Sprites, Blue Jets, and Elves: Optical Evidence of Energy Transport Across the Stratopause

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Abstract. Sprites, blue jets, blue starters, and elves are recently documented optical evidence of previously unknown forms of upward electrical energy transport across the stratopause. These energetic processes have not been incorporated into most models or descriptions of middle- and upper-atmospheric dynamics, in part because the details of the processes themselves are still poorly understood. The earliest (1995) ground based red spectral observations of neutral molecular nitrogen emissions from sprites indicate a low energy phenomena compared to the neutral and ionized emissions observed in lightning or aurora. However, recent sprite observations of ionized molecular nitrogen emissions indicate the presence of higher energy processes. In 1998, the EXL98 aircraft campaign characterized the blue emissions of sprites, blue jets, and elves. Aircraft measurements include filtered images, at 427.8 nm (N_2^+(1NG)) and 340.7 nm (N_2(2PG)), as well as NUV/blue spectral observations between 320-460 nm, while ground based time-resolved photometric measurements were also made in this wavelength range. We discuss the filtered and spectral NUV observations in conjunction with earlier red (640-920 nm) spectral and filtered photometer observations. The identification of ionized nitrogen emissions requires processes with electron energies of at least 18.6 eV to produce these emissions, assuming excitation is directly from the N_2 ground state. This paper provides middle- and upper-atmospheric scientists an introduction to these recently discovered phenomena and the current best estimates of the energetic contributions of these phenomena to the atmosphere above the tropopause.

1. Introduction

A serendipitous video observation of what was then called a "cloud-to-stratosphere discharge" [Franz *et al.*, 1990] provided the first recorded image of optical emissions in the middle- and upper-atmosphere associated with thunderstorms, and launched a rapidly evolving field of both observational [Sentman, 1998; Rodger, 1999] and theoretical efforts [reviewed in Rowland, 1998]. Since then a number of phenomena have been discovered, which are now called sprites, blue jets and blue starters, and elves. The common sources of energy

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driving these processes in the stratosphere and mesosphere are tropospheric thunderstorms and lightning. The electric field generated by these storms heats ambient electrons which result in electron impact excitation of the ambient N_2 leading to the observed optical emissions. Thus, these emissions are evidence of rapid transmissions of electromagnetic energy from the troposphere, across the stratopause, to altitudes as high as the lower thermosphere/ionosphere. In this paper, we discuss optical and temporal characteristics of sprites, blue jets and starters, and elves. Our primary focus will be on the most recent observations to provide insight into the energetics of these events. Modeling efforts will also be discussed with regard to energy implications. Although there are numerous issues remaining to be resolved prior to including sprites in our global understanding of the middle- and upper-atmosphere, this paper provides atmospheric scientists information necessary to consider possible mesospheric effects of these newly discovered phenomenon.

The optical energy (between 395-700 nm) radiated by a sprite has been estimated to be 12-60 kJ per event [Sentman *et al.*, 1995b]. The radiated optical energy represents only a small fraction of the total energy deposited in the middle- and upper-atmosphere. This energy was calculated by convolving spectral observations with the camera response. Based on these values of radiated energy and a number of assumptions about the kinetic processes which affect the emissions in this wavelength range, estimates of the total energy deposition into O_2 and N_2 (vibrational and electronic states), range from ~250 MJ to ~1 GJ per event.

The energy per sprite is calculated as follows: Stellar calibrations were used to determine absolute photon flux measurements of sprites in the UAF 1994 measurements, yielding total optical energies of ~50 kJ per sprite. The 1994 observations were based on color camera measurements with response between 395-700 nm. The observed emissions are primarily from the N_2(1PG) group. Based on the vibrational distributions determined by the spectral fitting presented in Section **??** and the camera response convolved with the N_2(1PG) emissions, only ~5% of the N_2(1PG) emissions are detected by the color camera. Matching the observed photon flux in the image of the sprite to the observed spectrum yields a photon spectrum of the sprite. The color camera photon calibration assumed all emissions were centered at the peak response of the red channel, or 650 nm.

This energy flux is used to calculate the total energy deposited in molecular nitrogen and oxygen as follows. Geometrical integration of the stellar calibrations yields a total flux $1.81 \mathrm{x} 10^{23}$ photons per sprite. Because only 5% of the photons emitted from radiating $N_2(B^3\Pi_g)$ molecules are in the color camera bandpass, there are $3.62 \mathrm{x} 10^{24}$ radiating $N_2(B^3\Pi_g)$ molecules. Assuming that half of the $B^3\Pi_g$ state N_2 molecules which are excited via electron impact are quenched, the total $N_2(B^3\Pi_g)$ population is $7.24 \mathrm{x} 10^{24}$. For 1 eV excitation energy, the ratio of all N_2 electronically excited states to $B^3\Pi_g$ electronic state excitation is 3.45 [Slinker and Ali, 1982]. This gives $2.5 \mathrm{x} 10^{25}$ total N_2 electronically excited molecules. Assuming that the upper states all cascade down to the $N_2(A^3\Sigma_u^+)$ state, each molecule has energy ~6.5 eV. Therefore the total energy stored in electronic excitation is ~26 MJ.

Energy is also distributed amongst vibrationally excited states within the electronic states, so we calculate the vibrational energy similarly. From above, there are $3.62 \mathrm{x} 10^{24}$ $N_2(B^3\Pi_g)$ molecules. The ratio of N_2 vibrationally excited states to the $N_2(B^3\Pi_g)$ state is 2674 [Slinker and Ali, 1982], so the total number of vibrationally excited N_2 states is $1.94 \mathrm{x} 10^{28}$. Assuming the average vibrational energy is 0.3 eV, there is ~930 MJ of energy in the vibrationally excited N_2 states. Combining the vibrational and electronic energy calculated above, we find ~950 MJ deposited in molecular nitrogen by a sprite whose optical energy is 50 kJ. Assuming similar excitation in O_2, scale by the relative densities of N_2 and O_2 for a total energy deposition of 1.2 GJ per sprite in the middle- and upper-atmosphere. Considerations of molecular nitrogen energy transfer processes may decrease the above calculation of energy deposition by a factor of four. For comparison, recent calculations of the available energy in a sprite, made using electrostatic field magnitude considerations finds 1-10 MJ.

One of the major goals of current research is to reduce the broad range of these estimates by way of more accurate observation. A second measure of the energetics is the determination of the distribution of energy required to produce the observed emissions, that is, what is the energy associated with the processes occurring in the middle atmosphere which cause the optical emissions? We present evidence of ionized emissions from N_2^+ which have an energy threshold of 18.6 eV assuming excitation is occurring directly from the ground electronic state of N_2.

Molecular nitrogen (N_2) is the major constituent (~80%) of the atmosphere in the region (20-90 km, or ~10 pressure scale heights) where blue jets, blue starters, sprites, and elves occur. N_2 is a spectroscopically rich molecule with many excited electronic states which produce significant emission. These provide a good diagnostic for studying the energetic processes occurring in sprites, blue jets, elves, in a similar manner as has been done with airglow and aurora. The primary optical emission of sprites is from the molecular nitrogen first positive group (N_2(1PG)) [Mende *et al.*, 1995; Hampton *et al.*, 1996].

The optical emissions observed in sprites, blue jets, and elves are caused by collisions of energetic (heated) electrons with neutrals. These emissions are similar to those observed in the aurora [Vallance Jones, 1974] and are discussed in detail in the following sections. A fundamental difference between auroral and sprite observations involves the altitude where these emissions are produced. At lower altitudes, where sprites are produced, quenching plays an important role in understanding the observed emissions. The energies of the various N_2 electronic states are used in conjunction with the observed emissions to determine the energetics of processes associated with sprites, blue jets/blue starters, and elves. State energies are often characterized in terms of monoenergetic electrons as can be measured in the laboratory while physical processes in nature generally have a more complex energy distribution. Modeling and analysis efforts typically describe an electron distribution similar to a Boltzmann distribution with characteristic energy of ∼1 eV but modified to also have an additional 'high' energy tail (a Druvysteyn distribution has been suggested by Green *et al.* [1996]).

2. Phenomenology

Since initial documentation in 1989, three types of phenomena occurring above thunderstorms have been documented: sprites, blue jets, and elves, as illustrated in Figure 1. Also shown in this figure are typical vertical temperature and electron density profiles which provide context for the three types of phenomena. Two characteristics separating the phenomena into these three groups are duration and altitude. Sprites span the altitude between ∼40-95 km and last ∼10-100 ms. Elves, while not currently triangulated for accurate altitude determination, are estimated to occur between 75-95 km altitudes, lasting less than 1 ms. Blue jets appear from cloud tops (∼20 km) and propagate upwards in the shape of an expanding cone to altitudes of ∼40 km, over a period of ∼200-300 ms. Blue starters appear to propagate upward from storm tops, and are similar to jets. However, at altitudes of ∼25 km or less, the starters extinguish rather than propagating to 40 km as with a blue jet.

gure 1

Lightning discharges are classified into four types, based on direction of propagation (cloud-to-ground or ground-to-cloud) and the net charge removed (positive or negative) [Berger, 1978]. Negative cloud-to-ground discharges remove negative charge from the thunderstorm to ground and constitute approximately 90% of lightning activity. Positive cloud-to-ground discharges constitute almost all the remainder of lightning activity (positive and negative ground-to-cloud discharges are rare, occurring from tall human structures or mountains). Positive cloud-to-ground discharges often occur away from the most electrically active convective cores of thunderstorms, and generally occur during the later stages of large thunderstorms. Sprites generally occur in association with large positive cloud-to-ground (CG) lightning rather than over the more electrically active convective core [Boccippio *et al.*, 1995].

Great progress has been made in the theoretical understanding of sprites, elves, blue jets and blue starters since the first video recordings. These phenomena can be classified by the source of the electric fields that generate them. Experimentally sprites and elves are clearly associated with lightning discharges, which can be detected by instruments on the ground (e.g., the National Lightning Detection Network - NLDN). Jets and starters are the least understood of the phenomena, don't appear to be associated with detectable lightning, and may be associated directly with breakdown near charge centers in the storm (similar to normal lightning). In a thunderstorm, electrical charges are accumulated in a number of charge centers by a slow process, typically minutes or 10's of minutes [MacGorman and Rust, 1998]. A lightning discharge is a rapid rearrangement of these charges and consequently intense electric fields are generated. These fields have two primary sources, one electromagnetic and one electrostatic.

The current change (di/dt) in a lightning stroke radiates a large electromagnetic pulse (EMP). The EMP fields propagate upward, with amplitude decreasing inversely with distance $1/r$ (like the far field of an antenna) until reaching the bottom of the ionosphere. These fields are not large enough to cause breakdown in the atmosphere at low altitudes, but the atmospheric density and, thus, the field required for breakdown decreases exponentially with altitude (the scale height in the middle atmosphere is ∼7 km). The theoretical studies discussed below (originating with work by Inan *et al.* [1991]) show that breakdown from the EMP field will occur in the region between the bottom of the ionosphere at about 95 km and about 75 km, consistent with some of the larger current changes associated with lightning. The EMP fields are associated with the generation of elves. The 100 μs duration of elves is close to the 10-100 μs duration of the high current portions of typical lightning strokes. Elves also have a large horizontal extent (100's of km) matching expectations from the $1/r$ drop in field strength.

Sprites are associated with the Quasi-Electrostatic (QE) fields of lightning, as first suggested by Wilson [1925]. Their sources are the electrostatic fields from the charges in thundercloud. A lightning stroke rapidly removes charge from the thunderstorm, resulting in a rapid change in the charge configuration of the storm giving rise to an electrostatic field. These 'near-fields' fall-off as r^{-3} from the source (the dipole made up of cloud charge and ground image) and have an amplitude proportional to the charge moment ($Q \times L$). If the upper atmosphere were not conducting, only a change in the electrostatic field level that is delayed by the speed of light propagation time would be observed. However, in the stratified conducting atmosphere the behavior is more complex. Free charge carriers in the atmosphere respond to the new electrostatic field configuration and 'shield-out' the field. This process can be accomplished on approximately the local relaxation time scale (σ/ϵ_0) which is 10's of ms at 80 km and a few seconds at 40 km altitude. Because of the very different time scales for cloud charging (minutes), electrical relaxation (milliseconds to seconds) and lightning discharge (microseconds to milliseconds) the QE fields in the upper atmosphere have a rapid onset followed by a decay to a lower level. The field from the original cloud charge configuration does not significantly penetrate to high altitudes because a shielding charge configuration has developed during the slow thunderstorm charge buildup. A lightning stroke changes the electrostatic field of the thunderstorm. The initial amplitude of the QE field is essentially the same as the electrostatic field change expected in a non-conducting atmosphere since the atmosphere does not have time to relax. The typical lifetime of sprites (10's of milliseconds) corresponds well with the relaxation time at higher altitudes 60-90 km. Positive cloud-to-ground lightning flashes tend to neutralize greater charge from higher altitudes than other types of lighting, partially explaining the strong correlation between sprites and positive flashes.

2.1. Sprites

Anecdotal reports of flashes above thunderstorms from ground based observers and airplane pilots date back to the late 19th century [Vaughan and Vonnegut, 1989, and references therein]. Early considerations of thunderstorm effects on the middle atmosphere included breakdown ionization [Wilson, 1925]. The first recorded observation of non-lightning optical emissions associated with thunderstorm activity was made on July 6, 1989 with an intensified low light level camera being calibrated for a sounding rocket campaign [Franz *et al.*, 1990; Winckler, 1995]. This initial evidence led to several large campaigns to characterize sprites, many of these were centered around the Yucca Ridge Field Station in Colorado [Lyons, 1995, 1996] and aircraft flights over the central plains of the United States [Sentman *et al.*, 1995b; Wescott *et al.*, 1995].

The brightest features of sprites (the 'body') occur at ∼70 km altitude. Often bright 'branches' diverge upward from the 'body' of the sprite. Further, there is usually also 'hair' topping the sprite, with no presently resolvable structure, and 'tendrils' extend to regions below the 'body' of the sprite. The upper and lower extremes in altitude have been triangulated to extend above 95 km and below 40 km [Sentman *et al.*, 1995b; Wescott *et al.*, 1998b]. The horizontal extent of a sprite event can be as large as 50 km, but there is a great deal of both vertical and horizontal structure in sprites [Moudry *et al.*, 1998]. Recently, a telescope/imaging system recorded filament-like structures only several tens of meters wide (the resolution of the imaging system) in the 'body' of sprites [**?**]. In general, as the resolving capabilities of sprite observing instrumentation has increased, further structure has been found indicating sprites are highly structured on a fine scale rather than simply a diffuse glow.

Intensified imaging systems used for sprite, jet, and elves observations have primarily been standard television video rate systems (providing 17 ms resolution from interlaced fields). One of the first optical observations of sprites was made in 1993 using photometers (with 100 μs resolution) in a comparative study of optical and Very Low Frequency (VLF) electric field observations [Winckler *et al.*, 1996]. In 1995, observations of sprites and elves using a 4 channel 15 μs resolution photometer were made by Fukunishi *et al.* [1996]. The photometers were occasionally run with a red-pass filter (passing light with wavelength greater 650 nm). One channel in this study was operated with a wide field of view, while three channels were positioned in a vertical array. This study determined that sprites generally begin at ∼70 km and then propagate both upward and downward. Sprites were also observed to start with predominantly blue emissions (lasting less than 100 μs) followed by a much longer red emission from sprites

[Takahashi *et al.*, 1995]. Photometers filtered for specific N_2 groups operated at 1.3 ms time resolution were used to make measurements in 1995-1998 [Armstrong *et al.*, 1998] and are discussed further in the energetics section. In 1996, a blue filtered imager made observations in conjunction with a 50 μs resolution blue filtered photometer [Suszcynsky *et al.*, 1998]. The photometer observations and high speed imager observations (with 1 ms resolution) Stanley *et al.* [1999] show that sprites develop and evolve at sub-millisecond time scales. All the spectral observations discussed later in this paper are made using video imaging systems (17 ms resolution) and therefore average over much of the temporal evolution of sprites.

2.2. Blue Jets and Blue Starters

On July 1, 1994 University of Alaska scientists aboard aircraft were observing a thunderstorm over Arkansas as part of a three week sprite campaign. Because of the storm/aircraft geometry (the cameras were viewing away from the sunset), the observations began about one hour earlier than most other nights. Fifty-nine examples of luminous columns of light propagating up from the storm tops were recorded during a 22 minute period. At the time of observation, these new phenomena were obviously different from sprites in two ways: (1) the propagation speed was such that the upward motion was easily apparent at video rates and (2) the emissions were blue, as observed by an intensified color camera. Due to the upward motion and the color of the phenomena, they were given the name blue jets. Triangulation analysis of 34 blue jets observed simultaneously by both aircraft found an upper altitude of 37.2 ± 5.3 km and an upward velocity of 112 ± 24 km/s [Wescott *et al.*, 1995]. The blue jets do not occur in association with either positive or negative cloud-to-ground lightning as reported by the National Lightning Detection Network. The blue jets do occur over regions of storms actively producing negative cloud-to-ground discharges and heavy hail activity, but the jets are not temporally coincident with a single discharge.

A similar phenomena, blue starters, propagate up from the top of the thunderstorm [Wescott *et al.*, 1996]. However, starters terminate at an average altitude of $\sim$25.5 km and have a velocity range of 27-153 km/s. Intensified color camera observations record starters as the same color as blue jets. Thirty starters were observed in the same region of the storm as the blue jets, during the same 22 minute interval. On several other nights starters were observed over the active convective core of storms (but no blue jets were recorded). Blue starters were also observed during the EXL98 mission (described in the Energetics section). The starters were observed in blue filtered images and also in the near infrared. The implications of these observations will be discussed below.

2.3. Elves

A third phenomena observed above thunderstorms are elves (Emissions of Light and VLF perturbations due to EMP Sources [Fukunishi *et al.*, 1995]), very brief (less than 1 ms) red emissions at the bottom of the ionosphere (at the upper altitudes of sprites). Optical "airglow enhancements" associated with lightning were first reported based on shuttle observations [Boeck *et al.*, 1992] and possibly from sounding rockets [Li *et al.*, 1991]. The phenomena were named elves after further documentation [Lyons and Nelson, 1995; Desroschers *et al.*, 1995] and photometer observations determined the brief ($\sim$1 ms) lifetime of elves [Fukunishi *et al.*, 1996]. Strong Joule heating of the base of the ionosphere by tropospheric lightning EMP was predicted earlier [Inan *et al.*, 1991], and the possibility of optical emissions were first investigated by Taranenko *et al.* [1993b] stimulated by the observations of lightning associated airglow enhancements by Boeck *et al.* [1992]. The simple model for elves is the interaction between the (spherically expanding) EMP from a cloud-to-ground lightning discharge and the (planar) lower ionosphere [Inan *et al.*, 1996b]. The radially expanding disc (intersection of the expanding sphere and plane) was measured using a "fly's-eye" array of seventeen photometers operating at 40 kHz [Inan *et al.*, 1997].

Elves occur above thunderstorms, both in conjunction with sprites and alone. Elves observed in the intensified color camera are red, and spectral observations of elves identify the main emissions to be N_2(1PG) [Heavner, 2000]. Filtered observations of N_2(1PG) emission confirm the identification of elves emissions (personal communications, Mike Taylor). To date, triangulation analysis of elves has not been performed. Single station analysis using National Lightning Detection Network lightning location estimates the altitude of elves between 75-95 km, the typical vertical thickness is several km, and the horizontal extent as much as 530 km [Dial and Taylor, 1999]. Elves are observed above both positive and negative CG lightning [Barrington-Leigh and Inan, 1999].

3. Energetics

Color camera observations of sprites and blue jets from 1994 provided the first information about the energy processes producing middle atmospheric optical emissions [Sentman *et al.*, 1995b; Wescott *et al.*, 1995]. The optical signature from sprites appeared primarily in the red channel of the color camera with some blue emissions from the lower portions of sprites. Blue jets appear solely in the blue channel. Spectrographic observations of sprites in 1995 identified the brightest red emissions as the molecular nitrogen first positive group (N_2(1PG)) [Mende *et al.*, 1995; Hampton *et al.*, 1996]. Ground based blue filtered photometer observations and blue and red filtered observations were made in the summers of 1996, 1997, and 1998 to understand the blue emissions of sprites [Armstrong *et al.*, 1998; Suszcynsky *et al.*, 1998]. Most observations of optical emissions above thunderstorms are made at low slant angles (10° or less), so severe Rayleigh scattering is present and atmospheric transmission in the blue is poor (*c.f.* Section 2 of Morrill *et al.* [1998]). The EXL98 (Energetics of Upper Atmospheric Excitation by Lightning, 1998) campaign was designed specifically to study microphysical energy processes of sprites, blue jets, and elves. EXL98 [Sentman *et al.*, 1998] was centered on a series of aircraft flights during July 1998 with several intensified cameras. These cameras covered wavelengths from the near-UV (320 nm) to the near-IR (>1500 nm) and provided a unique opportunity to study the energetics of these phenomena. One reason for the use of aircraft in 1998 was to get above the dense atmosphere to facilitate blue observations.

3.1. Energetics of Sprites–Observations

Ground based red spectral observations of sprites were made during the northern hemisphere summers of 1995 and 1996. The first measured optical spectrum of a sprite was obtained June 21, 1995 from the Mt. Evans observatory in Colorado [Hampton *et al.*, 1996]. The 1995 red spectral observations characterized sprite emissions between 550-850 nm, documenting that the primary optical emissions from sprites is N_2(1PG) [Mende *et al.*, 1995; Hampton *et al.*, 1996], a molecular nitrogen group with red emissions brightest between 700-1000 nm. In 1996, spectral observations increased the red range of observations to 1000 nm and attempted to improve the characterization of blue emissions [Heavner *et al.*, 1996]. The observed N_2(1PG) emission are due to molecular nitrogen electronic transitions $\mathrm{N}_2(\mathrm{B}^3\Pi_g \rightarrow \mathrm{A}^3\Sigma_u^+)$, with a quenching altitude of ~53 km (see Table 1).

Table 1

One specific event, from July 24, 1996 at 03:58:23.975 required the inclusion of N_2^+(Meinel) emission to generate a reasonable synthetic spectral fit to the observed spectrum [Morrill *et al.*, 1998; Bucsela *et al.*, 1999]. The observed spectrum and synthetic spectral fit appear in upper panel of Figure 2. The resulting relative vibrational distribution for the $\mathrm{N}_2(\mathrm{B}^3\Pi_g)$ and $\mathrm{N}_2^+(\mathrm{A}^2\Pi_u)$ states are presented in the lower panel of Figure 2. This observation is interesting since the horizontal slit of the spectrograph was measuring sprite emissions from an altitude of 57 km, well below the quenching altitude of N_2^+(Meinel) (85-90 km). As discussed by Morrill *et al.* [1998] and Bucsela *et al.* [1999], the presence of N_2^+(Meinel) emission may be due, in part, to energy transfer processes beyond simple quenching. The possible presence of N_2^+(Meinel) emission in the spectra of Mende *et al.* [1995] and Hampton *et al.* [1996] was also discussed by Green *et al.* [1996]. The N_2^+(Meinel) emission requires at least 16.5 eV to excite the lowest vibration level of the upper state, indicative of higher energetic processes than N_2(1PG) emission (requiring only 7.5 eV to excite). Additionally, this event had the strongest signature of blue emissions (as observed using the blue filtered imager, see Figure 2 of Suszcynsky *et al.* [1998]). Blue emissions, whether N_2(2PG) or N_2^+(1NG), are indicative of a higher energy process than the red N_2(1PG) emissions.

Figure 2

Several molecular nitrogen electronic transitions are summarized in Table 1. The upper and lower electronic states are listed in this table of the emissions. The quenching altitude is the altitude at which 50% of the population of upper electronic state is collisionally deactivated before it undergoes radiative decay [Vallance Jones, 1974]. The threshold energy in the table is the energy between the lowest vibrational level of the upper state and the lowest vibrational level of the ground state of N_2, although the peak in the electron impact excitation cross-section occurs at slightly higher energy [Vallance Jones, 1974].

A series of recent photometric studies have examined time-resolved blue/NUV emissions. In 1995, Armstrong *et al.* [1998] used a filter centered at 431.7 nm with a FWHM (full width, half maximum) of 10.6 nm. In 1996, a second filter centered at 399.2 nm with a FWHM of 9.6 nm was used in conjunction with the 431.7 nm filter. Both of these filters include both N_2^+(1NG) and N_2(2PG) emissions in their bandpass, making definitive observations regarding ionized emissions from sprites difficult. However, the ratio of the two filtered photometers is able to discriminate between lightning, sprites, and elves. The 399.2/431.7 ratio for lightning is 1, in agreement with the expected continuum radiation. For sprites, the 399.2/431.7 ratio is ∼2 while elves alone (based on a lower number of observations) give a measured 399.2/431.7 ratio of ∼3. The temporal evolution of the ratio of the two filters suggests an initial process with an electron temperature equivalent to ∼10 eV (for less than 1 ms) followed by a longer lasting ∼1 eV process. Similar observations were made by Suszcynsky *et al.* [1998] who used a 20 nm wide filter centered on 425 nm with a photometer to observe the 427.8 nm N_2^+(1NG)(0,1) emission. However, the filter bandpass also included the lower energy N_2(2PG)(1,5) emission at 426.8 nm as well as several other less intense N_2(2PG) emissions which may have contributed to a portion of the observed signal. A blue filtered camera (response centered at 410 nm with a passband between 350-475 nm) was used in conjunction with the photometer. The important point to note here is that both of these studies indicate the presence of N_2^+ emissions during the initial portion of the sprite.

The EXL98 campaign used an aircraft to get above the most dense portion of the atmosphere, in order to characterize the blue emissions of sprites. This involved both broad and narrow band video observation as well as NUV/blue spectral observations. The brightest N_2^+(1NG) emission is at 391.4 nm (1NG, (0,0) band), but instrumental response, atmospheric transmission, and the close 389.4 nm and 394.3 nm N_2(2PG) emissions made the second brightest N_2^+(1NG) emission at 427.8 nm (1NG, (0,1) band) the target for filtered imaging during EXL98. Knowledge of possible contamination by neutral N_2 emission (2PG) through the filter at 426.8 nm is critical in both the filter selection and data analysis. This is especially important for observations at the edge of the image due to the shift of the filter response toward the blue with increased angle.

The first NUV/blue spectral observations of sprites were recorded during the mission [Heavner *et al.*, 2000]. The primary blue N_2 emissions identified in the observed spectra is the N_2(2PG) neutral emission from the $N_2(C^3\Pi_u \rightarrow B^3\Pi_g)$ transition. N_2^+(1NG) emission from the $N_2^+(B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+)$ transition appears but is weak in these spectra. An example of the blue spectral observations from a sprite observed at July 28, 1998 06:41:01.278 is presented in Figure 3. The upper panel is from a panchromatic imager with a 13.7° x 10.0° field of view. The black box indicates the NUV spectrograph field of view defined by the spectrograph entrance slit. The lower panel is the observations from the NUV spectrograph. The observed spectrum is plotted with a solid line, and a synthetic fit to the spectrum including both N_2(2PG) and N_2^+(1NG) is overplotted (see Bucsela and Sharp [1997] for a discussion of the fitting technique). The higher energy component (N_2^+(1NG)) of the synthetic fit is plotted as a separate curve. The observed blue spectrum is from the "body" of the sprite, while both color and filtered images of sprites show the majority of blue light is from the lower portions [Sentman *et al.*, 1995b]. There is no signal from the sprite in the 427.8 nm imager in the sprite body, in agreement with the observed spectrum. The sprite occurred at a great circle distance of 329 km from the EXL98 aircraft (flying at ∼14 km altitude).

gure 3

In contrast to the lack of any blue ionized nitrogen signature in the previous example, a second EXL98 observation, from July 24, 1998 04:57:43 is presented in Figure 4 [Heavner *et al.*, 1998]. The upper panel of Figure 4 is an image of the sprite from the wide field-of-view (FOV) camera, with the white square indicating the FOV of the narrow field camera. The lower right panel is the cropped image from the 427.8 nm filtered and the lower left panel is from an identical camera which was not filtered. The 427.8 nm image has been processed with histogram equalization, a method of stretching the dynamic range of the image. The observations of the sprite in the 427.8 nm filtered imager indicates a higher energy process occurring in the tendrils (18.6 eV electrons are required to excite the lowest N_2^+(1NG) state from the N_2 ground state). The post flight calibration of the EXL98 filtered cameras is currently underway. Once complete these results will provide improved estimates of electron energies occurring in the various portions of sprites.

Figure 4

3.2. Energetics of Sprites–Models

Three types of models have been proposed to describe sprites using the quasi-electrostatic heating and runaway electron mechanisms (see Rowland [1998] for a review of models). These models take a tropospheric lightning discharge as the initial energy source and propose mechanisms for the propagation of this energy to the electron impact excitation of middle- and upper-atmospheric molecular nitrogen, resulting in the observed optical emissions. The quasi-electrostatic heating model and the EMP-induced breakdown model describe the heating of ambient thermal electrons through electric fields while the runaway electron model proposes the energization of neutrals directly by high energy electrons. In these models, heated/accelerated electrons collisionally transfer energy to the neutrals to produce optical emissions, ionization and possible long-term (hour time scale) heating of the upper atmospheric neutrals [Picard *et al.*, 1997].

The quasi-electrostatic heating model [Pasko *et al.*, 1997] postulates electric fields which are a result of the sudden reconfiguration of thunderstorm charge due to the removal of charge by a lightning discharge. A large positive cloud to ground flash removes positive charge from the upper charge center (*e.g.* 300 C removed from 10 km altitude) which produces a large change in the electric field (greater than 100 V/m at 70 km altitude). The field persists for approximately the local relaxation time (milliseconds at 85 km altitude, but seconds at 45 km altitude). The strength of the field is determined by charge moment ($Q \times L$) of the lightning flash. In order to test the model, experimental determination of charge moment from ELF/VLF (10 Hz - 30 kHz) measurements has been developed [Cummer *et al.*, 1998]. Similar to the quasi-electrostatic model is the EMP induced breakdown model which includes the addition of an upward propagating EMP associated with a large lightning stroke that can produce breakdown at altitudes above 60 km [Taranenko *et al.*, 1993a, b; Inan *et al.*, 1996a; Fernsler and Rowland, 1996; Rowland *et al.*, 1995, 1996; Milikh *et al.*, 1995].

The runaway electron model postulates a high energy seed electron (possibly a cosmic ray secondary) accelerated by the electric field above a thunderstorm [Roussel-Dupré *et al.*, 1998; Taranenko and Roussel-Dupré, 1996; Lehtinen *et al.*, 1996]. If the seed electron has enough kinetic energy, a collision between the seed electron and a low energy (ambient) electron can result in two relativistic electrons. This process is predicted to produce a beam of avalanching runaway electrons. Optical emissions produced from this mechanism would have a much higher characteristic energy than the quasi-electrostatic heating model predicts.

3.3. Energetics of Blue Jets/Starters

Blue jets and starters are upward propagating cones of blue emissions. At the altitudes of blue jets (below $\sim$40 km), the N_2(1PG) upper state ($N_2(B^3\Pi_g)$) is strongly quenched (*e.g.* the upper state is collisionally deactivated more rapidly than decay by spontaneous emission), so no red N_2(1PG) emission is observed in blue jets. The blue light is affected strongly by Rayleigh scattering at long path lengths, while the close proximity to the storm required for short path lengths ($\sim$150 km) make blue jet/starter observations a geometrical problem: the blue jets and starters occur over the active cores of storms, so large storm systems may have intervening clouds blocking viewing of blue jets/starters. For these reasons, the dearth of ground based observations of blue jets may not be truly indicative of their frequency of occurrence.

The blue emissions in jets are most likely either from N_2(2PG) or N_2^+(1NG) emissions. Analysis of color camera observations of blue jets found emissions from the lower energy N_2(2PG) alone could not sufficiently account for the observations [Wescott *et al.*, 1998b], so N_2^+(1NG) emission were suggested. No blue jets or starters were observed with the NUV/Blue spectrograph on EXL98, but several starters were clearly recorded by the 427.8 nm imager. Blue starters are similar to blue jets, propagating from cloud tops, but terminate abruptly after less than 10 km of upward travel. A blue starter observed July 17, 1998 during the EXL98 campaign is presented in Figure 5 [Deehr *et al.*, 1998]. The left panel is a view of the 340.7 nm (a neutral N_2(2PG) emission) filtered observation. The right panel is the unfiltered narrow imager, and the center panel is the 427.8 nm filtered image. The starter is bright in the 427.8 nm filtered camera. This confirms the suggestion of ionized emissions in starters (and likely blue jets as well). Blue jets possibly have the signature of higher total energy processes than either sprites or elves because of the ionized emissions, and blue jets last 10-100 times longer than other phenomena. Wescott *et al.* [1998a] estimate that the average blue jet or starter transfers about 10^9 J of energy to the stratosphere.

Figure 5

In addition to blue emission, jets have been observed in the near-IR during EXL98. These emissions are most likely some combinations of N_2(1PG) and N_2^+(M). Considering the quenching heights in Table 1 N_2(1PG) and N_2^+(Meinel) emission should be strongly quenched. However, energy transfer processes may enhance the population of the lower vibrational level of the N_2(1PG) and N_2^+(Meinel) upper electronic states. Another possibility would be emission from atomic species (O and N) as is observed in lightning. The existence of atomic emissions would indicate a much more energetic process than is thought to occur in sprites and elves. This issue will best be resolved by spectroscopic observations of blue jets and starters.

Two models based on streamer-type phenomena have been proposed to explain blue jets [Pasko *et al.*, 1996; Sukhorukov *et al.*, 1996; Sukhorukov and Stubbe, 1998; Yukhimuk *et al.*, 1998]. Based on modeling efforts, a single jet has been postulated to cause local density perturbations of nitric oxide (10%) and ozone (0.5%) at 30 km altitude [Mishin, 1997]. As mentioned above, if the processes leading to blue jets and sprites are energetic enough to create atomic species of N and O, the implications for other chemical effects is significantly increased.

3.4. Energetics of Elves

Elves have been described by models as heating from the EMP from tropospheric lightning [Inan *et al.*, 1997; Pasko *et al.*, 1998]. The optical emissions of elves have been identified as originating from N_2(1PG) [Heavner, 2000]. The short duration of elves suggests that individual elves are less important energetically than sprites or jets. However, elves (optical emissions) may represent only the high energy component of the effect of lightning discharges transferring energy to the middle atmosphere. Lower energy lightning discharges may not cause optical emissions, but the majority of tropospheric lightning discharges can still cause neutral heating in the middle and upper atmosphere but do not stimulate optical emissions. Before the documentation of elves, the neutral heating of the upper atmosphere by lightning was proposed as a mechanism for creating a long-term (hour time scale) infrared glow above thunderstorms [Inan *et al.*, 1991; Picard *et al.*, 1997]. The mechanism described the vibrational excitation of ground state N_2 by electron impact followed by energy transfer via $N_2(X^1\Sigma_g^+)(v>0)\rightarrow CO_2$. Because elves are observed to occur above both positive and negative CG's they may occur more frequently than sprites.

4. Global Frequency

The majority of sprite observations have been made during the northern hemisphere summers and with large thunderstorms over the midwestern high plains of North America. Few observations from a platform which has a global view have been made – a total of 19 sprites have been identified in the video observations from the U.S. space shuttle [Boeck *et al.*, 1998]. The distinct signature of a sprite has not been reported in any satellite observations.

In February-March 1995, an aircraft campaign to explore the global distribution of sprites was based in Lima, Peru [Sentman *et al.*, 1995a; Heavner *et al.*, 1995]. Although Amazonia is one of the most active lightning regions of the world only ∼20 sprites were observed during a two week period. Similar aircraft campaigns over the central United States observed hundreds of events. The observed low activity level is likely due in part to logistical and observational challenges of the particular observations: a border war between Peru and Ecuador was being fought during the campaign, and a system such as the U.S. National Lightning Detection network was not available to identify regions of strong positive lightning activity. The NLDN data greatly improves the identification of likely sprite producing regions of storms. Effects of the nearly horizontal magnetic field of the Earth near the equator is another possible factor for the apparent low frequency of sprite observations in low latitude regions. Theorists postulating a runaway electron beam associated with sprites and blue jets generally agree that a horizontally aligned Earth's magnetic field will deacrease the formation of the runaway electron beams [Lehtinen *et al.*, 1997; Gurevich *et al.*, 1996; Taranenko and Roussel-Dupré, 1997]. The proposed QE heating models do not generally address any dependence on the orientation of the local Earth's magnetic field.

Research has also been underway in Australia during southern hemisphere summers since 1997 [Hardman *et al.*, 1998] and recently observations of sprites occurring above Japanese winter thunderstorms have been made [Fukunishi *et al.*, 1999]. Intensified cameras aboard the space shuttle have observed at least one sprite above thunderstorms in Africa, as well as several above South America [Boeck *et al.*, 1998].

In order to approach the questions of global rates and distributions of sprites, elves, and blue jets, more observations are required. The identification of a global synoptic detection method of these events would enhance such measurements. Attempting to estimate the global occurrence of sprites is an elusive problem. The latest estimate of the global cloud to ground lightning flash rate of between $10s^{-1}$ and $14s^{-1}$ [Mackerras *et al.*, 1998]. Positive flashes are less than 10% of the total lightning flashes, and not every positive flash produces an optically detectable sprite. Therefore a preliminary upper limit for the global occurrence of sprites is estimated at 1 per second. However, this is based on the assumption that the global sprite distribution is similar to global lightning distribution. While current observations are biased geographically, lightning and sprites do not appear to necessarily have the same spatial distribution. Blue jets are rarely recorded by ground based observers and even aircraft campaigns record many more sprites than blue jets/starters. However, the dearth of jet observations may be partially explained by Rayleigh scattering and observational difficulties described earlier. The long duration of blue jets and the observation of strong N_2^+(1NG) emissions indicate that blue jets may be an important energetic process in the stratosphere. Elves are associated with both positive and negative cloud-to-ground lightning, so the global elves occurrence rate is probably higher than the global sprite rate.

5. Summary

In the past decade, several types of optical emissions occurring above thunderstorms have been identified. The emissions span the middle- and upper-atmosphere between thunderstorm tops and ~95 km. Spectroscopic and filtered observations of sprites and blue jets have been presented and discussed. The observed nitrogen emissions indicate electrons with energies of at least 18.6 eV are required to describe some of the observed emissions. A 1 eV Boltzmann electron distribution (modified with a high energy tail component) matches the observations and is physically realistic. Based on observations of the total optical energy emitted by a sprite, we estimate the total energy depositied into active molecular nitrogen (both vibrational and electronic state energy) to range from 250 MJ to 1 GJ. Recent observations from EXL98 under current analysis will help clarify and confirm these values. The preliminary estimate on global occurrence rates of sprites, blue jets, and elves, is on the order of 1 per second.

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References

Armstrong, R. A., J. A. Shorter, M. J. Taylor, D. M. Suszcynsky, W. A. Lyons, and L. S. Jeong, Photometric measurements in the SPRITES '95 & '96 campaigns of nitrogen second positive (399.8 nm) and first negative (427.8 nm) emissions, *J. Atmos. Solar Terr. Physics*, *60*, 787–799, 1998.

Barrington-Leigh, C. P. and U. S. Inan, Elves triggered by positive and negative lightning discharges, *Geophys. Res. Let.*, *26*(6), 683–686, 1999.

Berger, K., Blitzstrom-parameter von aufwärtsblitzen, *Bull. Schweiz. Elektrotech. Ver.*, *69*, 353–360, 1978.

Besser, V., D. R. Moudry, M. J. Heavner, D. D. Sentman, E. M. Wescott, J. S. Morrill, C. Siefring, D. L. Osborne, and D. L. Hampton, Case study of a sprite, *EOS Supplement*, *79*(45), F165, 1998.

Boccippio, D. J., E. R. Williams, S. J. Heckman, W. A. Lyons, I. T. Baker, and R. Boldi, Sprites, Extreme-Low-Frequency transients, and positive ground strokes, *Science*, *269*, 1088–1091, 1995.

Boeck, W. L., O. H. Vaughan, Jr., R. Blakeslee, B. Vonnegut, and M. Brook, Lightning induced brightening in the airglow layer, *Geophys. Res. Let.*, *19*, 99–102, 1992.

Boeck, W. L., O. H. Vaughan, Jr., R. J. Blakeslee, B. Vonnegut, and M. Brook, The role of the space shuttle videotapes in the discovery of sprites, jets and elves, *J. Atmos. Solar Terr. Physics*, *60*, 669–677, 1998.

Bucsela, E., M. J. Heavner, J. S. Morrill, S. Berg, C. Seifring, W. Benesch, E. M. Wescott, D. Sentman, D. L. Hampton, and D. R. Moudry, $N_2(B^3\Pi_g)$ and $N_2^+(A^2\Pi_u)$ vibrational distributions observed in sprites, *Geophys. Res. Let.*, 1999, in prep.

Bucsela, E. J. and W. E. Sharp, NI 8680 and 8629 Å multiplets in the dayglow, *J. Geophys. Res.*, *102*, 2457–2466, 1997.

Cummer, S. A., U. S. Inan, T. F. Bell, and C. P. Barrington-Leigh, ELF radiation produced by electrical currents in sprites, *Geophys. Res. Let.*, *25*(8), 1281–1284, 1998.

Deehr, C. S., E. M. Wescott, D. D. Sentman, H. C. Stenbaek-Nielsen, M. J. Heavner, D. R. Moudry, C. L. Siefring, J. S Morrill, and E. J. Bucsela, New evidence for ionization of blue starters and blue jets, *EOS Supplement*, *79*(45), F136, 1998.

Desroschers, J. T., M. J. Heavner, D. L. Hampton, D. D. Sentman, and E. M. Wescott, A preliminary morphology of optical transients above thunderstorms, *EOS Supplement*, *76*(46), F105, 1995.

Dial, R. and M. Taylor, Investigation of lightning induced elves over the great plains, CEDAR 1999 Workshop.

Fernsler, R. and H. Rowland, Models of lightning-produced sprites and elves, *J. Geophys. Res.*, *101*, 29653, 1996.

Franz, R. D., R. J. Nemzek, and J. R. Winckler, Television images of a large upward electrical discharge above a thunderstorm system, *Science*, *249*, 48–51, 1990.

Fukunishi, H., Y. Takahashi, M. Kubota, and K. Sakanoi, Lower ionosphere flashes induced by lightning discharges, *EOS Supplement*, *76*(46), F114, 1995.

Fukunishi, H., Y. Takahashi, M. Kubota, K. Sakanoi, U. S. Inan, and W. A. Lyons, Elves: Lightning-induced transient luminous events in the lower ionosphere, *Geophys. Res. Let.*, *23*, 2157–2160, 1996.

Fukunishi, H., Y. Takahashi, A. Uchida, M. Sera, and K. R. Miyasato, Occurrences of sprites and elves above the Sea of Japan near Hokuriku in winter, *EOS Supplement*, *80*(46), F217, 1999.

Green, B. D., M. E. Fraser, W. T. Rawlins, L. Jeong, W. A. Blumberg, S. B. Mende, G. R. Swenson, D. L. Hampton, E. M. Wescott, and D. D. Sentman, Molecular excitation in sprites, *Geophys. Res. Let.*, *23*(23), 2161–2164, 1996.

Gurevich, A. V., J. A. Valdivia, G. M. Milikh, and K. Papadopoulos, Runaway electrons in the atmosphere in the presence of a magnetic field, *Radio Science*, *31*, 1541, 1996.

Hampton, D. L., M. J. Heavner, E. M. Wescott, and D. D. Sentman, Optical spectral characteristics of sprites, *Geophys. Res. Let.*, *23*(1), 89–92, 1996.

Hardman, S. F., R. L. Dowden, J. B. Brundell, J. L. Bahr, Z. Kawasaki, and C. J. Rodger, Sprites in Australia's Northern Territory, *EOS Supplement*, *79*(45), F135, 1998.

Heavner, M. J., *Optical Spectroscopic Observations of Sprites, Blue Jets, and Elves: Inferred Microphysical Processes and Their Macrophysical Implications*, Ph.D. thesis, University of Alaska, Fairbanks, 2000.

Heavner, M. J., D. L. Hampton, D. D. Sentman, and E. M. Wescott, Sprites over Central and South America, *EOS Supplement*, *76*(46), F115, 1995.

Heavner, M. J., D. R. Moudry, D. D. Sentman, E. M. Wescott, and J. T. Descroschers, Spectral observations of sprites, *EOS Supplement*, *77*(46), F60, 1996.

Heavner, M. J., D. R. Moudry, D. D. Sentman, E. M. Wescott, J. S. Morrill, C. Siefring, E. J. Bucsela, D. L. Osborne, J. T. Desrochers, H. Stenbaek-Nielsen, J. Winick, J. Kristl, T. Hudson, L. M. Peticolas, and V. Besser, Ionization in sprites, *EOS Supplement*, *79*(45), F165, 1998.

Heavner, M. J., J. S. Morrill, E. J. Bucsela, D. D. Sentman, C. L. Siefring, E. Wescott, and D. R. Moudry, NUV/Blue spectral observations of sprites in the 320-460 nm region: N_2 (2PG) emissions, *Geophys. Res. Let.*, 2000, in prep.

Inan, U., C. Barrington-Leigh, S. Hansen, V. S. Glukhov, T. F. Bell, and R. Rairden, Rapid lateral expansion of optical luminosity in lightning-induced ionospheric flashes referred to as 'elves', *Geophys. Res. Let.*, *24*(5), 583–586, 1997.

Inan, U. S., T. F. Bell, and J. V. Rodrigues, Heating and ionization of the lower ionosphere by lightning, *J. Geophys. Res.*, *18*, 705–708, 1991.

Inan, U. S., S. C. Reising, G. J. Fishman, and J. M. Horack, On the association of terrestrial gamma-ray bursts with lightning and implications for sprites, *Geophys. Res. Let.*, *23*, 1017–1020, 1996a.

Inan, U. S., W. A. Sampson, and Y. N. Taranenko, Space-time structure of optical flashes and ionization changes produced by lightning-EMP, *Geophys. Res. Let.*, *23*(2), 133–136, 1996b.

Lehtinen, N. G., M. Walt, U. S. Inan, T. F. Bell, and V. P. Pasko, γ-ray emission produced by a relativistic beam of runaway electrons accelerated by quasi-electrostatic thundercloud fields, *Geophys. Res. Let.*, *23*(19), 2645–2648, 1996.

Lehtinen, N. G., T. F. Bell, V. P. Pasko, and U. S. Inan, A two-dimensional model of runaway electron beams driven by quasi-electrostatic thundercloud fields, *Geophys. Res. Let.*, *24*(21), 2639–2642, 1997.

Li, Y. Q., R. H. Holzworth, H. Hu, M. McCarthy, R. D. Massey, P. M. Kintner, J. V. Rodrigues, U. S. Inan, and W. C. Armstrong, Anomalous optical events detected by rocket-borne sensor in the WIPP campaign, *J. Geophys. Res.*, *96*(A2), 1315–1326, 1991.

Lyons, W. A., Low-light video observations of frequent luminous structures in the stratosphere above thunderstorms, *Monthly Weather Review*, *122*, 1940, 1995.

Lyons, W. A., Sprite observations above the U.S. High Plains in relation to their parent thunderstorm systems, *J. Geophys. Res.*, *101*, 29641–29652, 1996.

Lyons, W. A. and T. E. Nelson, The Colorado SPRITES '95 campaign: Initial results, *EOS Supplement*, *76*(46), 113, 1995.

MacGorman, D. R. and W. D. Rust, *The Electrical Nature of Storms*. Oxford University Press, New York, NY, 1998.

Mackerras, D., M. Darveniza, R. E. Orville, E. R. Williams, and S. J. Goodman, Global lightning: Total, cloud and ground flash estimate, *J. Geophys. Res.*, *103*(D16), 19791–19809, 1998.

Mende, S. B., R. L. Rairden, and G. R. Swenson, Sprite spectra: $N_2$1PG band identification, *Geophys. Res. Let.*, *22*, 2633–2636, 1995.

Milikh, G. M., K. Papadopoulos, and C. L. Chang, On the physics of high altitude lightning, *Geophys. Res. Let.*, *22*, 85–88, 1995.

Mishin, E., Ozone layer perturbation by a single blue jet, *Geophys. Res. Let.*, *24*(15), 1919–1922, 1997.

Morrill, J. S., E. J. Bucsela, V. P. Pasko, S. L. Berg, M. J. Heavner, D. R. Moudry, W. M. Benesch, E. M. Wescott, and D. D. Sentman, Time resolved N_2 triplet state vibrational populations and emissions associated with red sprites, *J. Atmos. Solar Terr. Physics*, *60*, 811–829, 1998.

Moudry, D. R., M. J. Heavner, D. D. Sentman, E. M. Wescott, J. S. Morrill, and C. Siefring, Morphology of sprites, *EOS Supplement*, *79*(45), F136, 1998.

Pasko, V. P., U. S. Inan, and T. F. Bell, Blue jets produced by quasi-electrostatic pre-discharge thundercloud fields, *Geophys. Res. Let.*, *23*(3), 301–304, 1996.

Pasko, V. P., U. S. Inan, T. F. Bell, and Y. N. Taranenko, Sprites produced by quasi-electrostatic heating and ionization in the lower ionosphere, *J. Geophys. Res.*, *102*(A3), 4529–4561, 1997.

Pasko, V. P., U. S. Inan, and T. F. Bell, Ionospheric effects due to electrostatic thundercloud fields, *J. Atmos. Solar Terr. Physics*, *60*(7), 863–870, 1998.

Picard, R. H., U. S. Inan, V. P. Pasko, J. R. Winick, and P. P. Wintersteiner, Infrared glow above thunderstorms?, *Geophys. Res. Let.*, *24*(21), 2635–2638, 1997.

Rodger, C. J., Red sprites, upward lightning and VLF perturbations, *Reviews of Geophysics*, *37*(3), 317–336, 1999.

Roussel-Dupré, R., E. Symbalisty, Y. Taranenko, and V. Yukhimuk, Simulations of high-altitude discharges initiated by runaway breakdown, *J. Atmos. Solar Terr. Physics*, *60*(7), 917–940, 1998.

Rowland, H., R. Fernsler, J. Huba, and P. Bernhardt, Lightning drive EMP in the upper atmosphere, *Geophys. Res. Let.*, *22*, 361–364, 1995.

Rowland, H., R. Fernsler, and P. Bernhardt, Breakdown of the neutral atmosphere in the D-region due to lightning driven electromagnetic pulses, *J. Geophys. Res.*, *101*, 7935–7945, 1996.

Rowland, H. L., Theories and simulations of elves, sprites, and blue jets, *J. Atmos. Solar Terr. Physics*, *60*(7), 831–844, 1998.

Sentman, D., Electrical excitation of the middle and upper atmosphere by lightning: Special issue of the Journal of Atmospheric and Solar-Terrestrial Physics, *J. Atmos. Solar Terr. Physics*, *60*(7-9), 667, 1998.

Sentman, D. D., E. M. Wescott, D. L. Osborne, M. J. Heavner, and D. L. Hampton, The Peru95 sprites campaign: Overview, *EOS Supplement*, *76*(17), S66, 1995a.

Sentman, D. D., E. M. Wescott, D. L. Osborne, D. L. Hampton, and M. J. Heavner, Preliminary results from the Sprites94 aircraft campaign: 1. Red Sprites, *Geophys. Res. Let.*, *22*, 1205–1208, 1995b.

Sentman, D. D., E. M. Wescott, J. Winick, C. Siefring, J. Morrill, D. Baker, P. Bernhardt, M. Heavner, D. Moudry, D. Osborne, J. Desrochers, L. Peticolas, and V. Besser, The EXL98 sprites campaign, *EOS Supplement*, *79*(45), F164, 1998.

Slinker, S. and A. W. Ali, Electron excitation and ionization rate coefficients for N_2, O_2, NO, N, O, Technical report, Naval Research Labs, 1982.

Stanley, M., P. Krehbiel, M. Brook, C. Moore, W. Rison, and B. Abrahams, High speed video of initial sprite development, *Geophys. Res. Let.*, *26*(20), 3201–3204, 1999.

Sukhorukov, A. I. and P. Stubbe, Problems of blue jet theories, *J. Atmos. Solar Terr. Physics*, *60*, 725–732, 1998.

Sukhorukov, A. I., E. A. Rudenchik, and P. Stubbe, Simulation of the strong lightning pulse penetration into the lower ionosphere, *Geophys. Res. Let.*, *23*, 2911, 1996.

Suszcynsky, D. M., R. Roussel-Dupré, W. A. Lyons, and R. A. Armstrong, Blue-light imagery and photometry of sprites, *J. Atmos. Solar Terr. Physics*, *60*(7), 801–809, 1998.

Takahashi, Y., M. Kubota, K. Sakanoi, H. Fukunishi, U. S. Inan, and W. A. Lyons, Spatial and temporal relationship between lower ionospheric flashes and sprites, *EOS Supplement*, *76*(106), 1995.

Taranenko, Y. and R. Roussel-Dupré, Reply, *Geophys. Res. Let.*, *24*(21), 2645–2646, 1997.

Taranenko, Y. N. and R. Roussel-Dupré, High-altitude discharges and gamma-ray flashes: A manifestation of runaway air breakdown, *Geophys. Res. Let.*, *23*(5), 571–574, 1996.

Taranenko, Y. N., U. S. Inan, and T. F. Bell, Interaction with the lower ionosphere of electromagetnic pulses from lightning: heating attachment, and ionization, *Geophys. Res. Let.*, *20*, 1539–1542, 1993a.

Taranenko, Y. N., U. S. Inan, and T. F. Bell, The interaction with the lower ionosphere of electromagnetic pulses from lightning: excitation of optical emissions, *Geophys. Res. Let.*, *20*, 2675–2678, 1993b.

Vallance Jones, A., *Aurora*. D. Reidel Publishing Co., 1974.

Vaughan, Jr., O. H. and B. Vonnegut, Recent observations of lightning discharges from the top of a thundercloud into the clear air above, *J. Geophys. Res.*, *94*, 13179–13182, 1989.

Wescott, E. M., D. D. Sentman, D. L. Osborne, D. L. Hampton, and M. J. Heavner, Preliminary results from the Sprites94 aircraft campaign: 2. Blue Jets, *Geophys. Res. Let.*, *22*, 1209–1212, 1995.

Wescott, E. M., D. D. Sentman, M. J. Heavner, D. L. Hampton, D. L. Osborne, and O. H. Vaughan, Jr., Blue starters: Brief upward discharges from an intense Arkansas thunderstorm, *Geophys. Res. Let.*, *23*(16), 2153–2156, 1996.

Wescott, E. M., D. D. Sentman, M. J. Heavner, D. L. Hampton, and O. H. Vaughan, Jr., Blue Jets: their relationship to lightning and very large hailfall, and their physical mechanisms for their production, *J. Atmos. Solar Terr. Physics*, *60*, 713–724, 1998a.

Wescott, E. M., D. D. Sentman, M. J. Heavner, D. L. Hampton, W. A. Lyons, and T. Nelson, Observations of 'Columniform' sprites, *J. Atmos. Solar Terr. Physics*, *60*, 733–740, 1998b.

Wilson, C. T. R., The electric field of a thunderstorm and some of its effects, *Proc. Roy. Soc. London*, *37*, 32D, 1925.

Winckler, J. R., Further observations of cloud-ionosphere electrical discharges above thunderstorms, *J. Geophys. Res.*, *100*, 14335, 1995.

Winckler, J. R., W. A. Lyons, T. E. Nelson, and R. J. Nemzek, New high-resolution ground-based studies of sprites, *J. Geophys. Res.*, *101*, 6997–7004, 1996.

Yukhimuk, V., R. A. Roussel-Dupré, E. M. D. Symbalisty, and Y. Taranenko, Optical characteristics of blue jets produced by runaway air breakdown, simulation results, *Geophys. Res. Let.*, *25*(17), 3289–3292, 1998.

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Table 1. Several neutral and ionized N_2 emissions observed in sprites, blue jets, and elves, as well as the aurora. The first observations of sprites showed only N_2(1PG) emission, which requires the lowest threshold energy of the N_2 states that emit optically. The threshold energies reported are based on filling the lowest vibration energy level of the electronic state. This table is based on Table 4.7 of Vallance Jones [1974].

Name	Upper State	Lower State	Lifetime	Quench Alt.	Energy
N_2(1PG)	$N_2(B^3\Pi_g)$	$N_2(A^3\Sigma_u^+)$	6 μs	53 km	7.50 eV
N_2(2PG)	$N_2(C^3\Pi_u)$	$N_2(B^3\Pi_g)$	50 ns	30 km	11.18 eV
N_2^+(1NG)	$N_2^+(B^2\Sigma_u^+)$	$N_2^+(X^2\Sigma_g^+)$	70 ns	48 km	18.56 eV
N_2^+(M)	$N_2^+(A^2\Pi_u)$	$N_2^+(X^2\Sigma_g^+)$	14 μs	85-90 km	16.54 eV
N_2(VK)	$N_2(A^3\Sigma_u^+)$	$N_2(X^1\Sigma_g^+)$	2 s	145 km	6.31 eV

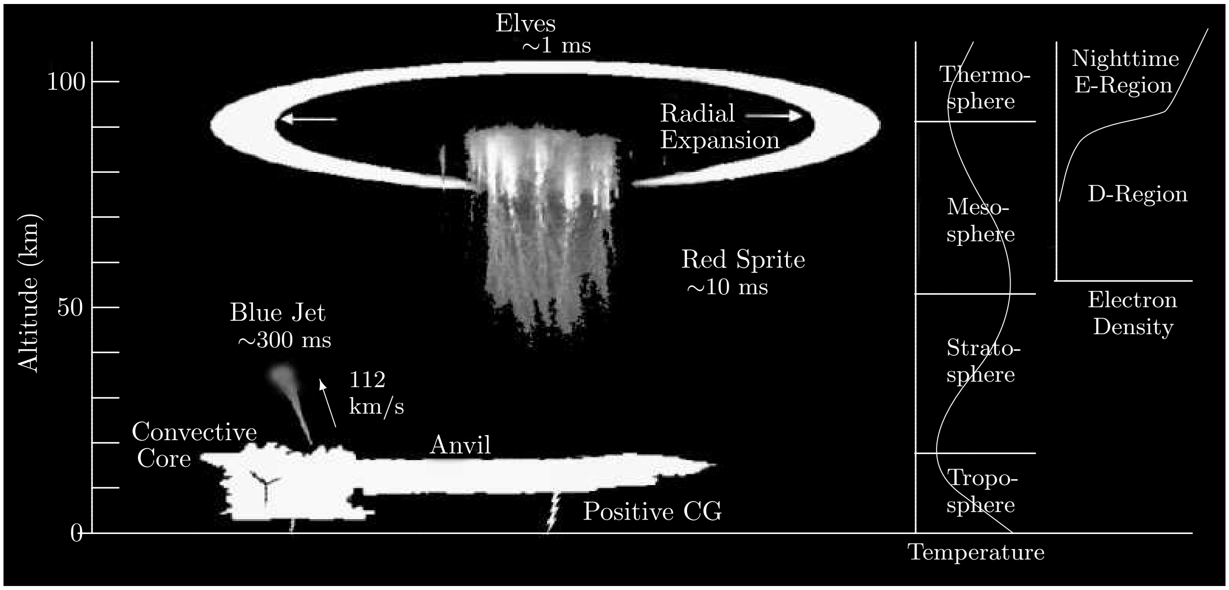

Figure 1. The three types of transient optical events above thunderstorms recorded in the past decade are summarized. Sprites are brief emissions occurring between approximately 40-95 km, associated with large positive cloud-to-ground lightning discharges. Blue jets are cones of light which propagate upward from the top of the electrically active convection core of thunderstorms at an average velocity of 112 km/s to a terminal altitude of ~37 km. Elves occur over both positive and negative CG's at the base of the ionosphere and expand radially to horizontal diameters as large as ~500 km and vertical widths of several km.

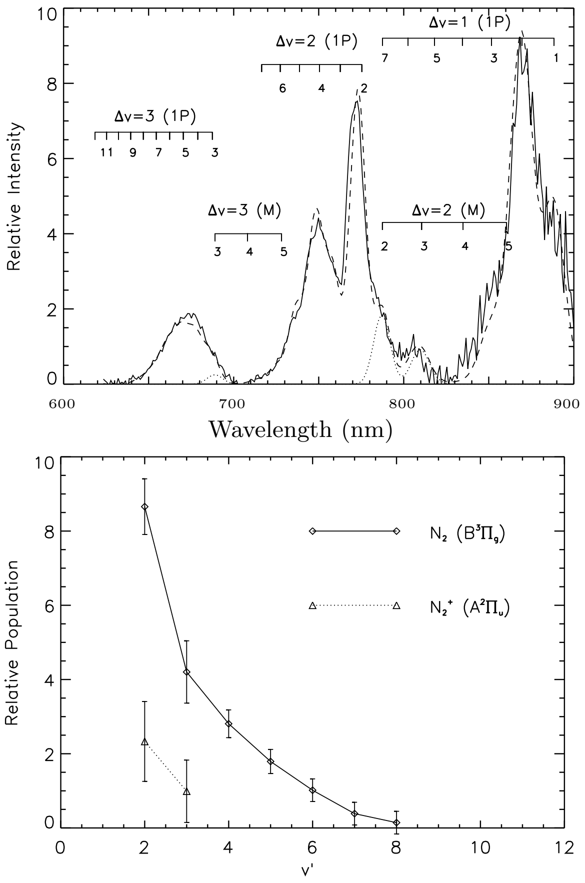

Figure 2. Sprite spectrum of the 1996/07/24 03:58:24 event with a least-squares fit consisting of both N_2(1PG) and N_2(Meinel) synthetic spectra. The higher energy N_2(Meinel) component is shown separately as a dotted line. The vibration distributions determined in the fit are shown in the lower panel. This plot is reproduced from figure 2 of Morrill *et al.* [1998].

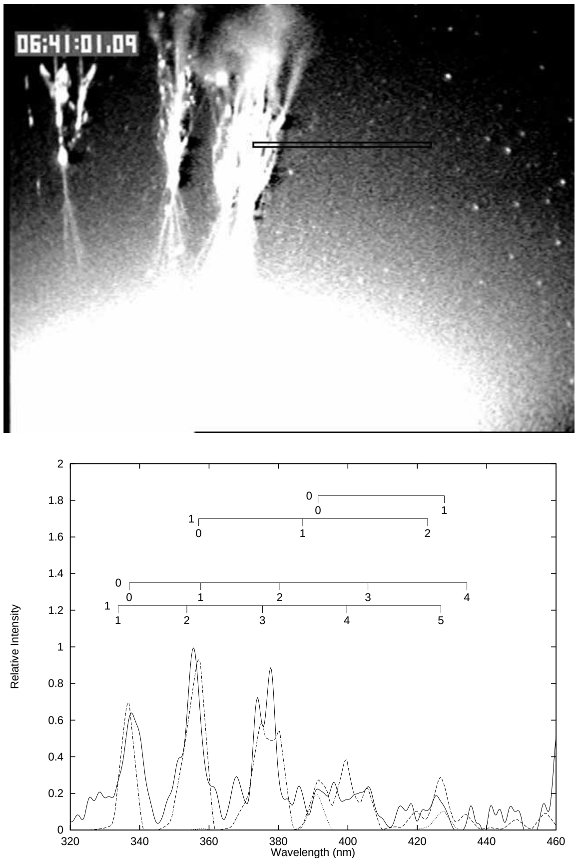

Figure 3. The 1998/07/28 06:41:01 sprite as imaged by an unfiltered camera on the EXL98 aircraft is presented in the upper panel. The black box indicates the field of view of the NUV/Blue spectrograph. The solid line in the lower panel is the observed spectrum. A synthetic fit of the spectrum including both N_2(2PG) and N_2^+(1NG) emissions is shown as a dashed line, while just the N_2^+(1NG) contribution to the fit is indicated as a dotted line. This blue spectral observation of a sprite has no ionized emissions above the noise levels of the observation. A 427.8 nm filtered imager recorded no emissions from the sprite, in agreement with the spectral observations. The wavelength of the band head of emissions and the upper and lower vibration levels of the N_2^+(1NG) and N_2(2PG) transitions are indicated.

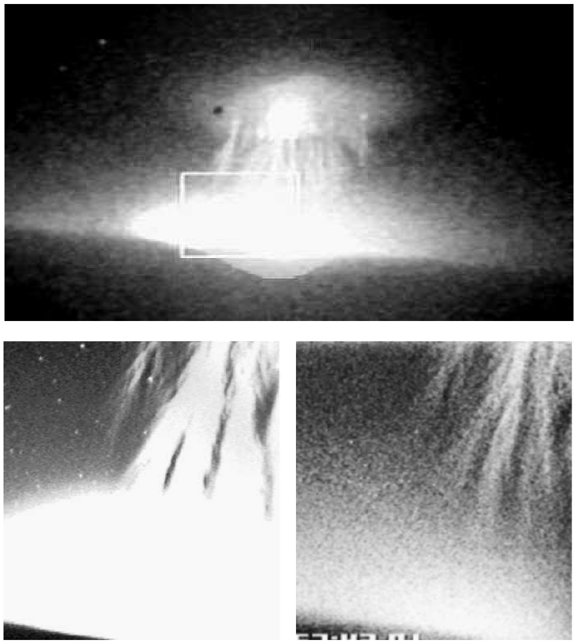

Figure 4. The 1998/07/22 04:57:43 sprite, at a great circle distance of ~200 km, as seen by three cameras on the EXL98 aircraft is presented [Besser *et al.*, 1998]. The upper panel is the unfiltered wide field of view (~40°) camera, illustrating the entire sprite event with a white box indicating the approximate field of view of the other cameras. The lower left image is the cropped image from the unfiltered narrow field of view camera and the lower right image is from the 427.8 nm filtered imager. Significant N_2^+(1NG) emission is observed at 427.8 nm indicating energetic processes occurring in the tendrils of sprites. Unfortunately, on July 22, the NUV camera (which recorded the blue spectrum in Figure 3) was not operating in spectrographic mode.

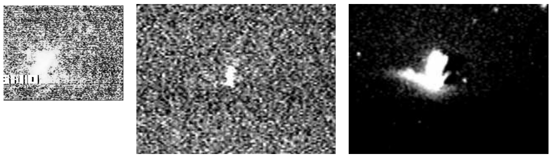

Figure 5. Observations of the July 17, 1998 starter from the EXL98 aircraft [Deehr *et al.*, 1998]. The left image is from the 340.7 nm filtered imager. The 427.8 nm filtered image is the center image and the right image is from the unfiltered imager. The 340.7 nm and 427.8 nm images have been histogram equalized to stretch the dynamic range of the images. The 427.8 nm and unfiltered images are identical cameras with the same field of view, while the 340.7 nm image is from a camera with a different field of view. The emission at 427.8 nm from N_2^+(1NG) indicates that electron energies of at least 18.6 eV are present in the processes causing blue starters.