NUV/Blue spectral observations of sprites in the 320-460 nm region: 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 N_2(2PG). The negligible level of 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.

1. Introduction

Sprites are brief (∼10 ms) optical phenomena that occur above thunderstorms at altitudes between 40-95 km, which have been well documented only durring 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 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 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 eximated other N_2 emissions such as the 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 N_2^+(M) (ionized molecular nitrogen Meinel) emissions for a best fit to the observations [Morrill *et al.*, 1998]. The N_2(1PG) and 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 positive (N_2(2PG)) and N_2^+(1NG) are generally of shorter duration (∼5 ms) than the N_2(1PG) red emissions (which may last up to ∼100 ms). Furthermore, according to the photometer data, the ionized N_2^+(1NG) are more brief (∼1 ms) than the N_2(2PG) emissions. In addition to the poor atmospheric transmission in the blue, due to Rayleigh scattering (see Fig. 1 of Morrill *et al.* [1998]), the shorter duration of the blue emissions compared to the red emissions is a factor making blue observations of sprites more difficult. The shorter duration of the blue emissions is simply a factor of the shorter lifetime (nanoseconds rather than microseconds, as shown in Table 1) of the $N_2(C^3\Pi_u)$ and $N_2^+(B^2\Sigma_u^+)$ upper states of the N_2(2PG) and N_2^+(1NG) blue bands. Other recent analysis of space based observations by Kuo *et al.* [2005] has examined 2PG/1NG emission ratios and yield characteristic energies between 4.5 and 6.5 eV.

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 molecular nitrogen and molecular oxygen optical emissions observed in the aurora. The transitions associated with the nitrogen band systems are the $N_2(B^3\Pi_g) \rightarrow N_2(A^3\Sigma_u^+)$ transition yielding the N_2(1PG) emission, the $N_2(C^3\Pi_u) \rightarrow N_2(B^3\Pi_g)$ transition yielding the N_2(2PG) emission, the $N_2^+(B^2\Sigma_u^+) \rightarrow N_2^+(X^2\Sigma_g^+)$ transition giving the N_2^+(1NG) emission, and the $N_2^+(A^2\Pi_u) \rightarrow N_2^+(X^2\Sigma_g^+)$ 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

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dominant red N_2(1PG) emission is that the upper state of N_2(1PG), $N_2(B^3\Pi_g)$, is partially filled via cascading from the $N_2(C^3\Pi_u)$ 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 issues for the $N_2^+(B^2\Sigma_u^+)$ and $N_2(C^3\Pi_u)$ 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 comapred 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 [Bucsela *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].

2. 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 9.3deg x 7.0deg field-of-view (FOV) as well as a NUV/Blue spectrograph.

Two imaging instruments were designed specifically to observe neutral N_2(2PG) and ionized N_2^+(1NG) emissions. A Dage/MTI SIT VE1000 camera with a Fuji f/0.7 lens was used to measure images of the N_2^+(1NG)(0,1) band emissions with a narrow passband filter at approxiately 427.8 nm. The '427.8' nm filter is a carefully selected filter for observation of N_2^+(1NG). It is a 1.44 nm FWHM filter actually centered at 428.3 nm, specifically selected slightly red of the N_2(2PG) 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 N_2(2PG) (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.* [2010].

3. 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 temporally associated with the observed sprite. Fig. 2 (a) is from the unfiltered imager (9.3deg x 7.0deg 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 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^+(1NG) and N_2(2PG) 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^+(1NG) 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^+(1NG) 427.8 nm emissions from the sprite are apparent (in agreement with the spectral fit shown in Fig. 2(c)).

4. Discussion

Earlier spectral observations near the top of sprites, $\sim$ 65 km, show that the primary optical emission is the N_2(1PG) and here we confirm that the blue component is predominantly N_2(2PG) . 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(2PG) / N_2^+(1NG) ratio to be of order 4×10^4 in the 65 km region thus confirming the lack of N_2^+(1NG) 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/μ_e, where D_e is the electron transverse diffusion coefficient and μ_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 [1975]. 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 $N_2^+(1NG)$ emissions for sub-1 ms time scales while a longer (10+ ms) $N_2(2PG)$ emission is expected from sprite bodies.

Other studies by Kuo *et al.* [2005] who studies $N_2(2PG)$ / $N_2^+(1NG)$ ratios observed from space derived characteristic energies in the range of 4.5-6.5eV 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 $N_2^+(1NG)$ component would necessarily be present. Additional blue/UV sprite spectral observations with wider altitude range and higher temporal resolution are clearly needed.

5. 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 roghly 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 studies, additional blue/NUV observations are needed to confirm these results.

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Table 1. Atmospheric Species. Several neutral and ionized N_2 and O_2 optical emissions that are observed in the aurora. The earliest spectral observations of sprites identified N_2(1PG) emissions, which are the lowest threshold energy of the N_2 states that emit optically.

Name	Upper State	Lower State	Lifetime	Quench Altitude	Quench Particle	Threshold Energy
N_2(1PG)	$N_2(B^3\Pi_g)$	$N_2(A^3\Sigma_u^+)$	6 μs	53 km	N_2	7.50 eV
N_2(2PG)	$N_2(C^3\Pi_u)$	$N_2(B^3\Pi_g)$	50 ns	30 km	O_2	11.18 eV
N_2^+(1NG)	$N_2^+(B^2\Sigma_u^+)$	$N_2^+(X^2\Sigma_g^+)$	70 ns	48 km	N_2, O_2	18.56 eV
N_2^+(M)	$N_2^+(A^2\Pi_u)$	$N_2^+(X^2\Sigma_g^+)$	14 μs	85-90 km	N_2	16.54 eV
N_2(VK)	$N_2(A^3\Sigma_u^+)$	$N_2(X^1\Sigma_g^+)$	2 s	145 km	O	6.31 eV
O_2^+(1NG)	$O_2^+b^4\Sigma$	$O_2^+X^2\Pi_g$	1.2 μs	60 km	N_2	18.2 eV

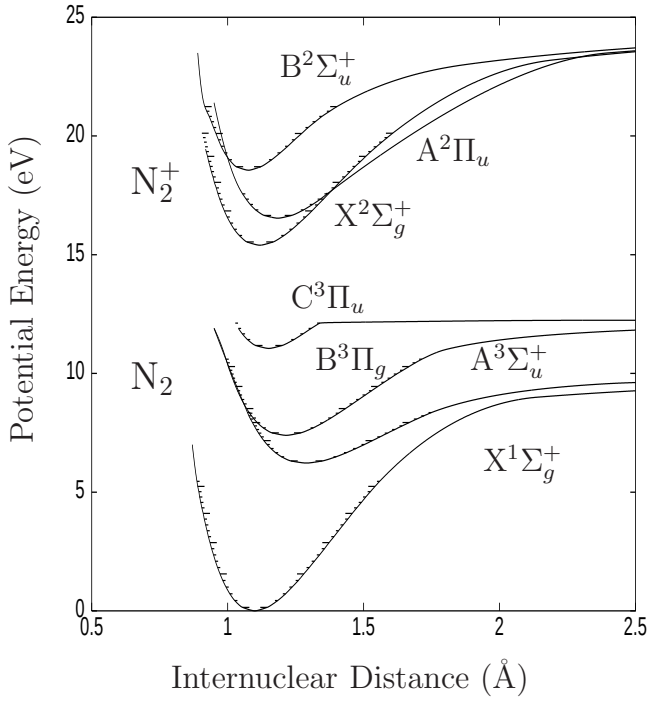

Figure 1. Grotrian Energy Diagram for N_2, with selected electronic states plotted. The N_2(1PG), N_2(2PG), N_2^+(1NG), and N_2^+(M) transitions are indicated. This figure was made using Tables 80 and 81 from Lofthus and Krupenie [1977].

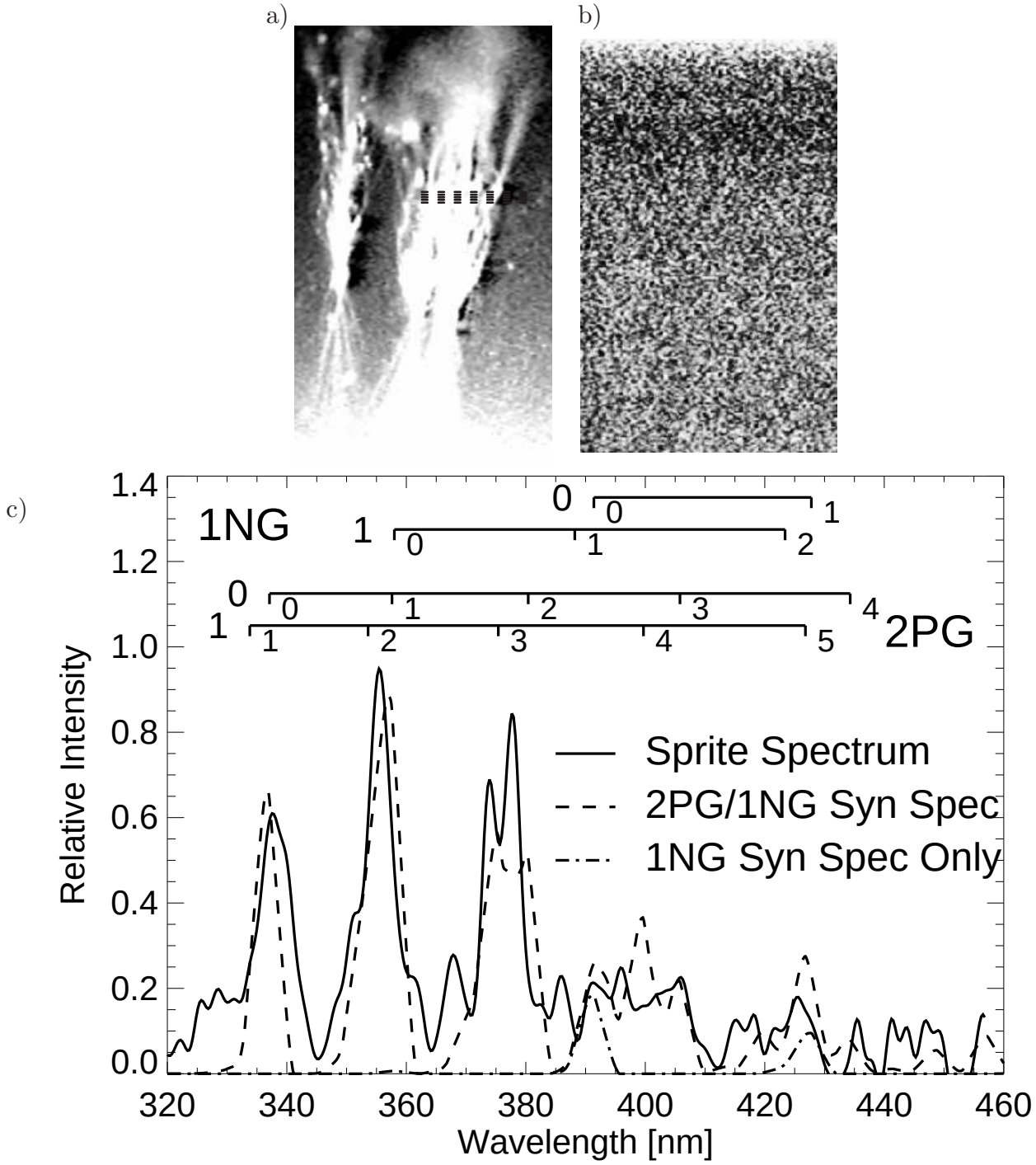

Figure 2. Blue Spectrum of July 28, 1998 06:41:01.278 Sprite. (a) is the broadband image of the sprite with a black dashed line indicating the field of view of the slit spectrograph. (b) is the histogram equalized 427.8 nm filtered imager data. The imager detected no 427.8 nm emissions, agreeing with 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 N_2(2PG) and ionized N_2^+(1NG). The ionized contribution to the fit is shown as a dash-dot line (primarily near the 391.4 nm and 427.8 nm bands).