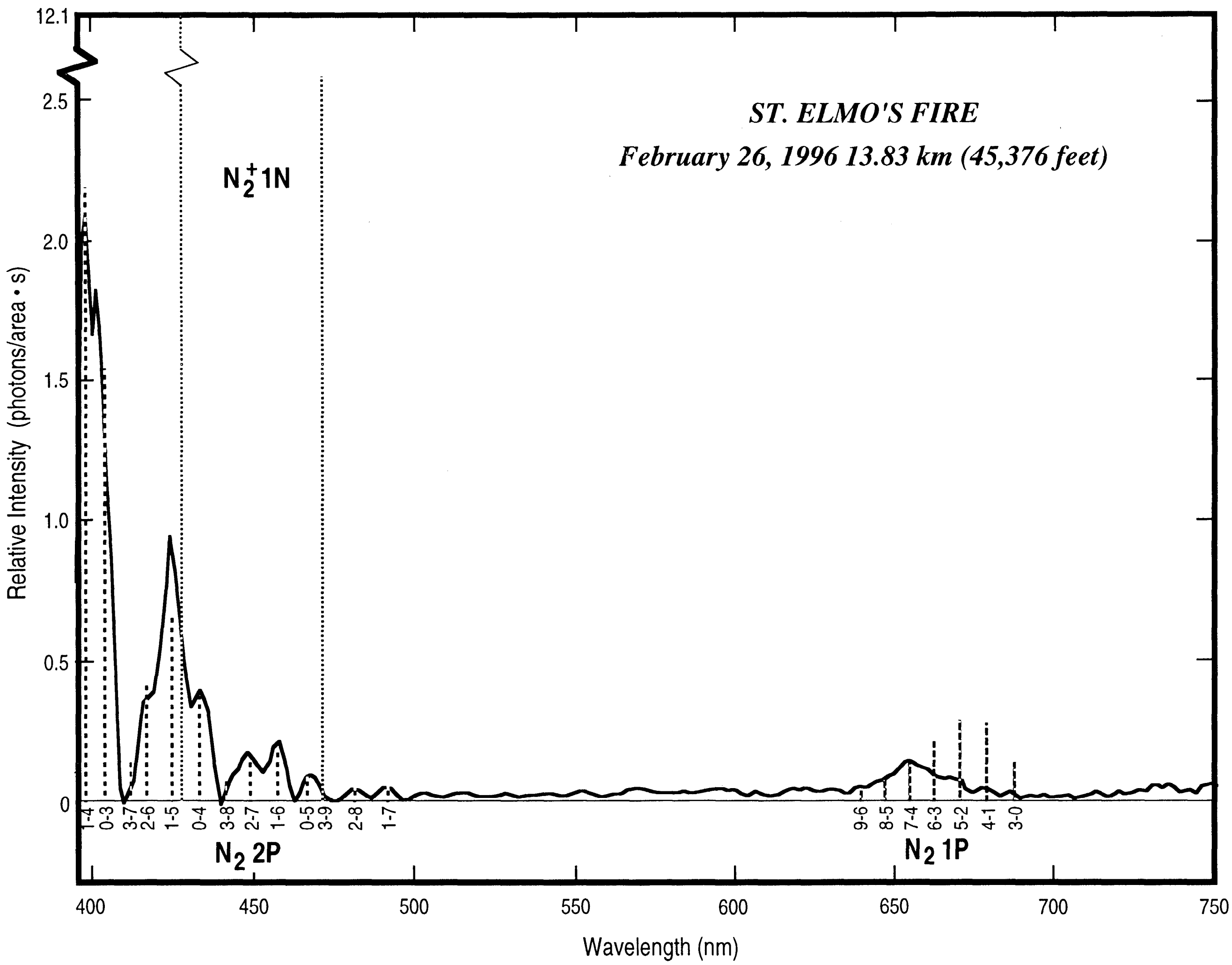

Figure 3. Spectrum of the St. Elmo's fire shown in Figure 2. The N_2 2P band heads [*Vallance-Jones*, 1974] within the range of the spectrograph are shown as vertical heavy dashed lines of relative intensity (as observed in the aurora) normalized to the 2-6 and 0-4 transitions. Two band heads of N_2^+ 1N (427.8 nm and 470.9 nm, dotted lines) are shown to the same relative scale. The broad feature near 650 nm is not identified. The $\Delta v = 3$, N_2 1P bands are shown as dashed lines on an arbitrary scale, normalized to the 7-4 transition.

Table 1. Molecular transitions.

Species	Transition	System Designation
N_2	$B^3\Pi_g \rightarrow A^3\Sigma^+_u$	First Positive (1P)
N_2	$C^3\Pi_u \rightarrow B^3\Pi_g$	Second Positive (2P)
N_2^+	$B^2\Sigma^+_u \rightarrow X^2\Sigma^+_g$	First Negative (1N)

lines of relative intensity (as observed in the aurora) normalized to the 2-6 and 0-4 transitions. The N_2 2P band heads out to the 1-7 vibrational transition can be identified. Below 400 nm, the system response correction is large, and small uncertainties in the signal background are amplified. Nonetheless, the magnitudes of the features in this range are in reasonable agreement with expected values. There is also a broad feature in the region from 640 to 680 nm which will be addressed in the discussion section.

At one point during the display a bright flash filled the entire field of view. In the scene camera recordings one can see a branching discharge, which may have been a lightning strike very near, or possibly connecting to, the right wing pod. However, a close inspection later did not show any evidence of a direct hit. Figure 4 shows the response-corrected spectrum of the discharge, with H_α, H_β, and several atomic nitrogen and atomic oxygen lines identified. The spectrum resembles lightning spectra published by *Orville and Henderson*, [1984]. However there are differences in that lines at the green and blue end have less amplitude, and the NII lines are either missing or very much reduced in our spectrum.

Discussion

Kip [1939] and *English*, [1948] showed that the light from pre-onset streamers in air came largely from the highly excited second positive band system of the N_2 molecule. Our St. Elmo's fire spectrum agrees fairly well with those of *Grum and Costa* [1976], who measured the spectral emissions of coronal discharges in N_2, He and air using a high resolution (0.04 nm) absolute spectrofluorimeter described by *Costa et al.* [1969]. They made their measurements at a pressure of 0.062 kg/cm^2, whereas our spectrum was obtained at a pressure of about 0.154 kg/cm^2.

There is a broad peak near 650 nm, both in our spectrum and in the N_2 and air spectra of *Grum and Costa* [1976]. *Grum and Costa* [1976] identified the peak with some of the

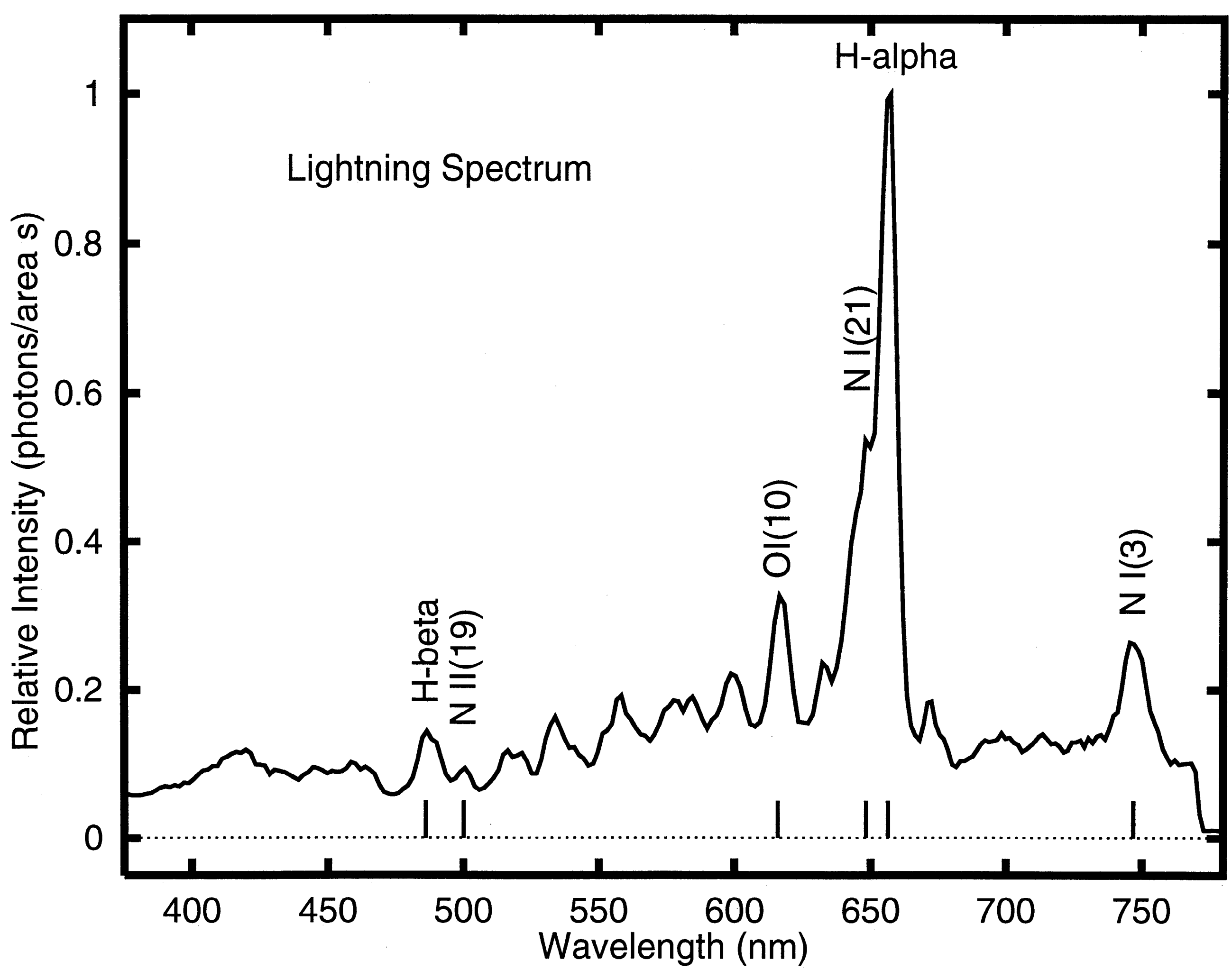

Figure 4. Spectrum of near intracloud lightning discharge recorded during the interval when the St. Elmo's fire was observed. Numbers in parentheses refer to multiplet designators [*Orville and Salanave*, 1970].

less energetic red first positive N_2 bands ($B^3\Pi_g \rightarrow A^3\Sigma^+_u$, 678.7 and 612.6 nm). If they were correct in their identification, the bands are very much reduced compared to auroral intensities, presumably because of rapid quenching at the aircraft altitude. The N_2 gas used by *Grum and Costa* [1976] was 99.995% pure with no evidence of Hg contamination at 435.8 nm, the brightest Hg spectral line. However they found a broad feature centered near 580.0 nm in both their N_2 and air spectra which they could not identify. We did not see this feature in our spectrum.

It is uncertain if the broad feature near 650 nm corresponds to the higher level vibrational terms ($v' > 4$) of the N_2 1P $\Delta v = 3$ sequence. The peak of the emissions is shifted toward shorter wavelengths relative to a low pressure discharge, as can be seen by the relative amplitudes of the band as reported by Vallance-Jones [1974] (normalized to the 7-4 band). This sort of shift has been explained by inter-system collisional transfer (ICT) between the W and B states of N_2 [*Morrill and Benesch*, 1996, and references therein]. However it seems physically impossible to have a vibrational distribution for which both the $\Delta v=4$ and the $\Delta v=2$ bands would be unobservable assuming the observed broad peak is from the $\Delta v=3$ bands. It should also be mentioned that the small spectral features in the green region are not "noise", but are real but unidentified St. Elmo's emissions.

We were unable to identify an unambiguous signature from the N_2^+ 1N series at 427.8 nm and 470.9 nm. In Figure 3, these bands are identified as thin dotted lines (scaled at 5/7 of the N_2 2P scaling for simple lifetime considerations) illustrating that the emissions would be partially obscured by the overlap with N_2 2P 1-5 and 3-9 vibrational transitions respectively. However, if there was any significant ionization of N_2, the emissions would be present. They are quenched more severely than the second positive bands, but less so than the first positive emission [*Vallance-Jones*, 1974]. Specifically, any emission at 470.9 nm is less than 1% of that seen in auroras with comparable intensities of N_2 second positives. We also did not detect emissions from the first negative series of O_2^+ (527.5 nm, 560.8 nm, and 600.0 nm). These require approximately the same energy as the N_2^+ 1N emissions (18 eV), but they are quenched somewhat more efficiently than the N_2 1P bands.

The lack of O_2^+ 1N bands (18 eV), and N_{2+} 1N bands (19 eV) implies that the electron population has a characteristic energy well below the ionization threshold. Accordingly, we expect that there is no avalanche of ionization. The free electrons probably originate from the metallic surfaces of the aircraft.

Wescott et al. [1995] reported observations of a new upper atmospheric phenomenon, named "blue jets", associated with certain active lightning storms. Blue jets are narrow cones of light that propagate upwards from the anvil top at speeds of the order 100 km/s. No spectra of these events have been obtained to date, but in the same low light level color camera that also recorded the St. Elmo's fire reported here, the light from blue jets also registered only in the blue tube. Blue jets have been seen extending from about 17 km up to 40 km. Although the pressure would be less than at the 13.8 km altitude of the St. Elmo's fire, we suggest that the spectrum might be similar.

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