NUV/Blue spectral observations of sprites in the 320-460 nm region: \( \text{N}_2 \) (2PG) Emissions

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Abstract. A near-ultraviolet (NUV) spectrograph (320-460 nm) was flown on the EXL98 aircraft sprite observation campaign during July 1998. In this wavelength range video rate (60 fields/sec) spectrographic observations found the NUV/blue emissions to be predominantly \( \text{N}_2 \) (2PG). The negligible level of \( \text{N}_2^+ \) (1NG) present in the spectrum is confirmed by observations of a co-aligned, narrowly filtered 427.8 nm imager and is in agreement with previous ground-based filtered photometer observations. The synthetic spectral fit to the observations indicates a characteristic energy of \(~1.8\) eV, in agreement with our other NUV observations.

Introduction

Sprites are brief (~10 ms) optical phenomena that occur above thunderstorms at altitudes between 40-95 km, which have been well documented only during the last two decades [see Sentman, 1998; Sentman et al., 2008]. Broadband, spectral, and filtered photometric observations have been made across the visible wavelengths. Color camera observations show that sprites are primarily red, becoming blue at the lower altitudes [Sentman et al., 1995].

Ground-based spectroscopic measurements of sprites in the optical bandpass of 400-850 nm [Mende et al., 1995; Hampton et al., 1996] show the strongest optical emission from sprites is \( \text{N}_2 \) (1PG), first positive molecular nitrogen emission, which is excited via electron impact. Analysis of red spectral observations estimated a 1 eV Boltzmann electron distribution would produce the observed spectral vibrational distribution [Green et al., 1996; Milikh et al., 1997] independently modeled the observed red spectra with similar results. Based on modelling of the red spectral observations of \( \text{N}_2 \) (1PG) emissions, several early predictions of blue emissions in sprites were published [Pasko et al., 1997; Cho and Rycroft, 1998; Morrill et al., 1998; Roussel-Dupré et al., 1998]. More recent modeling efforts have estimated other \( \text{N}_2 \) emissions such as the \( \text{N}_2 \)LBH in the UV [Liu and Pasko, 2005]. These predictions are compared with the reported observations in the discussion section below.

Analysis of one red spectral observation of a sprite required \( \text{N}_2^+ \) (M) (ionized molecular nitrogen Meinel) emissions for a best fit to the observations [Morrill et al., 1998]. The \( \text{N}_2 \) (1PG) and \( \text{N}_2^+ \) (M) observations and analysis are the subject of another paper [Bucsela et al., 2003]. Photometric studies of sprites from the ground by [Armstrong et al., 1998] and [Suszcynsky et al., 1998] found the blue neutral molecular nitrogen second pos-
The primary band systems of molecular nitrogen which lead to near-optical emissions (300-1000 nm) are the $N_2$(1PG) and $N_2$(2PG) neutral and the $N_2^+$(1NG) and $N_2^+$(Meinel) ionized molecular nitrogen emissions. Table 1 provides an overview of nitrogen and oxygen optical emissions observed in the aura. The transitions associated with the nitrogen band systems are the $N_2$(B$^3Π_u$) $→$ N$_2$($A^3Σ^+_u$) transition yielding the N$_2$(1PG) emission, the N$_2$(C$^3Π_u$) $→$ N$_2$(B$^3Π_g$) transition yielding the N$_2$(2PG) emission, the N$_2^+$(B$^3Σ_u^+$) $→$ N$_2^+$(X$^2Σ_g^+$) transition giving the N$_2^+$(1NG) emission, and the N$_2^+$(A$^2Π_u$) $→$ N$_2^+$(X$^2Σ_g^+$) transition giving the N$_2^+$(Meinel) emission. The potential energy curves of both neutral and ionized molecular nitrogen electronic states involved in the above transitions and the ground neutral state are also shown in Fig. 1. The N$_2$(2PG) and N$_2^+$(1NG) bands occur at NUV and blue wavelengths (< 450 nm, with brightest emissions < 400 nm), while the N$_2$(1PG) and N$_2^+$(Meinel) bands occur at red and near infrared (NIR) wavelengths.

Because of the uncertainties associated with N$_2^+$(Meinel) quenching and energy transfer, characterization of N$_2^+$(ionized molecular nitrogen) is best accomplished by observation of N$_2^+$(1NG) at shorter wavelengths. One reason for investigating the N$_2$(2PG) emission rather than the dominant red N$_2$(1PG) emission is that the upper state of N$_2$(1PG), N$_2$(B$^3Π_g$), is partially filled via cascading from the N$_2$(C$^3Π_u$) state (this cascading is evidence of the N$_2$(2PG) emissions). Also the N$_2$(1PG) upper state is more strongly affected by collisional processes than N$_2$(2PG) [Morrill and Benesch, 1996] complicating the accurate analysis of N$_2$(1PG).

The problems of both cascading and quenching are less severe for the N$_2^+$(B$^3Σ_u^+$) and N$_2^+$(C$^3Π_u$) upper electronic states [Morrill and Benesch, 1996]. Additionally, N$_2$(1PG) has the lowest excitation energy threshold of the four band systems discussed, so emissions from other groups are evidence of higher energy processes. Specifically, from Table 1, the N$_2$(1PG) threshold energy is 7.5 eV compared to 11.18 eV for N$_2$(2PG) 18.56 eV for N$_2^+$(1NG) and 16.54 eV for N$_2^+$(M).

In this paper we present an analysis of the recent blue spectral observations made during the EXL98 aircraft sprite-observing mission over the U.S. Midwest. Other papers will present further analysis associated with both specific ionization issues and the N$_2$(2PG) to N$_2^+$(1NG) ratio [Buscera et al., 2003; Morrill et al., 2002]. The EXL98 filtered blue imaging of sprites associated with ionized N$_2^+$ emissions are presented elsewhere [Heavner, 2000].

### Instrumentation

The Energetics of Upper Atmospheric Excitation by Lightning (EXL98) campaign was a collaboration between the University of Alaska, Fairbanks (UAF), the
Naval Research Laboratory (NRL), and the Air Force Research Laboratory. This program was designed to investigate the energy budget of middle and upper atmospheric processes excited by lightning using several imaging and photometric observations from a Gulfstream II aircraft. In this paper we present results from a ‘427.8 nm’ filtered imager and a bore mounted unfiltered imager both have a 9.3° x 7.0° field-of-view (FOV) as well as a NUV/Blue spectrograph.

Two imaging instruments were designed specifically to observe neutral \( \text{N}_2(2\text{PG}) \) and ionized \( \text{N}_2^+(1\text{NG}) \) emissions. A Dage/MTI SIT VE1000 camera with a Fuji f/0.7 lens was used to measure images of the \( \text{N}_2^+(1\text{NG})(0,1) \) band emissions with a narrow passband filter at approximately 427.8 nm. The ‘427.8’ nm filter is a carefully selected filter for observation of \( \text{N}_2^+(1\text{NG}) \). It is a 1.44 nm FWHM filter actually centered at 428.3 nm, specifically selected slightly red of the \( \text{N}_2(2\text{PG}) \) 426.8 nm emissions which would contaminate the filter if it had been centered on 427.8 nm.

A GEN IIUV V53-1845 Video Scope camera and a Lyman Alpha II f/1.7 lens system was was optimized for NUV observations. Originally the camera was used as a filtered imager, with a 340.7 nm filter, in order to make observations of \( \text{N}_2(2\text{PG}) \) (neutral) emissions. During the later portion of the campaign, this instrument was refitted as a NUV spectrograph. The NUV spectrograph consisted the GEN IIUV V5301845 Video Scope camera as the detector for light which passed through a Jobin Yvon-Spex CP200 f/2.9 spectrograph and a 133 line/mm grating. The primary input lens focused the incoming light on an 8 mm collimating entrance slit. The slit was oriented horizontally in order to increase the probability of sprite observations. The data was recorded at 60 fields per second and all cameras on aircraft and ground were GPS synchronized providing video images with a common time base to 0.5 µs or better.

Other instrumentation and the overall EXL98 campaign are described by [Siefring et al. 2009](#).

### Observation

Sprites observed July 28, 1998 at 06:41:01.278 UT are shown in Fig. 2. The aircraft was flying at an altitude of 14,040 m at a great circle distance of 306 km from the positive cloud-to-ground lightning discharge reported by the National Lightning Detection Network temporarily associated with the observed sprite. Fig. 2(a) is from the unfiltered imager (9.3° x 7.0° FOV). The horizontal black band indicates the approximate FOV of the slit in the NUV spectrograph. After gamma correction and background subtraction of the video image of the NUV spectrograph output, three video fields were averaged together for a total time integration of 40 ms (the spectral data were on the upper portion of the scan read-out imager, the time integration only includes a portion of the third field and is not the entire

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**Figure 2.** Blue Spectrum of July 28, 1998 06:41:01.278 Sprite. (a) is the broadband image of the sprite with a black dashed line indicating the field of view of the slit spectrograph. (b) is the histogram equalized 427.8 nm filtered imager data. The imager detected no 427.8 nm emissions, agreeing with the lack of any such signature in the spectral observations. (c) shows the spectrum observed by the NUV/Blue spectrograph as the solid line. The dashed line is the synthetic fit to the observations including both neutral \( \text{N}_2(2\text{PG}) \) and ionized \( \text{N}_2^+(1\text{NG}) \). The ionized contribution to the fit is shown as a dash-dot line (primarily near the 391.4 nm and 427.8 nm bands).
50 ms of the three fields). The 10 video scan lines over which spectral information was present were also averaged, to improve the signal strength. Fig. 2(c) presents these corrected observations from the NUV spectrograph. The observed spectrum is the solid line while a synthetic spectral fit to the observations modeled with $N^+_2(1 \text{NG})$ and $N_2(2 \text{PG})$ is shown as a dashed line in Fig. 2(c) (the fit includes corrections for atmospheric transmission using MODTRAN [Morrill et al. 1998] and instrument response). The dotted line in Fig. 2(c) indicates the $N^+_2(1 \text{NG})$ contribution to the synthetic fit. The synthetic spectral code used to generate the fit are presented in detail by Bucsela and Sharp [1997]. Specifically, the vibrational distributions were determined by free-fit of the band progressions - adjusted for instrument response and atmospheric transmission - to the spectral data. An assumed rotational temperature of 230K was used, but given the resolution, the fit is not very sensitive to temperature [Bucsela et al. 2003]. Fig. 2(b) is the observation of the sprite from the 427.8 nm filtered imager, which has been histogram equalized to increase the contrast of the image. No indication of $N^+_2(1 \text{NG})$ 427.8 nm emissions from the sprite are apparent (in agreement with the spectral fit shown in Fig. 2(c)).

Discussion

Earlier spectral observations near the top of sprites, $\sim 65$ km, show that the primary optical emission is the $N_2(1 \text{PG})$ and here we confirm that the blue component is predominantly $N_2(2 \text{PG})$. Any weak molecular ion emission will be short lived and only present in the streamer heads know to makeup these events. EXL98 studies of filtered UV images indicate the $N_2(2 \text{PG})/N^+_2(1 \text{NG})$ ratio to be of order $4 \times 10^{-3}$ in the 65 km region thus confirming the lack of $N^+_2(1 \text{NG})$ emission [Morrill et al. 2002]. The current results and our previous UV image ratio results indicate an estimated characteristic energy of $\sim 1.8$ eV. This reasonably matches the estimated energies in the streamer body from the work of Liu and Pasko [2005]. Specifically, characteristic energy is the average energy of electrons in a weakly ionized gas under an applied electric field. If the gas is collisional the energy distribution is non-Maxwellian. The characteristic energy is the $D_e/m_e$, where $D_e$ is the electron transverse diffusion coefficient and $m_e$ is the mobility [cf. Raizer 1991, p 21]. These parameters are derived from laboratory by observing the bulk diffusion and drift in an applied field. Characteristic energies versus electric field for various gas are tabulated in Dutton [1973]. Boltzmann solving models of sprites can also report the average/characteristic energy as in Morrill et al. 2002. Pasko et al. [1997] did a cross-comparison between more complicated Boltzmann-solving sprite models and those using empirical fits to laboratory data and found generally good agreement between the two methods. These observations are highly time averaged relative to natural sprite time scales and indicate that a significant portion of the observed sprite emission is produced in the body of the streamers. Unfortunately, the averaging of signal over multiple video frames was necessary to achieve significant signal to noise for the synthetic spectral fit. It is important to recognize the different time scales in sprites and related optical emissions–streamers with highly ionized tips most likely create $N^+_2(1 \text{NG})$ emissions for sub-1 ms time scales while a longer (10+ ms) $N_2(2 \text{PG})$ emission is expected from sprite bodies.

Other studies by Kuo et al. [2005] who studies $N_2(2 \text{PG})/N^+_2(1 \text{NG})$ ratios observed from space derived characteristic energies in the range of 4.5-6.5 eV below 60 km or 1.9 to 3.4 times the breakdown field. Our previous observations [Morrill et al. 2002] yielded energies at roughly the breakdown field so are significantly different results which warrant further examination. The 60 km altitude is below our currently observed altitude. Were observations made at this altitude a significant $N^+_2(1 \text{NG})$ component would necessarily be present. Additional blue/UV sprite spectral observations with wider altitude range and higher temporal resolution are clearly needed.

Conclusions

We report observations and analysis of the blue/UV sprite spectrum at 65 km altitude. The observed spectrum is well fitted by synthetic spectral code (assuming a 230K rotational temperature) after atmospheric transmission correction and system response correction. The synthetic fit identifies only 2PG emission and implies electron energies of roughly 1.8 eV. This corresponds to similar results from previous studies as well as generally agreeing with other model results for electron energies in streamer bodies in sprites. Because of limitations in temporal resolution and vertical heigh of the sprites in the reported studie, additional blue/NUV observations are needed to confirm these results.

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Table 1. Atmospheric Species. Several neutral and ionized \( \text{N}_2 \) and \( \text{O}_2 \) optical emissions that are observed in the aurora. The earliest spectral observations of sprites identified \( \text{N}_2(1\text{PG}) \) emissions, which are the lowest threshold energy of the \( \text{N}_2 \) states that emit optically.