Overview of Transient Luminous Events

(Red Sprites, Elves, Blue Jets, Halos, Pixies, Trolls, etc.)

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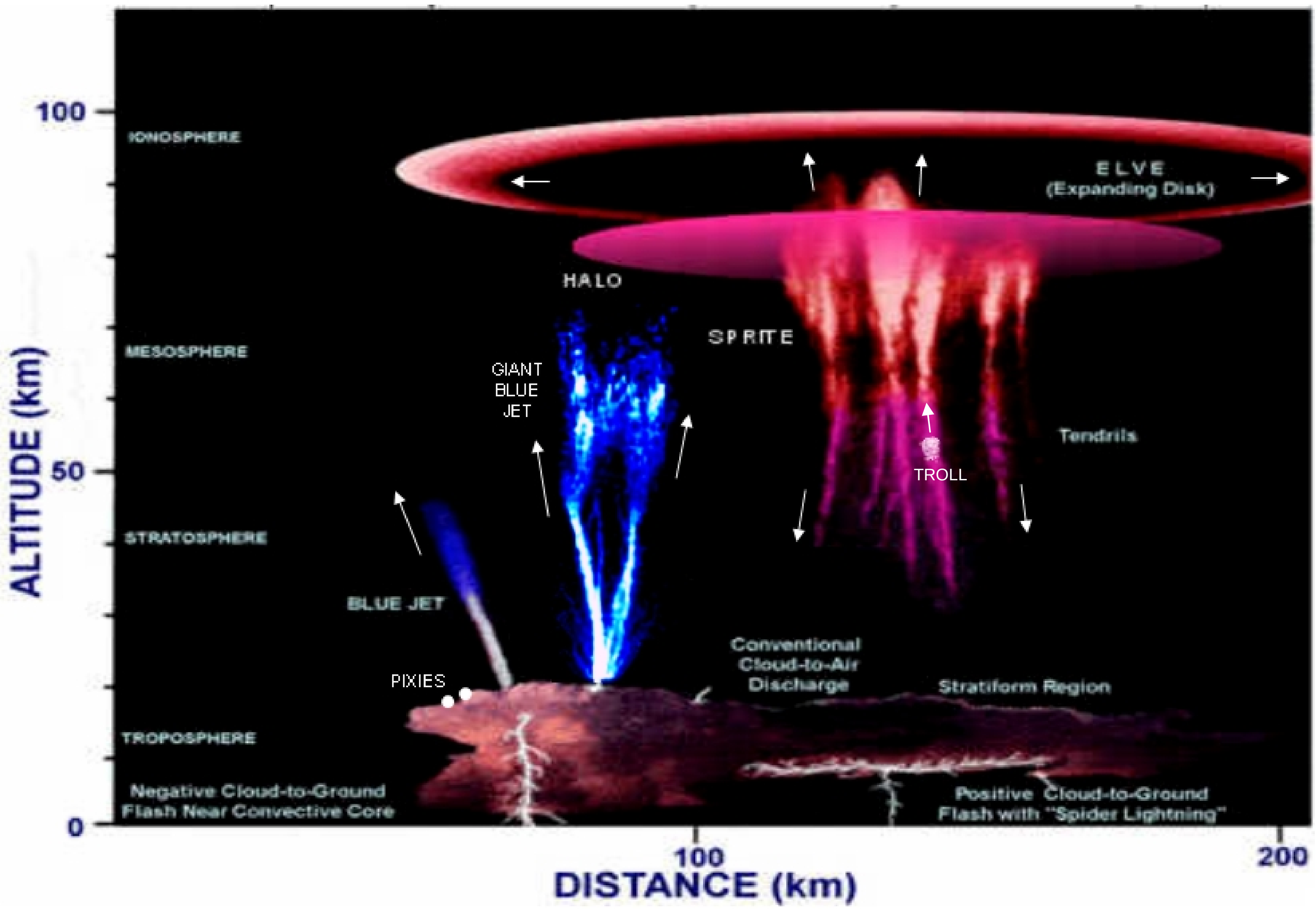
Outline

1. Observations
2. General Characteristics of the Major Classes of Events
3. Mechanisms

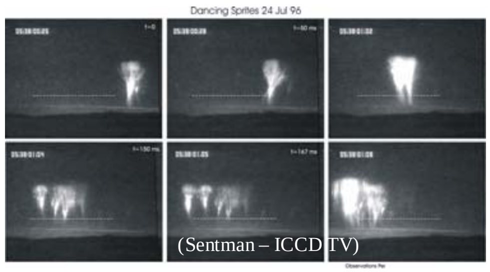
A bibliography of selected papers is included.

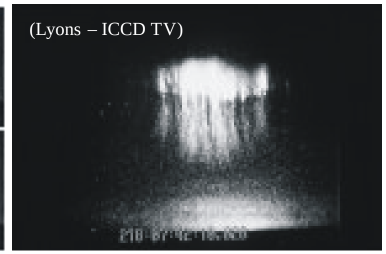
Varieties of Transient Luminous Events in the Upper Atmosphere

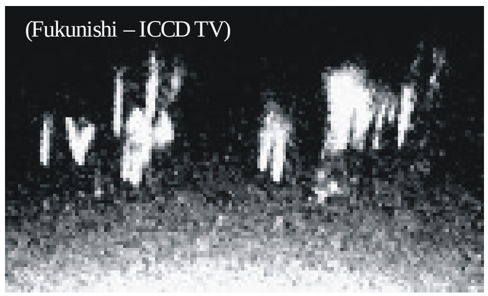


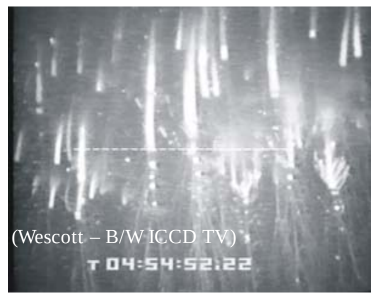
(Elaboration of figure by Lyons et al. 2000)

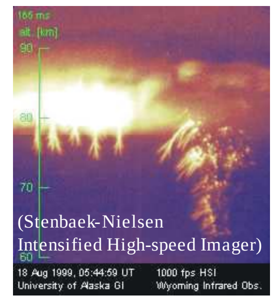
Sprite Gallery – Images From a Variety of Sources Obtained With a Variety of Cameras

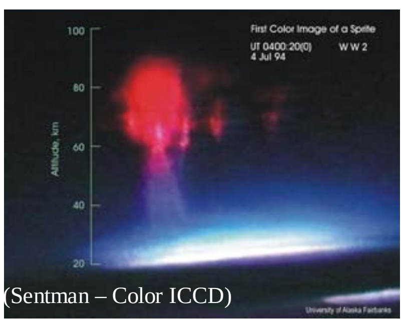


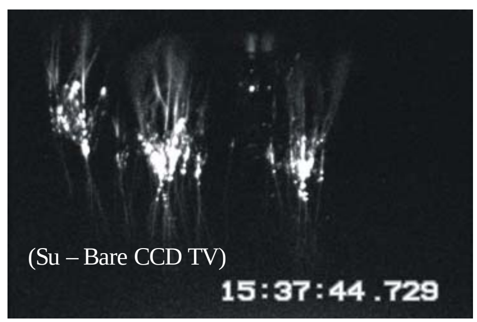


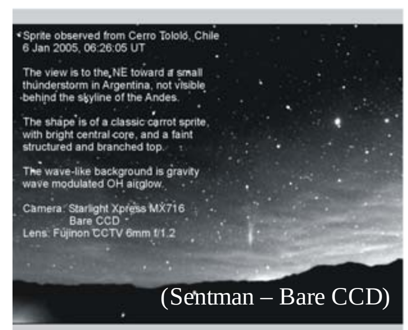








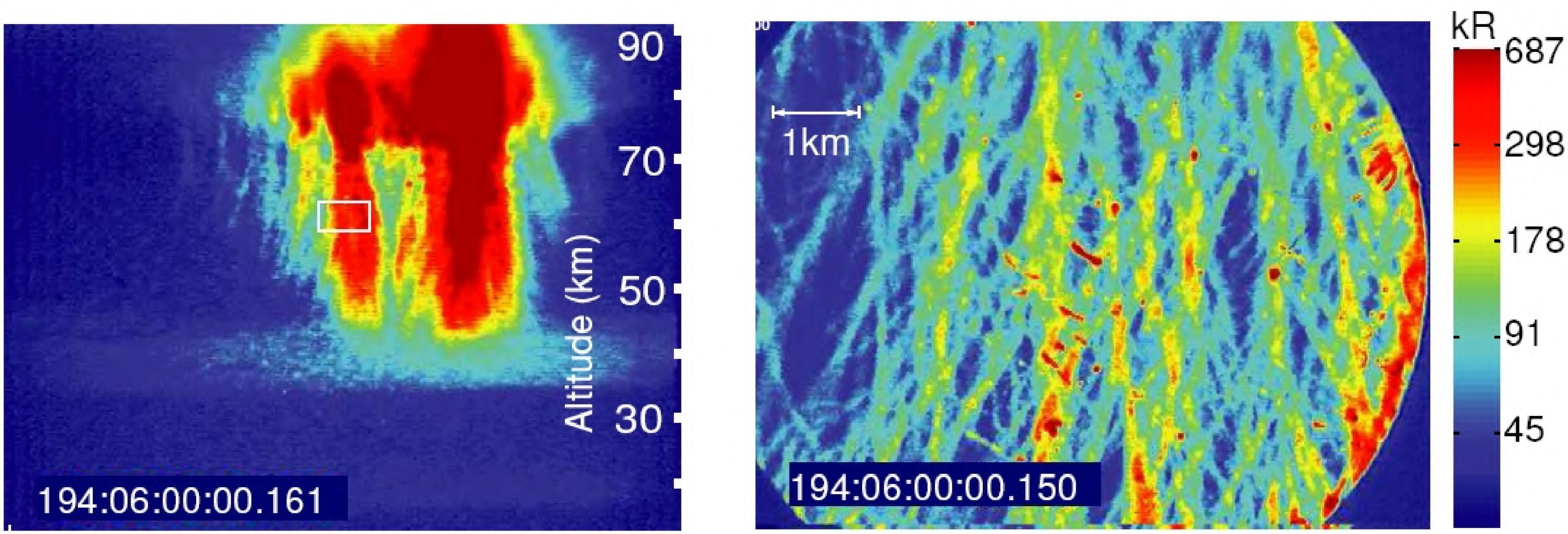




Early sprite imagers were intensified CCD TV cameras. Recent research has simultaneously moved in two directions: (1) high speed >1000 fps cameras, and (2) inexpensive bare CCD imagers, both TV and integrating systems. Sprites are bright enough (>> 1 MR) that both types of imagers work well.

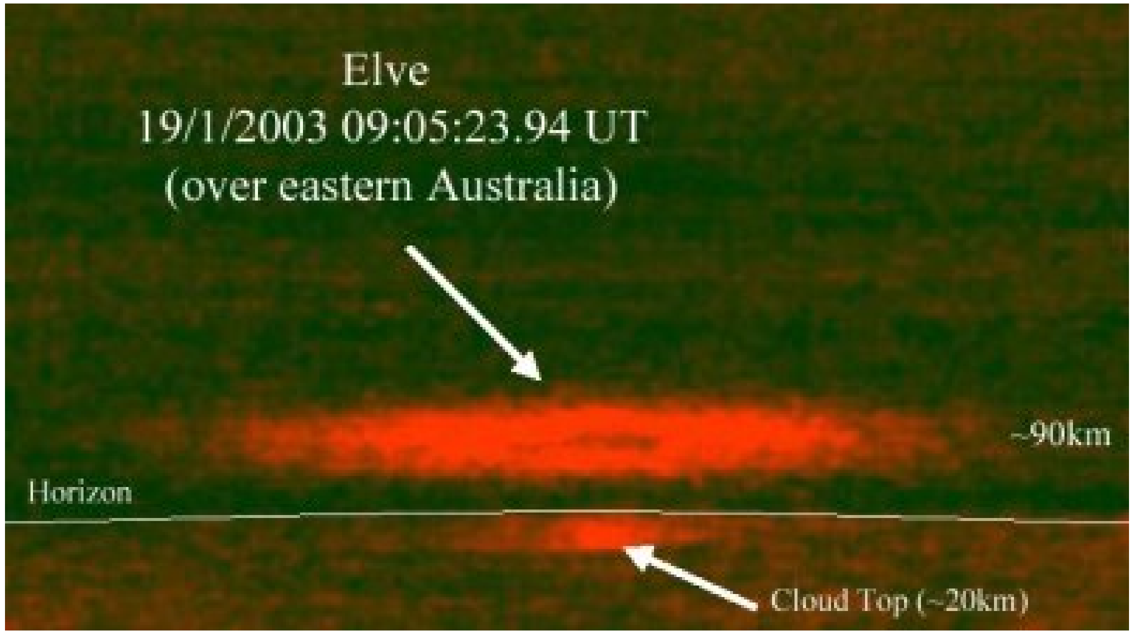
Telescopic Imaging of Sprites

- Wide (left panel) and narrow (right panel) field of view images of a bright sprite event [*Gerken et al.*, GRL, 27, 2637, 2000]:

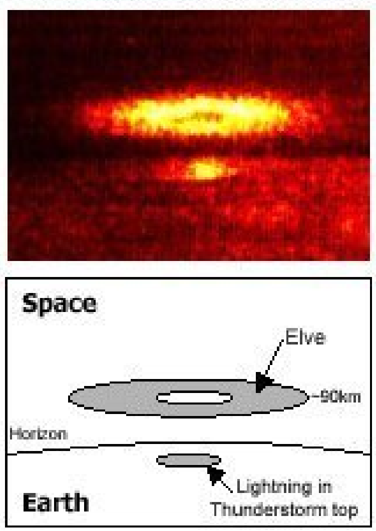


- The measured streamer diameters are 61-145, 150, 196 m, for altitude ranges 60-64, 76-80, 81-85 km, respectively [*Gerken et al.*, 2000].

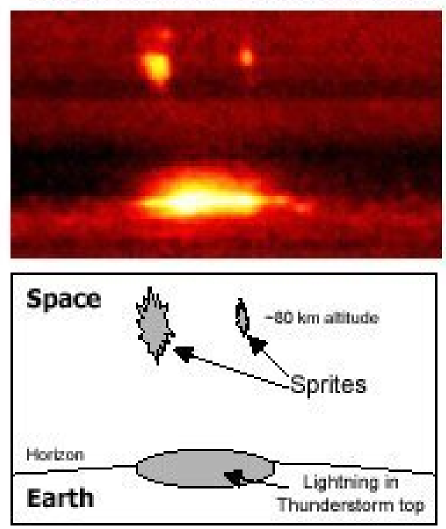
STS-107 Observations of ELVES and Sprites



Elve over South Pacific

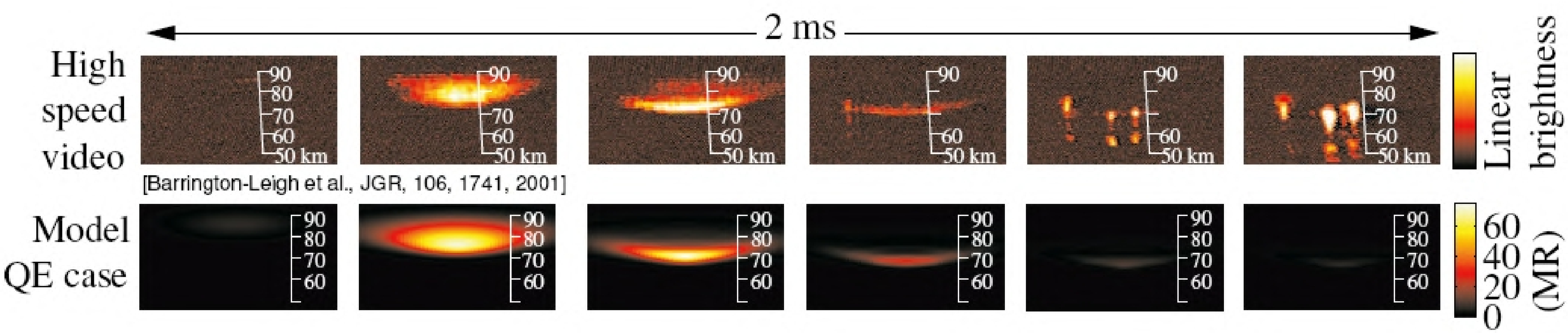


Sprites over SE Australia



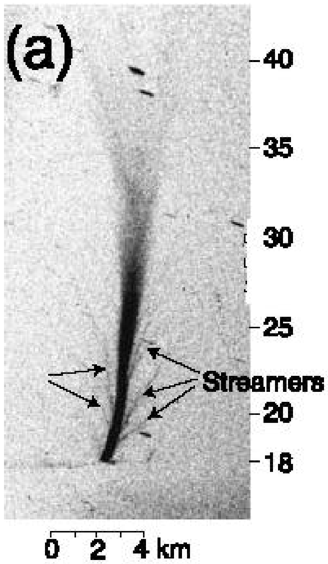
Sprite Halos

- *Barrington-Leigh et al.* [JGR, 106, 1741, 2001] conducted one-to-one comparison between high-speed video observations of sprites and a fully electromagnetic model of sprite driving fields and optical emissions. Sprite halos are brief descending glows with lateral extent 40-70 km, which sometimes observed to accompany or precede more structured sprites. The analysis conducted by *Barrington-Leigh et al.* [2001] for the first time identified sprite halos as being produced entirely by quasi-electrostatic thundercloud fields.

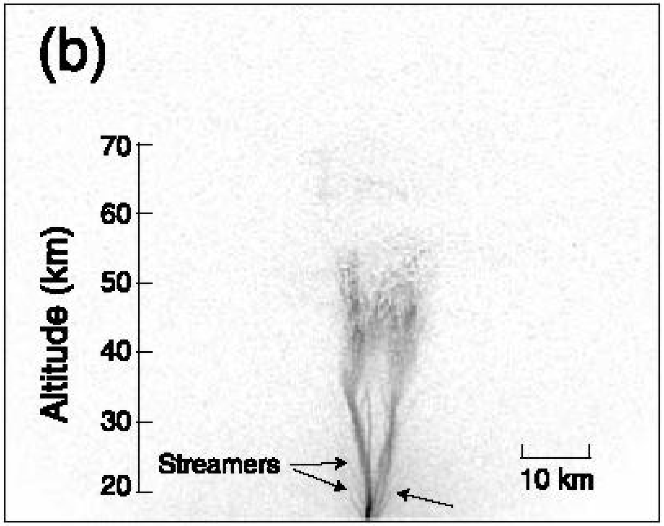


Blue Jets

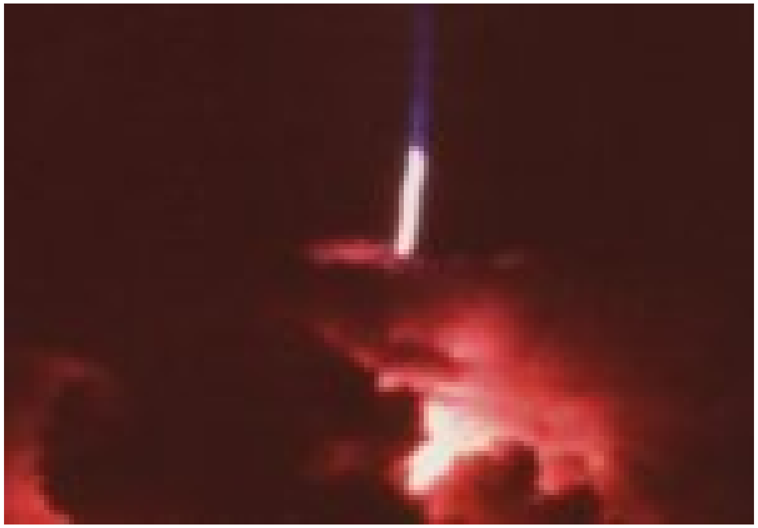
Blue Jets – Positive(?) Streamers from Cloud Tops



Wescott et al. 1999



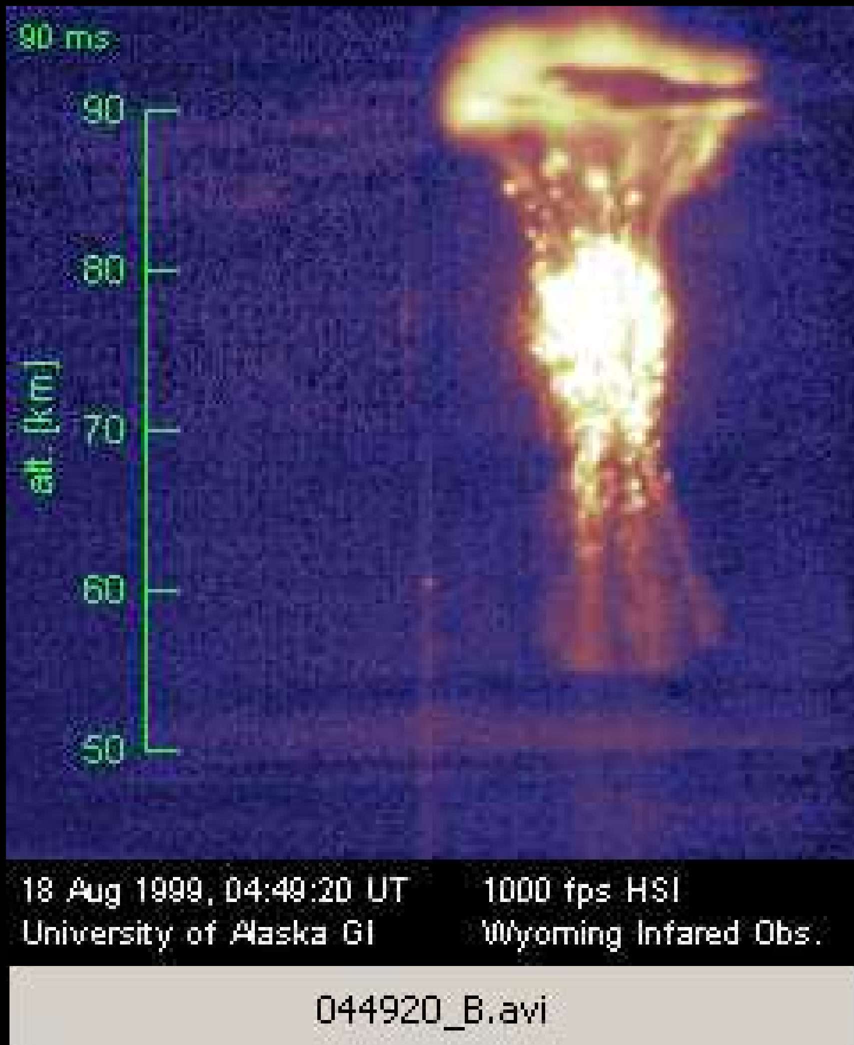
Pasko et al. 2000



Jarvis Australia Camera Image

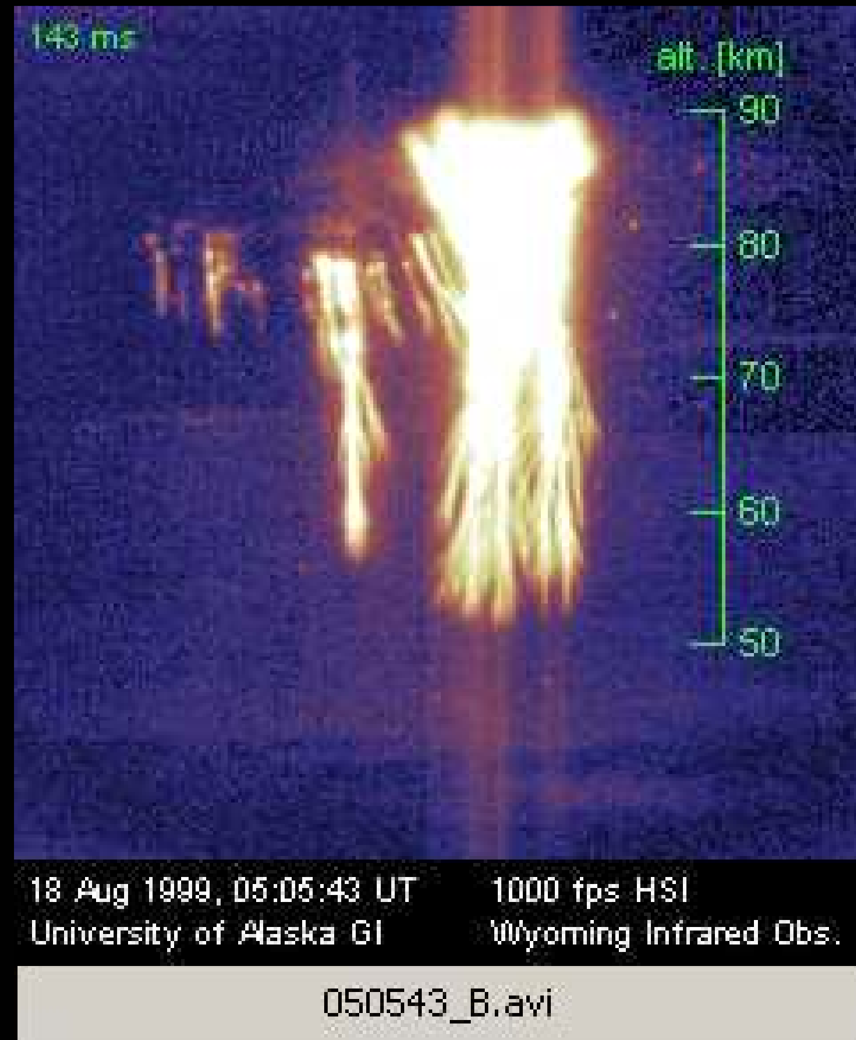
A Few Case Studies of Sprites

TLEs exhibit a complex variety of forms with considerable variation of structure and dynamics among individual events. Most of the various forms that have been given names (sprites, c-sprites, elves, halos, trolls), as well as numerous other features that have not yet been studied, are present in the following time-lapse sequences of sprites recorded at 1000 fps on 18 August 1999 as part of the NASA Sprites99 Balloon Campaign.



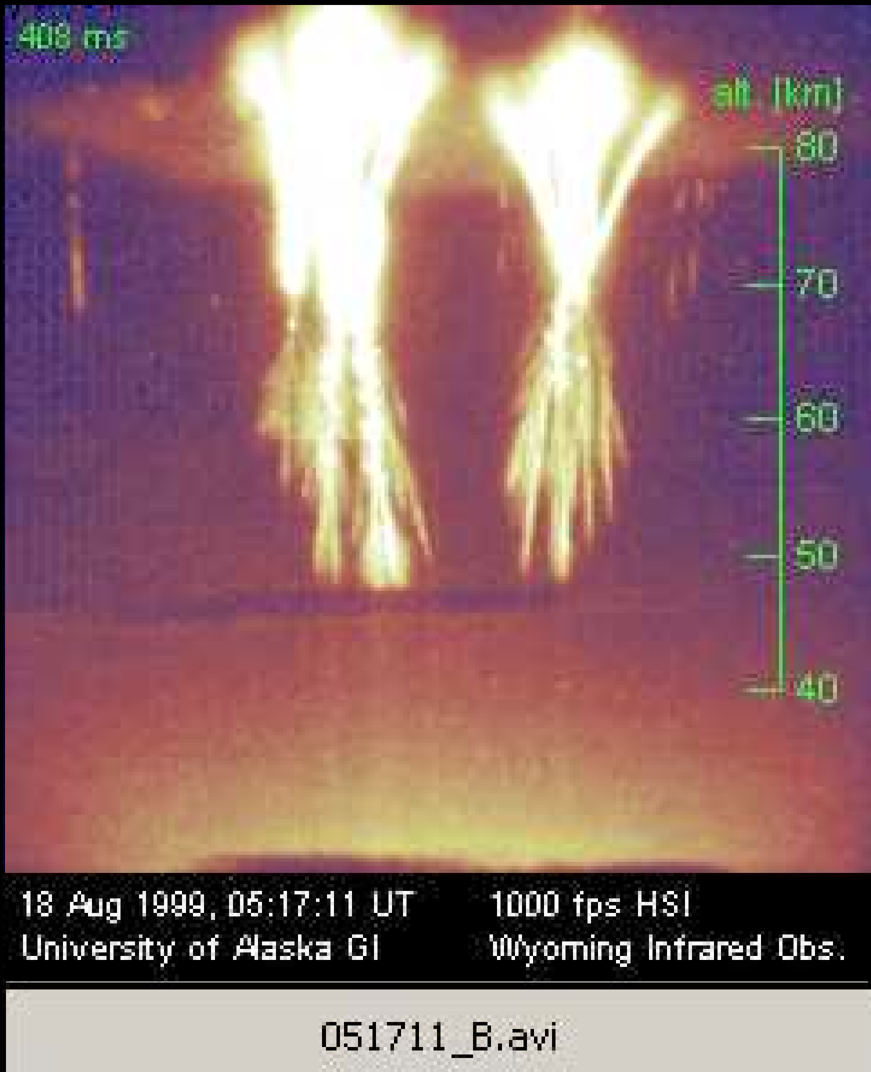
Halo followed by offset double sprites, weak downward "smoke" billows

(clip)



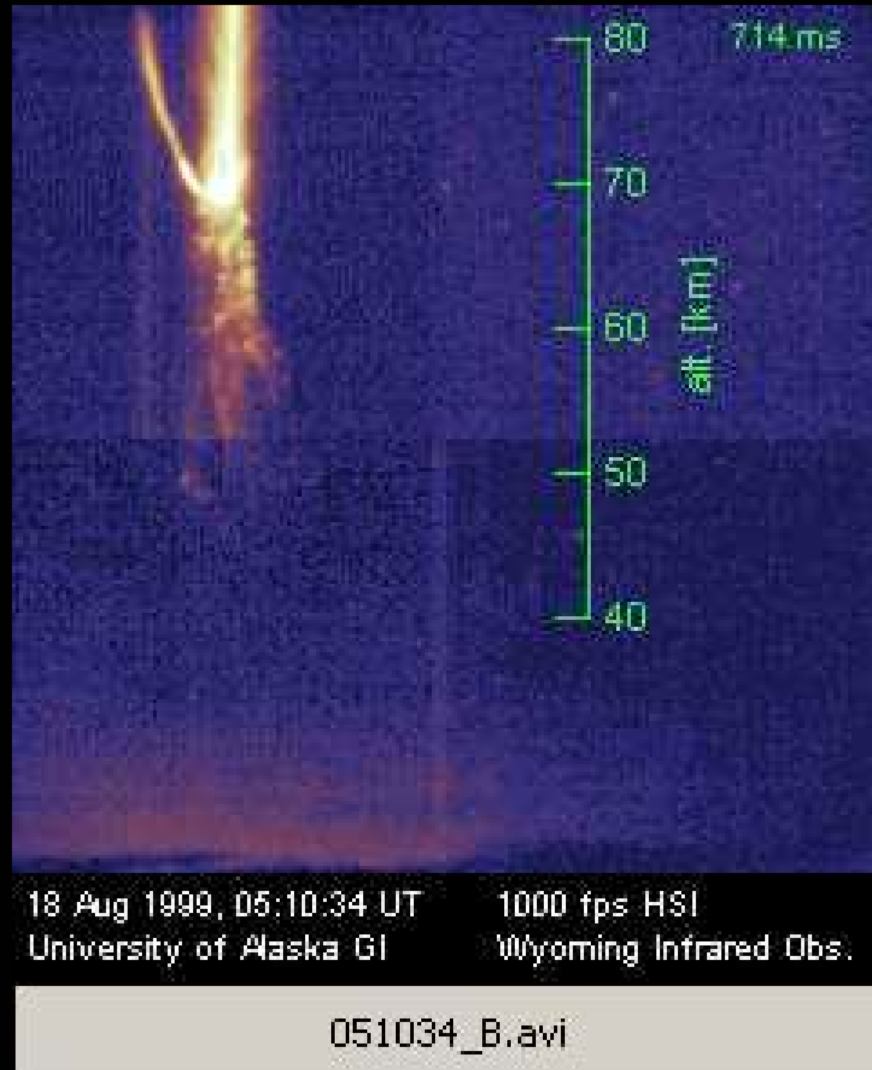
Halo, sprites, downward "smoke" billows

(clip)



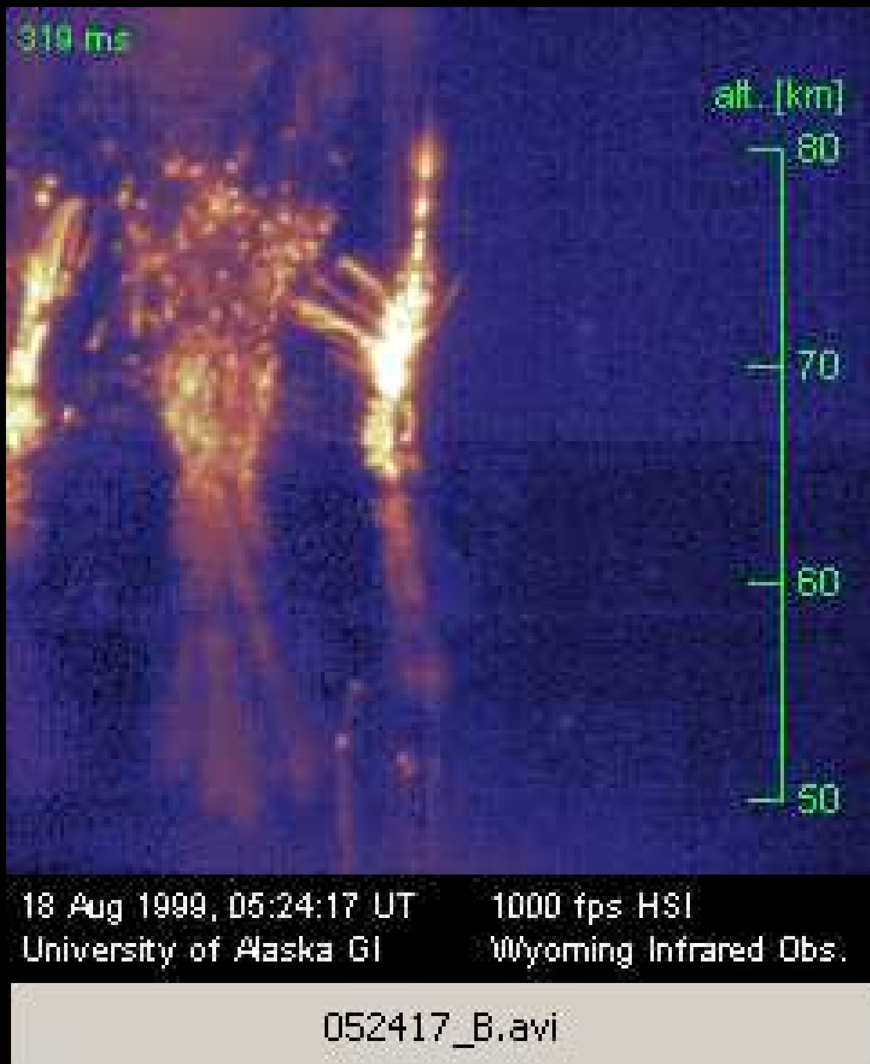
Halo, Sprites, persistent ascending “trolls” in tendrils

(clip)



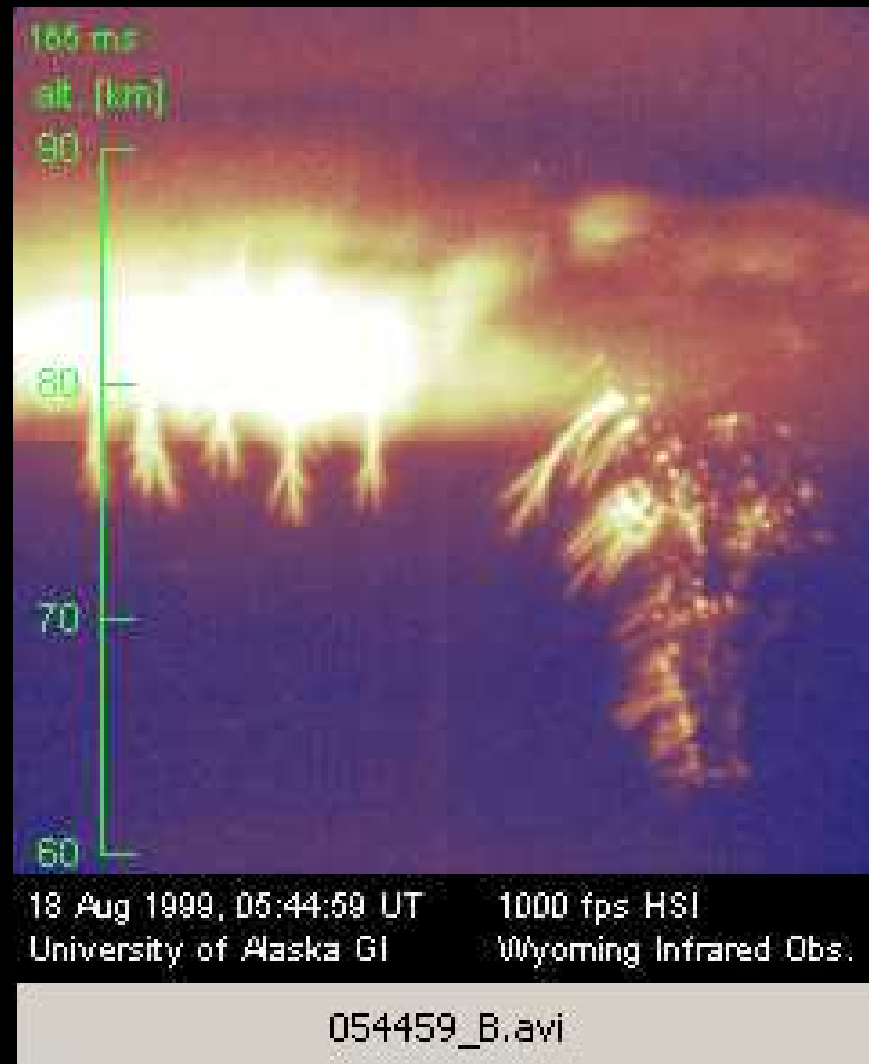
Sprites, ascending “trolls,” second sprite and rebrightening, weak “smoke” billows

(clip)

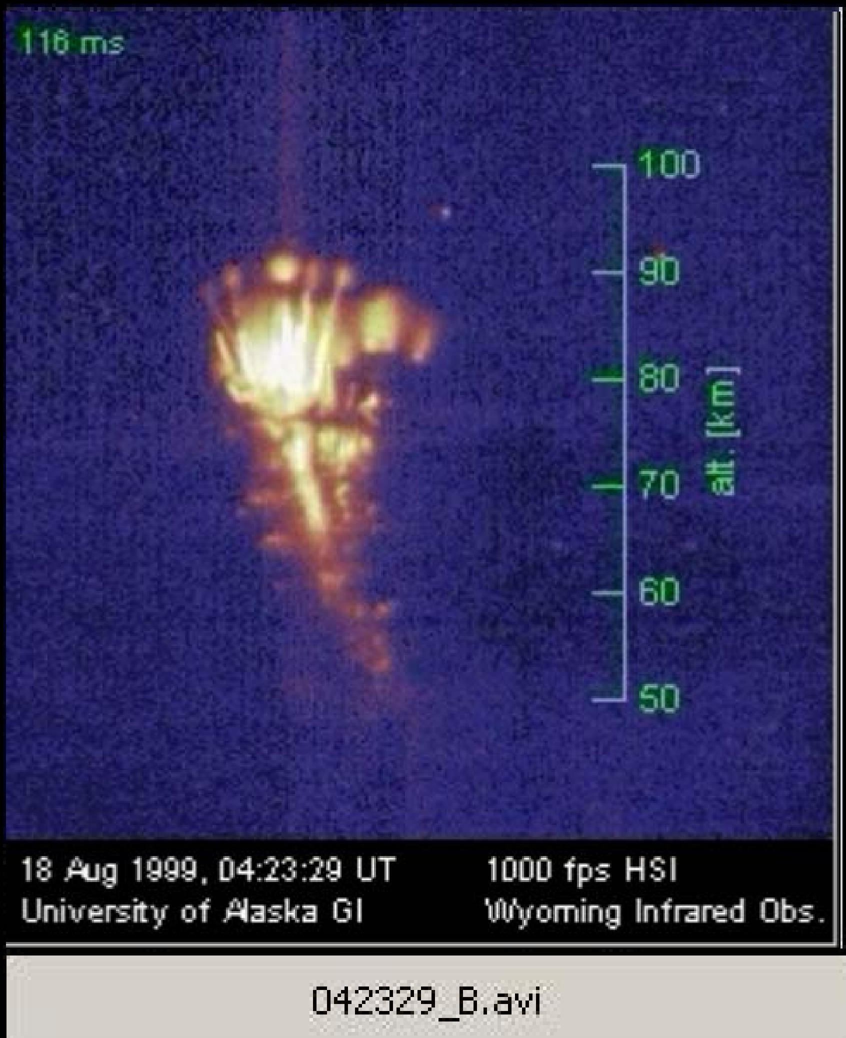


Complex sprite followed by “palm tree” ascending from below, sideways discharges, “smoke” billows

(clip)

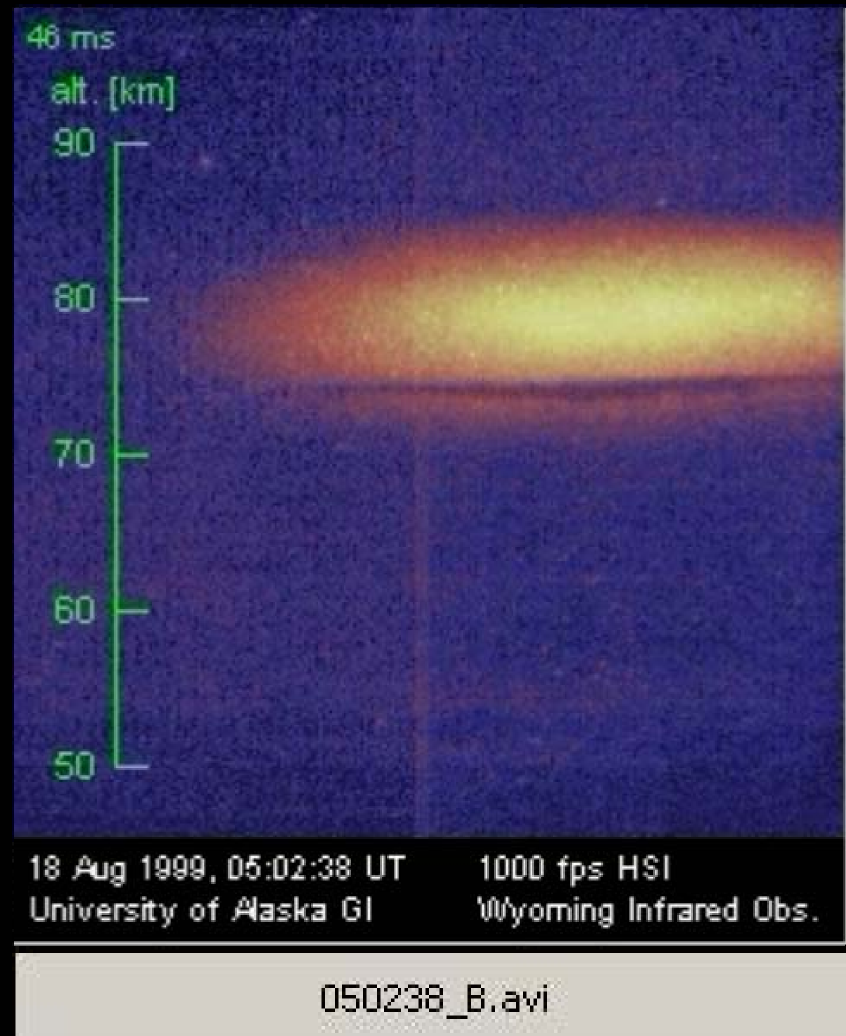


Fast downward precursor streamer preceding sprite, second upward precursor, retracing in second sprite features in first sprite. (clip)



Sprite, downward "smoke," late developing upward "stalks."

(clip)



Simple isolated sprite halo.

(clip)

Observations from Chile of Sprites over Argentina Storms

Observations of sprites from Cerro Tololo in the early morning hours of 15 Jan 2005 UT looking eastward over the Andes. The source of the sprites is a small convective system in Argentina at a distance of ~500 km. A crescent moon illuminates the landscape early in the clip. OH nightglow and gravity waves are prominent. About two dozen sprites are visible just above the mountain ridge on the right half of the images. (Shown here: first frame of video clip)

Camera 1:
- Starlight Xpress MX716
- CCD Sony ICX249AL
- 752x580x8.6 μm
- 16 bit samples, 2x2 binning
- 10s integration, 4s readout
- unfiltered

Lens:
- Fujinon CCTV 9mm f/1.4
- FOV: 40Hx30V deg

Control:
- IBM Thinkpad
- IEEE 802.11b wireless
- MaxIm DL

Camera 2:
- KT&C PC164C TV camera
- 640x480x6.8 μm
- 30 fps NTSC

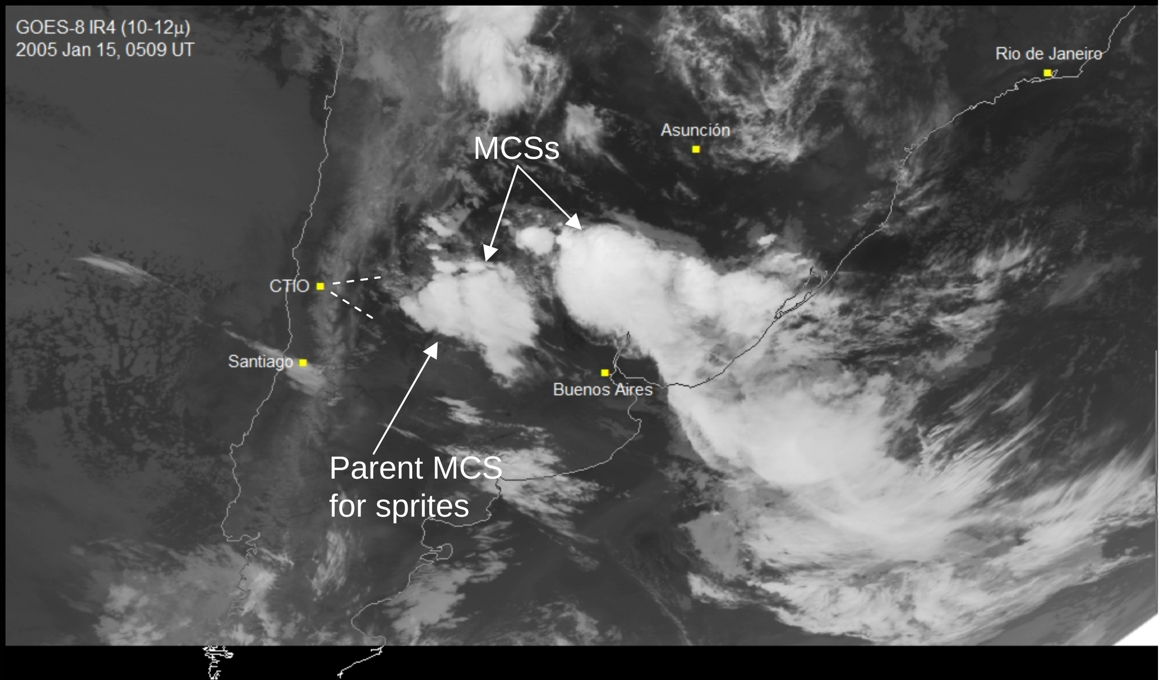
Lens:
- Fujinon CCTV 6mm f/1.2

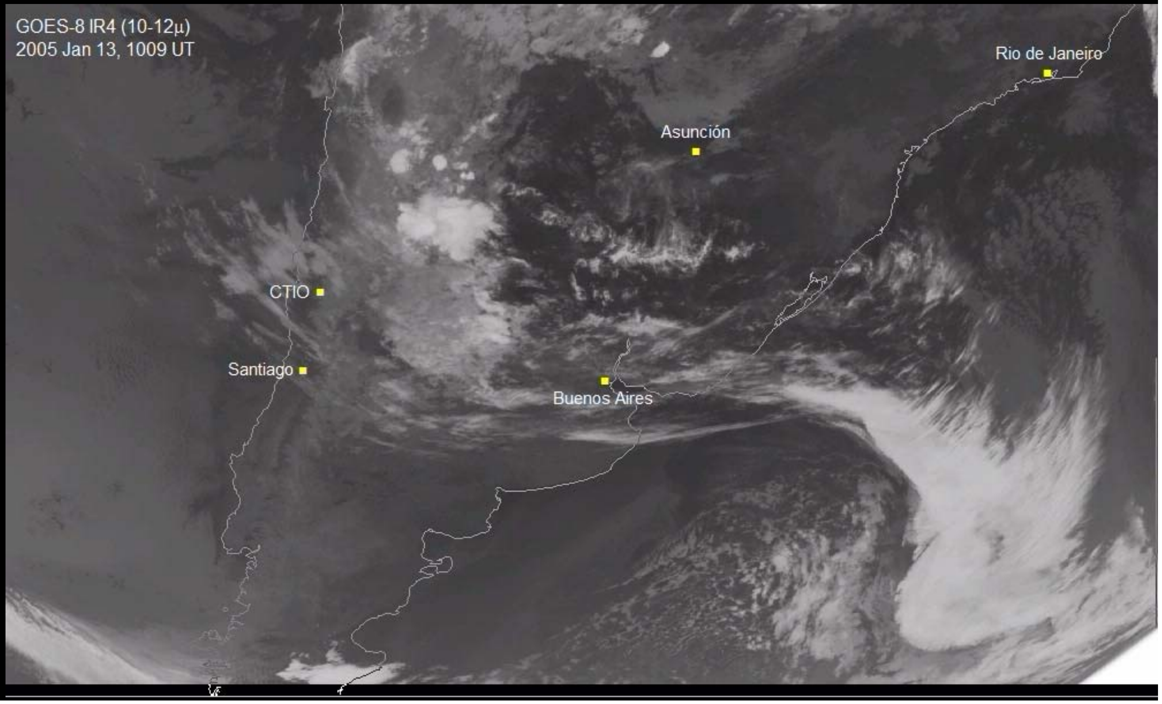
Recorder:
- Sony Digital Video Walkman miniDV recorder

GOES-8 IR4 (10-12μm) weather images of southern South America at the time of the observattions.

Above: 15 Jan 0509 UT, at the time of maximum sprite activity. There are two moderately sized Mesoscale Convective Systems (MCSs) in Argentina; one ~500 km to the east of CTIO and one to the north of Buenos Aires. CTIO, several large cities, and the parent storm of the sprites are marked. The FOV of the primary camera is indicated.

Below: Video clip of weather patterns beginning two days before the observations.





Spectroscopic Identification of Sprite Optical Emissions

Sprite and its emission spectra measured using a TV (30 fps) imager and slit spectrograph showing characteristic N_2 red 1PG and blue 2 PG emission line features.

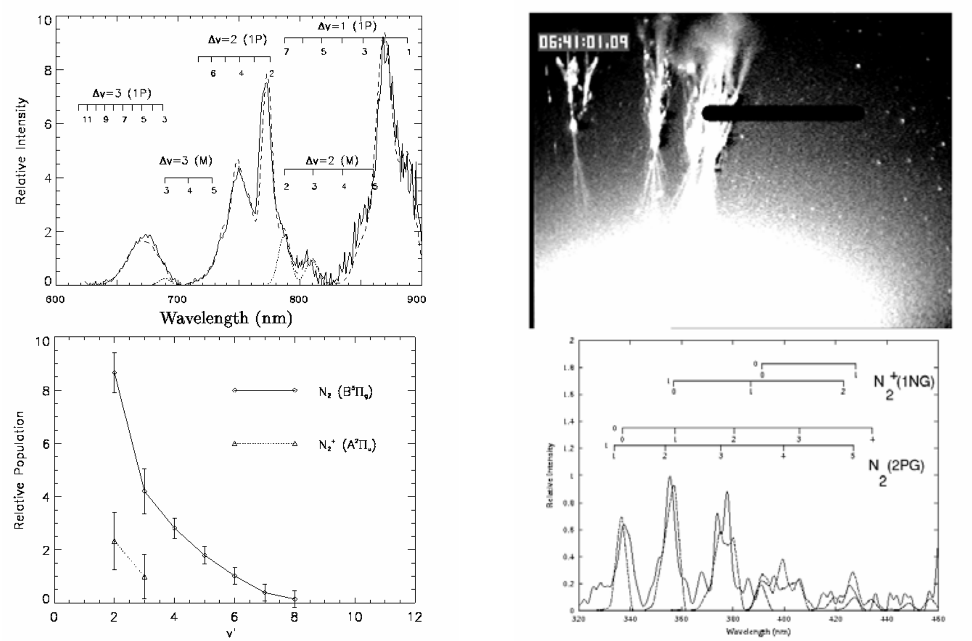
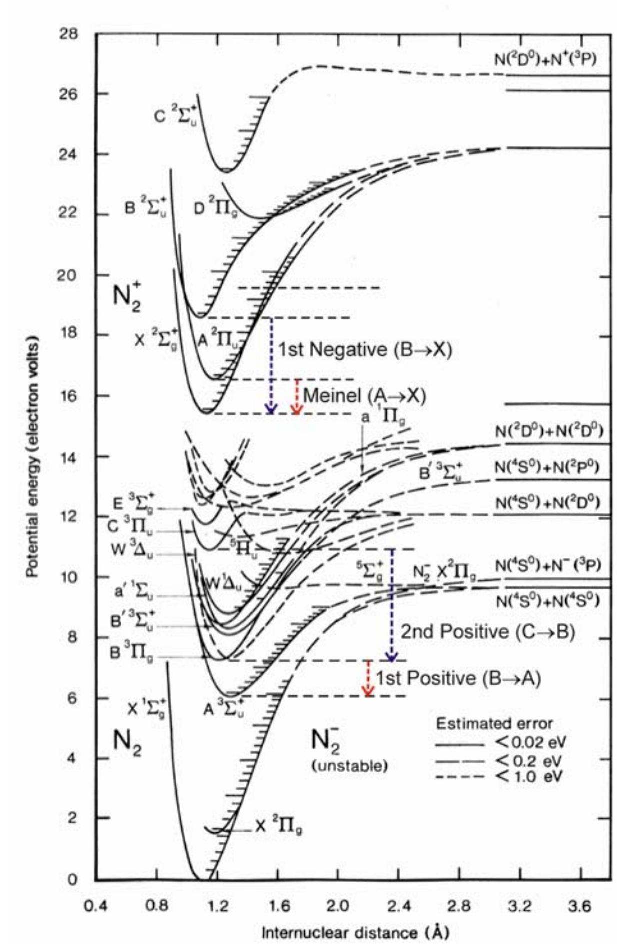


Table 1. Several neutral and ionized N_2 emissions observed in sprites, blue jets, and elves, as well as the aurora. The first observations of sprites showed only N_2(1PG) emission, which requires the lowest threshold energy of the N_2 states that emit optically. The threshold energies reported are based 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

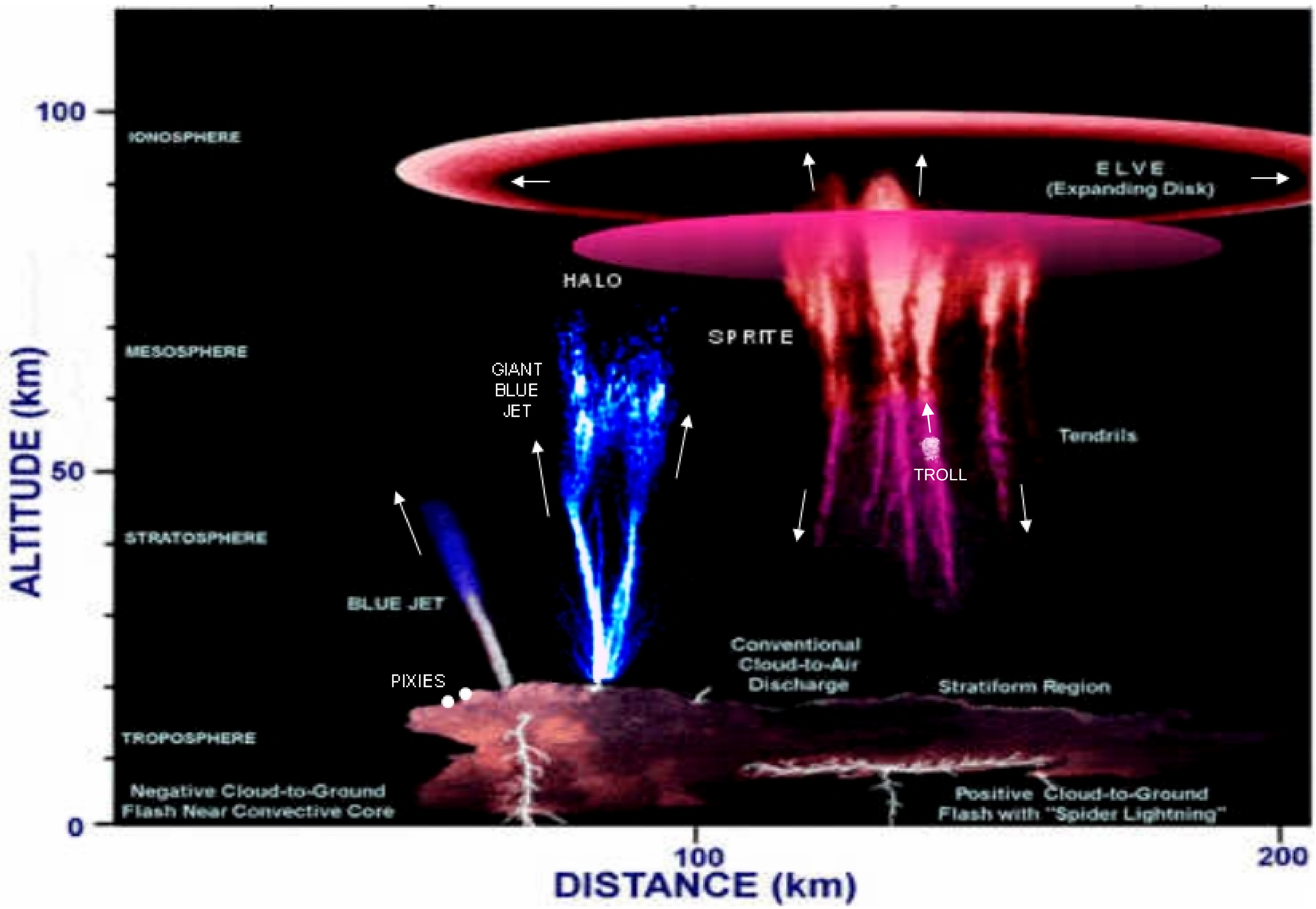
From Heavner et al. (2000)

N_2 energy diagram.



A noteworthy and unexpected feature of the measured spectrum is the absence of strong ion lines. This indicates that most of the optical brightness originates in neutral excited electronic states, although high speed photometric observations have detected a brief (< 1ms) burst of N_2^+ 1NG ion emissions at sprite onset .

Varieties of Transient Luminous Events in the Upper Atmosphere



(Elaboration of figure by Lyons et al. 2000)

Principal Types of Transient Luminous Events in the Upper Atmosphere Associated with Thunderstorms/Lightning						
Type of TLE	Altitude Regime	Transverse Dimensions	Spatial Characteristics	Apparent Motion	Duration	Inventory of Observations (est.)
Sprites	~ 50-90 km	~1-20 km	Top (>80 km) diffuse Bottom (<70 km) structured	Top- upward Bottom- downward	few ms	>10,000
Elves	~ 100 km	> 100 km	Diffuse	Lateral Expansion	few ms	100s
Blue Jets	~ 18-45 km	few km	Structured	Upward	100s ms	<100
Giant Blue Jets	~ 18-75 km	few km	Structured	Upward	100s ms	<10
Halos	~ 75 km	~ 50 km	Diffuse	Downward	~ ms	1000s
Trolls	~ 60-70 km	~ kms	Structured	Upward (Within decaying sprite tendrils)	100s ms	100s
Pixies	~ 15-18 km	~ 100s m	Compact	Stationary (Stormcloud tops)	100s ms	10s(?)

Low Energy (few eV) Electron Fluid Model for Gas Discharges

Diffusion-drift equations – Describe a wide variety of electrical discharges in neutral gases.

$$\frac{\partial n_e}{\partial t} + \nabla \cdot n_e \vec{v}_d - D_e \nabla^2 n_e = (\nu_i - \nu_a) n_e - \beta_{ep} n_e n_p + S_{ph}$$

$$\frac{\partial n_p}{\partial t} = \nu_i n_e - \beta_{ep} n_e n_p - \beta_{np} n_n n_p + S_{ph}$$

$$\frac{\partial n_n}{\partial t} = \nu_a n_e - \beta_{np} n_n n_p$$

$$\nabla \cdot \vec{E} = \frac{e}{\varepsilon_0} (n_p - n_e - n_n)$$

The first three equations are the continuity equations for electrons, positive and negative ions, respectively, and the last equation is Poisson's equation self-consistently linking the spatial structure of the electric field with the total charge distribution, including especially the charges created and lost during the discharge process. In the above, $\vec{E}$ is the electric field, n_e, n_p, and n_n are electron, positive ion, and negative ion number densities, $\vec{v}_d$ is the electron drift velocity, ν_z is the electron attachment frequency, β_{ep} and β_{np} are the electron-positive ion and negative-positive ion recombination coefficients, D_e is the electron spatial diffusion coefficient, S_{ph} is the electron-ion pair production function from photoionization, and e is the absolute value of the electron charge. The electron drift velocity is defined in terms of the mobility by $\vec{v}_d = -\mu_e \vec{E}$.

The Diffusion-drift model describes the initial stages of electrical breakdown, the formation and propagation of streamers, and the creation and loss of charge through ionization and recombination. The term involving the divergence of the electron current ($\nabla \cdot n_e \vec{v}_d$), which was neglected in many early sprite models, plays an especially critical role in the structural dynamics of streamers. The Diffusion-drift equations are highly non-linear and require numerical techniques to evaluate. Numerical methods that have been applied to its solution include the Corrected Flux Transport and the modified Sharfetter-Gummel algorithms, and more recently finite element (mesh) methods. Most work has been done in 1- or 2-dimensions, and it is only within the past few years that fully 3D studies have appeared.

Key References: *Raizer* (1997), *Liu and Pasko* (2004), papers by Kulikovsky.

Evaluation of Electron Distribution - Nonthermal

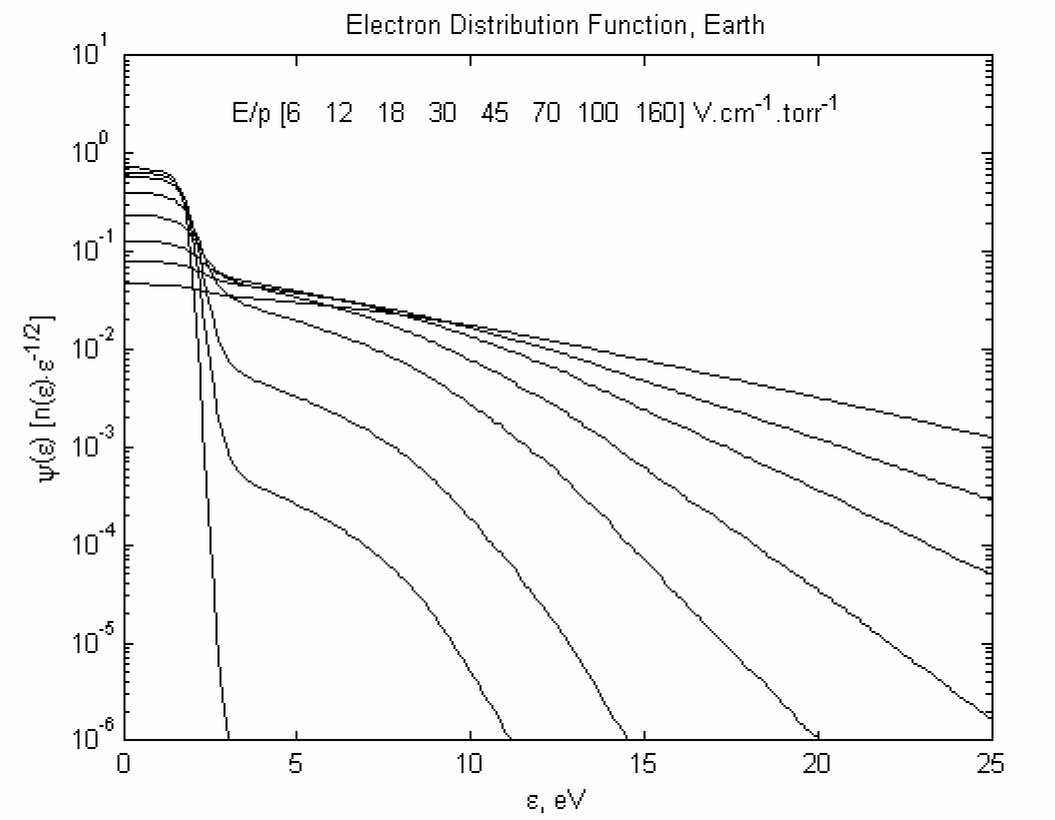
Solution of Time-Stationary Kinetic (Boltzmann) Equation (2-Term SH approximation)

$$\frac{\partial n}{\partial t} = \frac{\partial}{\partial \varepsilon}\left\{ A\varepsilon^{3/2}\frac{\partial}{\partial \varepsilon}\frac{n}{\varepsilon^{1/2}} + \underbrace{\frac{2m}{M}\varepsilon \nu_m n}_{\substack{\text{Momentum}\\ \text{Transfer}}} \right\} + \underbrace{Q(n)}_{\text{Inelastic}} = 0$$

$$\text{where } \varepsilon \text{ is energy}, n = n(\varepsilon),\ A = \frac{2e^2E^2}{3m\nu_m},\ E \text{ is electric field, and } \nu_m = \nu_m(\varepsilon)$$

At low electric fields electron energy distribution $n(\varepsilon)$ in air is determined primarily by rotational interactions with N_2 and O_2, and because of the dense number of rotational states it is approximately $n/\varepsilon^{1/2} \sim \exp(-\varepsilon/\varepsilon_0)$. At thermal energies greater than ~0.2 eV interactions with N_2 vibrational states become important, and the electron distribution becomes Druyvesteyn-like $n/\varepsilon^{1/2} \sim \exp(-\varepsilon^2/\varepsilon_0^2)$. At high reduced fields $\varepsilon/p > 10$ V/cm/torr that are a significant fraction of breakdown fields ($\varepsilon/p \sim 40$) a high energy tail begins to form above the $\varepsilon \sim$ 2-4 eV barrier in the N_2 vibrational cross sections. Electronic excitation of atomic and molecular species, ionization, molecular dissociation, and electron attachment-detachment are driven by the nonthermal tail of the electron distrubution.

The form of this distribution function shown on the right is characteristic of nitrogen. Other gases possess different equilibrium distributions.



Energy dependent electron collisions with neutral species play a fundamental role in determining the quasi-equilibrium EEDF.

Elastic collisions isotropize EEDF about the electric field direction. Inelastic collisions involving vibrational and electronic states of neutral species occur at energies greater than a few eV.

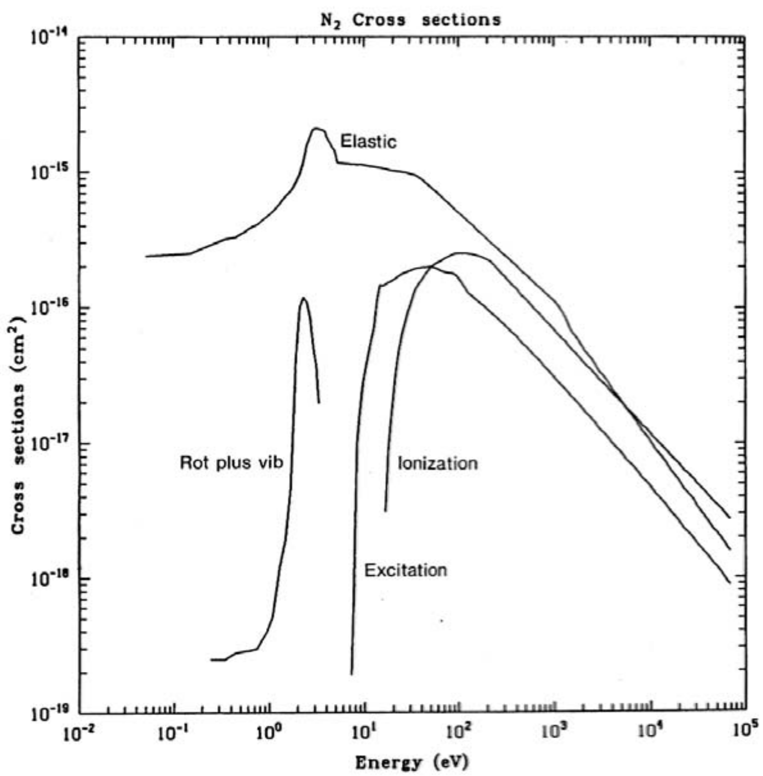


Fig. A4.1 N_2 cross sections.

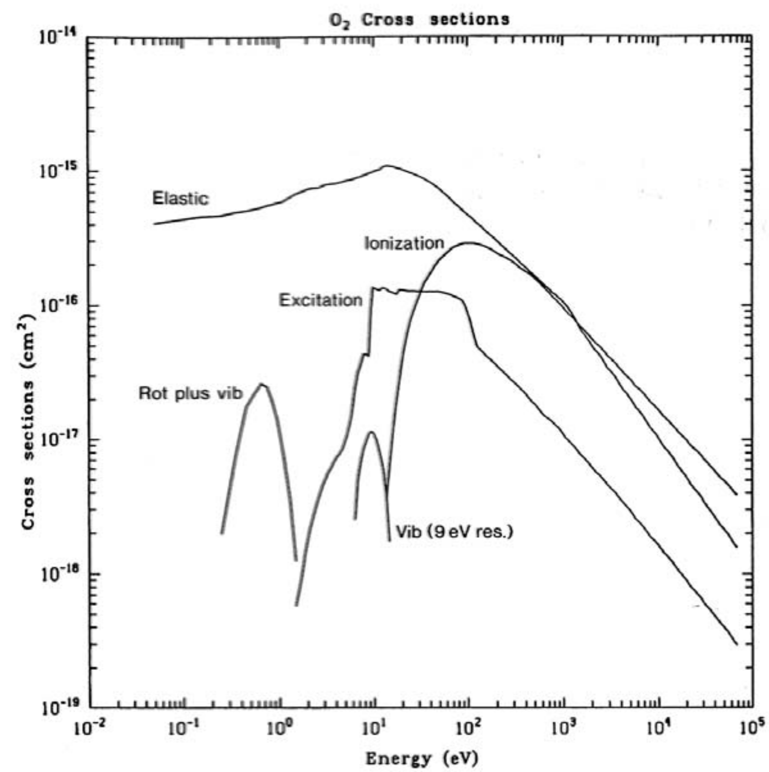


Fig. A4.2 O_2 cross sections.

From Rees, 1989

Ionization, Dissociative Attachment, and Vibrational Excitation Frequencies

Ionization coefficient

Process: $e^* + N_2 \rightarrow N_2^+ + 2e$

Modeled by:

$$\frac{\alpha}{p} = A_i \exp\left(-\frac{B_i}{E/p}\right)$$

Attachment coefficient

Process: $e + O_2 \rightarrow O^- + O$

Modeled by

$$\frac{\eta}{p} = A_a \left(\frac{E}{p}\right)^{-2} \exp\left(-\frac{B_a}{E/p}\right)$$

Electron mobility

Defined through drift speeed

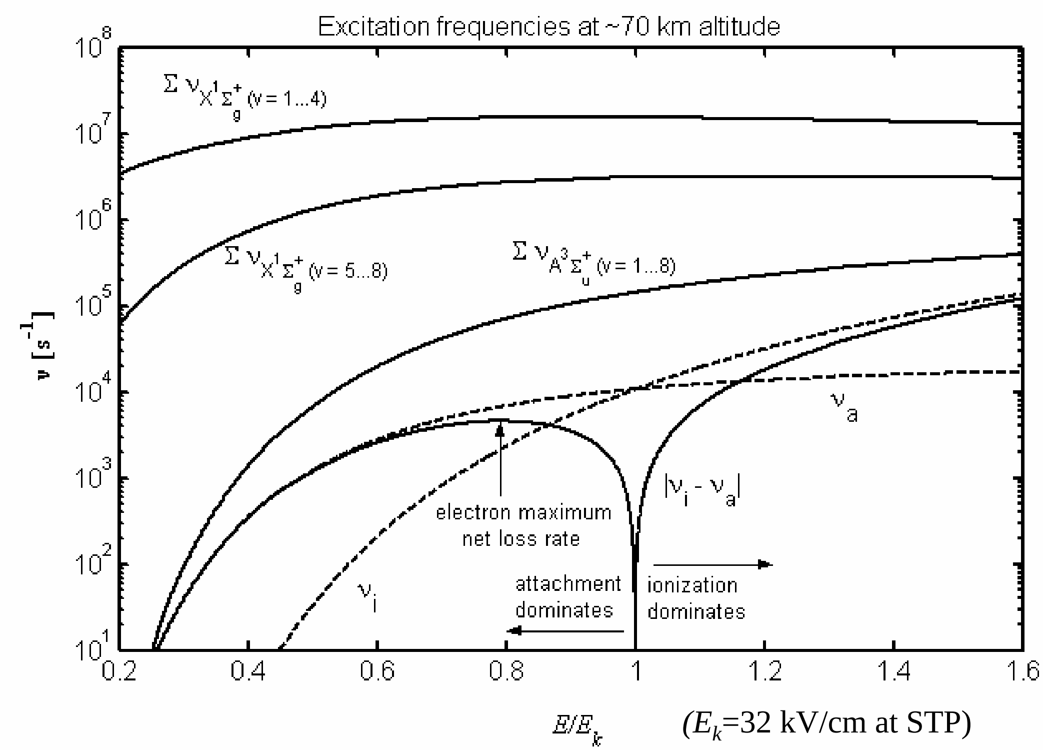
$$v_d = \mu_e E$$

Modeled by

$$\mu_e p = A_m \left(\frac{E}{p}\right)^{-\beta}$$

Ionization and attachment frequencies

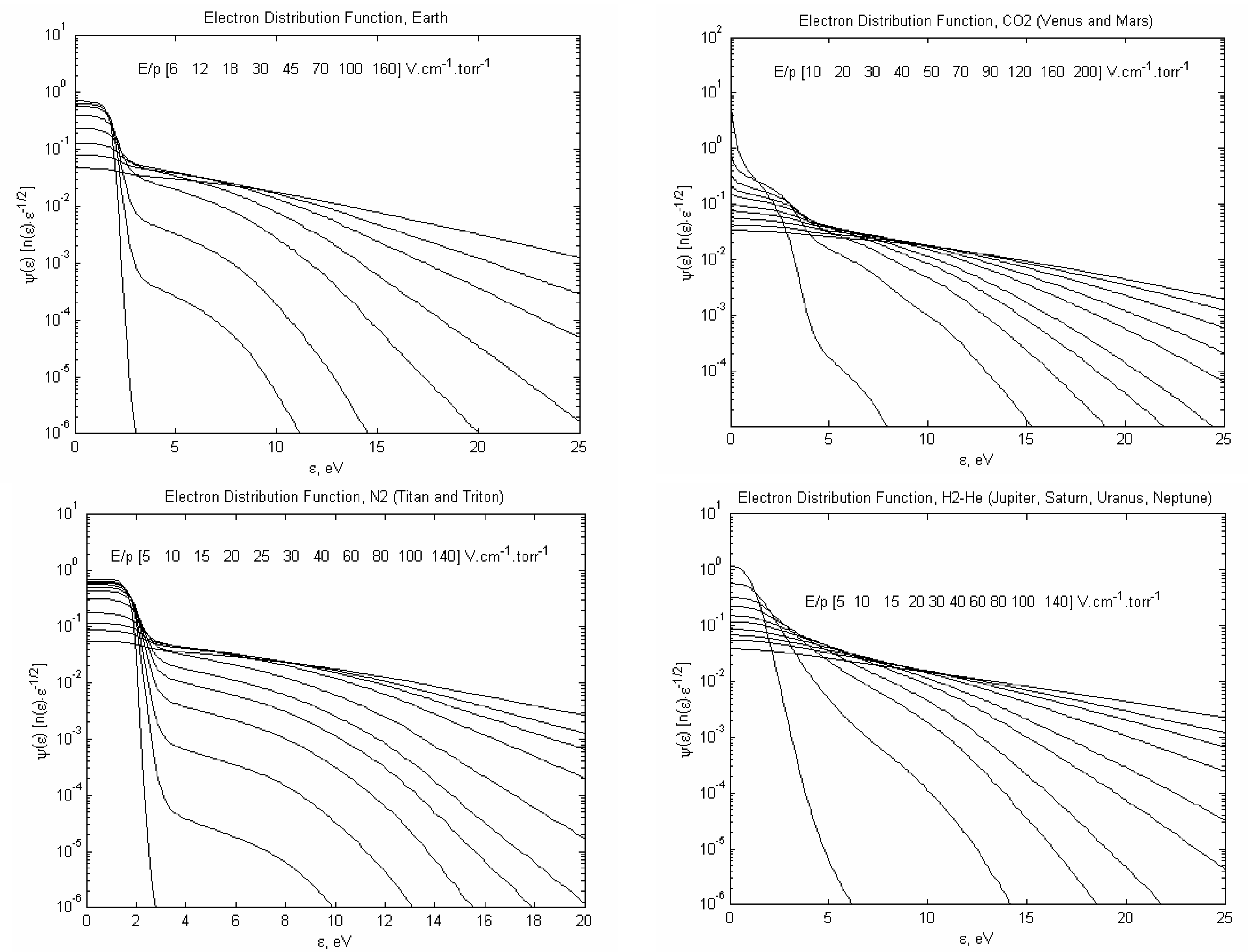
$$\nu_i = \alpha v_d = \alpha(\mu_e p)(E/p)$$
$$\nu_a = \eta v_d = \eta(\mu_e p)(E/p)$$



(E_k=32 kV/cm at STP)

Vibrational excitations play a significant role in determining the form of the EEDF. In general the excitation frequencies of the vibrational modes of both ground and excited states are much larger than the ionization/attachment frequencies at all undervoltage ($E < E_k$) and modest ($E > E_k$) overvoltage fields.

Electron Distribution Function vs Reduced Electric Field for the Four Major Atmospheric Composition Classes of Planetary Atmospheres



Selected Background References

(* Discovery reports, seminal works, standard 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 and '96 Campaigns of nitrogen second positive (399.8 nm) and first negative (427.8 nm) emissions. J. Atmos. Solar-Terr. Phys. , 60, 787-799. 1998.

Babich, L. P., I. M. Kutsyk, E. N. Donskoy, and A. Yu. Kudryavtsev, New data on space and time scales of relativistic runaway electron avalanche for thunderstorm development, *Phys. Lett. A*, **245**, 460, 1998.

Barrington-Leigh, C. P., U. S. Inan, M. Stanley, and S. A. Cummer, Sprites triggered by negative lightning discharges, *Geophys. Res. Lett.*, **26**, 3605, 1999.

Barrington-Leigh, D.P., V.P. Pasko, and U.S. Inan, Exponential relation of optical emissions in sprites, *J. Geophys. Res.*, **107**(A5), 1065, 2002.

Bering, E.A. III, A.A. Few and J.R. Benbrook, The Global Electrical Circuit. *Physics Today*, October, 24-30, 1998.

Bering, E.A. III, J. R. Benbrook, J. A. Garrett, A. Paredes, E. M. Wescott, D. R. Moudry, D. D. Sentman, H. C. Stenbaek-Nielsen, W. A. Lyons, The electrodynamics of sprites, *Geophys. Res. Lett.*, **29,** doi10.1029/2001GL013267, 2002.

Bell, T. F., V. P. Pasko, and U. S. Inan, Runaway electrons as a source of red sprites in the mesosphere, *Geophys. Res. Lett.*, **22**, 2127, 1995.

Bell, T.F., Intense continuing currents following positive cloud-to-ground lightning associated with red sprites, *Geophys. Res. Lett*.,**25**(8), 1285-1288, 1998.

Bulanov, S. V., M. Lontano, and P. V. Sasorov, Ionization rate in the presence of runaway electrons, *Phys. Plasmas*, **4**, 931, 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. Lett.*, **25**(8), 1281-1284, 1998.

*Dejnakarintra, M. and C. G. Park, Lightning-induced electrical fields in the ionosphere, *J. Geophys. Res.*, **79**, 1903, 1974.

*Dwyer, J. R. A fundamental limit on electric fields in air, *Geophys. Res. Lett.*, **30**(20), 2055, 2003.

Dwyer, J. R., et al. Energetic radiation produced during rocket triggered lightning, *Science*, 299, 694– 697, 2003.

Dwyer, J. R., J. R. H.K. Rassoul, M. Al-Dayeh, L. Caraway, B. Wright, A. Chrest , M. A. Uman, V.A. Rakov, K.J. Rambo, D.M. Jordan, J.Jerauld, and C. Smyth , Measurements of x-ray emission from rocket triggered lightning, *Geophys. Res. Lett.*, 31, L05118, 2004.

*Dwyer, J.R., H. K. Rassoul, M. Al-Dayeh, L. Caraway, B. Wright, and A. Chrest, M. A. Uman, V. A. Rakov, K. J. Rambo, D. M. Jordan, J. Jerauld, and C. Smyth, A ground level gamma-ray burst observed in association with rocket-triggered lightning, *Geophys. Res. Lett.*, **31**, L05119, 2004.

*Eack, K. B., W. H. Beasley, W. D. Rust, T. C. Marshall, and M. Stoltzenburg, X-ray pulses observed above a mesoscale convective system, *Geophys. Res. Lett.*, **23**, 2815, 1996.

Eack, K. B., W. H. Beasley, W. D. Rust, T. C. Marshall, and M. Stoltzenburg, Initial results from simultaneous observation of X rays and electric fields in a thunderstorm, *J. Geophys. Res.*, **101**, 29637, 1996.

*Fishman, G. J., P. N. Bhat, R. Malozzi, J. M. Horack, T. Koshut, C. Kouveliotou, G. N. Pendleton, C. A. Meegan, R. B. Wilson, W. S. Paciesas, S. J. Goodman, and H. J. Christian, Discovery of intense gamma-ray flashes of atmospheric origin, *Science*, **264**, 1313, 1994.

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

*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. Lett.*, **23**, 215-2160, 1996.

Gerken, E.A., U.S. Inan, and C.P. Barrington-Leigh, Telescopic imaging of sprites, *Geophys. Res. Lett.*, **27**, 2637, 2000.

*Gurevich, A. V., G. M. Milikh, and R. A. Roussel-Dupre, Runaway mechanism of air breakdown and preconditioning during a thunderstorm, *Phys. Lett. A*, **165**, 463, 1992.

Gurevich, A. V., G. M. Milikh, and R. A. Roussel-Dupre, Nonuniform runaway air-breakdown, *Phys. Lett. A*, **187**, 197, 1994.

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

Gurevich, A. V., G. M. Milikh, and J. A. Valdivia, Model of x-ray emission and fast preconditioning during a thunderstorm, *Phys. Lett. A*, **231**, 402, 1997.

Gurevich, A. V., K. F. Sergeichev, I. A. Sychov, R. Roussel-Dupr´e, and K. P. Zybin, First observations of runaway breakdown phenomenon in laboratory experiments, *Phys. Lett. A*, **260**, 269, 1999.

Gurevich, A. V. and G. M. Milikh, Generation of x-rays due to multiple runaway breakdown inside thunderclouds, *Phys. Lett. A*, **262**, 457, 1999.

Gurevich, A. V., K. P. Zybin, and R. A. Roussel-Dupre, Lightning initiation by simultaneous effect of runaway breakdown and cosmic ray showers, *Phys. Lett*. A, **254**, 79– 87, 1999.

*Hampton, D.L., M.J. Heavner, E.M Wescott and D.D. Sentman, Optical spectral characteristics of sprites, *Geophys. Res. Lett*., **23**, 89-92, 1996.

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

Heavner, M.J., D.D. Sentman, D.R. Moudry, E.M. Wescott, C.L. Siefring, J.S. Morrill, and E.J. Bucsela, "Sprites, Blue Jets, and Elves: Optical Evidence of Energy Transport Across the Stratopause," in *Atmospheric Science Across the Stratopause*(D. Siskind, editor), American Geophysical Union, Washington D.C., 2000.

Holzworth, R. H., M. C. Kelley, C. L. Siefring, L. C. Hale, and J. T. Mitchell, Electrical measurements in the atmosphere and the ionosphere over an active thunderstorm. 2. Direct current electric fields and conductivity, *J. Geophys. Res.*, **90**, 9824, 1985.

*Inan, U. S., 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. Lett.*, **24**, 583, 1997.

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

*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. Lett.*, **23**, 133, 1996.

Jacobson, A., How do the strongest radio pulses from thunderstorms relate to lightning flashes? *J. Geophys. Res*., **10**8(D24), 4778, 2003

Kunhardt, E. E., Y. Tzeng, and J. P. Boeuf, Stochastic development of an electron avalanche, *Phys. Rev. A*, 34, 440, 1986.

Kulikovsky, A. A., The mechanism of positive streamer acceleration and expansion in air in a strong external field, *J. Phys. D Appl. Phys*., **30**, 1515– 1522, 1997.

Kulikovsky, A. A. (2000), The role of photoionization in positive streamer dynamics, *J. Phys. D Appl. Phys*., **33**, 1514–1524, 2000.

Kurzan, B., K.-H. Steuer, and G. Fussman, Dynamics of runaway electrons in the magnetic field of a tokamak, *Phys. Rev. Lett.*, **75**, 4626, 1995.

Kutsyk, I. M. and L. P. Babich, Spatial structure of optical emissions in the model of gigantic upward atmospheric discharges with participation of runaway electrons, *Phys. Lett. A*, **253**, 75, 1999.

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. Lett.*, **23**, 2645, 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. Lett.*, **24**, 2639, 1997.

Lehtinen, N. G., T. F. Bell, and U. S. Inan, Monte Carlo simulation of runaway MeV electron breakdown with application to red sprites and terrestrial gamma ray flashes, *J. Geophys. Res.*, **104**, 24699, 1999.

Lehtinen, Nikolai G., "Relativistic Runaway Electrons Above Thunderstorms," Ph.D. Dissertation, Department of Physics, Stanford University, 2000.

*Liu, N., and V.P. Pasko, Effects of photoionization on propagation and branching of positive and negative streamers in sprites, *J. Geophys. Res.*, **109**, A04301, 2004.

*Lyons, W.A., Sprite observations above the U.S. High Plains in relation to their parent thunderstorm systems, *J. Geophys. Res.* **101**, 29,641-29,652, 1996.

Lyons, W.A., R.A. Armstrong, E.A. Bering, and E.R. Williams, The hundred year hunt for the sprite, *EOS Trans. Amer. Geophys. Union*, **81**(33), 373-377, 2000.

*Massey, R.S., and D.N. Holden, Phenomenology of transionospheric pulse pairs, *Radio Sci.*, **30** (5), 1645-1659, 1995.

Massey, R.S., D.N. Holden, and X.M. Shao, Phenomenology of trans-ionospheric pulse pairs: Further observations, *Radio Science*, **33** (6), 1755-1761, 1998.

*McCarthy, M. P. and G. K. Parks, Further observations of x-rays inside thunderstorms, *Geophys. Res. Lett.*, **12**, 393, 1985.

McCarthy, M. P. and G. K. Parks, On the modulation of X ray fluxes in thunderstorms, *J. Geophys. Res.*, **97**, 5857, 1992.

*Mende, S. B., R. L. Rairden, G. R. Swenson, and W. A. Lyons, Sprite spectra; N_2 1PG band identification, *Geophys. Res. Lett.*, **22**, 2633, 1995.

Milikh, G.M., K. Papadopoulos, and C.L. Chang, On the physics of high altitude lightning, *Geophys. Res. Lett.*, **22**(2), 85-88, 1995.

Milikh, G., and J.A. Valdivia, Model of gamma ray flashes due to fractal lightning, *Geophys. Res. Lett.*, **26**(4), 525-528, 1999.

Moore, C. B., K. B. Eack, G. D. Aulich, and W. Rison, Energetic radiation associated with lightning stepped-leaders, *Geophys. Res. Lett.*, **28**, 2141– 2144, 2001.

*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 resolve N_2 triplet state vibrational populations and emissions associated with red sprites, *J. Atmos. Solar-Terr. Phys.*, **60**, 811-830, 1998.

Nemiroff, R. J., J. T. Bonnell, and J. P. Norris, Temporal and spectral characteristics of terrestrial gamma flashes, *J. Geophys. Res.*, **102**, 9659, 1997.

Papadopoulos, K., G. Milikh, A. Gurevich, A. Drobot, and R. Shanny, Ionization rates for atmospheric and ionospheric breakdown, *J. Geophys. Res.*, **98**, 17593, 1993.

Pasko, V. P. and U. S. Inan, Recovery signatures of lightning-associated VLF perturbations as a measure of the lower ionosphere, *J. Geophys. Res.*, **99**, 17523, 1994.

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

*Pasko, V. P., U. S. Inan, T. F. Bell, and Y. N. Taranenko, Sprites produced by quasielectrostatic heating and ionization in the lower atmosphere, *J. Geophys. Res.*, **102**, 4529, 1997.

Pasko, V. P., U. S. Inan, and T. F. Bell, Ionospheric effects due to electrostatic thundercloud fields, *J. Atmos. Solar-Terr. Phys.*, **60**, 863, 1998.

Pasko, V. P., U. S. Inan, and T. F. Bell, Spatial structure of sprites, *Geophys. Res. Lett.*, *25*, 2123, 1998.

Pasko, V.P., U.S. Inan, and T.F. Bell, Mesospheric electric field transients due to tropospheric lightning discharges, *Geophys. Res. Lett.*, **26**(9), 1247-1250, 1999.

*Pasko, V.P., and J.J. George, Three-dimensional modeling of blue jets and blue starters, *J. Geophys. Res.*, **107**(A12), 1458, 2002.

Pasko, V.P., and H.C. Stenbaek-Nielsen, *Geophys. Res. Lett.*, **29**(10), 10.1029, 2002.

*Raizer, Y. P., *Gas Discharge Physics*, 2nd edition, Springer-Verlag, Berlin, 1997.

*Rees, M. H., *Physics and chemistry of the upper atmosphere*, 2nd edition, Cambridge University Press, 1989.

Rodriguez, J. V. and U. S. Inan, Electron density changes in the nighttime *D* region due to heating by very-low-frequency transmitters, *Geophys. Res. Lett.*, **21**, 93, 1994.

*Roussel-Dupre, R. A., A. V. Gurevich, T. Tunnel, and G. M. Milikh, Kinetic theory of runaway breakdown, *Phys. Rev. E*, **49**, 2257, 1994.

Roussel-Dupre, R. A. and A. V. Gurevich, On runaway breakdown and upward propagating discharges, *J. Geophys. Res.*, **101,** 2297, 1996.

Roussel-Dupre, R., E. Symbalisty, Y. Taranenko, and V. Yukhimuk, Simulations of high-altitude discharges initiated by runaway breakdown, *J. Atmos. Solar- Terr. Phys.*, **60**, 917, 1998.

Rowland, H.L., Theories and simulations of elves, sprites and blue jets, *J. Atmos. Solar-Terr. Phys.*, **60**, 831-844, 1998.

*Sentman, D.D., and Wescott, E.M., Video observations of upper atmospheric optical flashes recorded from an aircraft, *Geophys. Res. Lett.*, **20**, 2857-2860, 1993.

*Sentman, D. D., E. M. Wescott, D. L. Osborne, D. L. Hampton, and M. J. Heavner, Preliminary results from the Sprites94 campaign. 1. Red sprites, *Geophys. Res. Lett.*, **22**, 1205, 1995.

Suszcynsky, D. M., R. Roussel-Dupre´, and G. Shaw, Ground-based search for x-rays generated by thunderstorms and lightning, *J. Geophys. Res.*, **101**, 23,505– 23,516, 1996.

Shveigert, V. A., Development of electron avalanche in strong electric fields, *Sov. J. Plasma Phys.*, **14,** 373, 1988.

Sizykh, S. V., Runaway electron production rate in gaseous discharges, *High Temperature*, **31**, 1, 1993.

Stenbaek-Nielsen, H.C., D.R. Moundry, E.M. Wescott, D.D. Sentman, and F.T. Sao Sabbas, Sprites and possible mesospheric effects, *Geophys. Res. Lett*., **27**(23), 3829-3832, 2000.

Symbalisty, E. M. D., R. A. Roussel-Dupr´e, and V. A. Yukhimuk, Finite volume solution of the relativistic Boltzmann equation for electron avalanche rates, *IEEE Trans. Plasma Sci.*, **26**, 1575, 1998.

*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. Lett*., **20**, 2675-2678, 1993.

Taranenko, Y. and R. Roussel-Dupre, High altitude discharges and gamma-ray flashes: A manifestation of runaway air breakdown, *Geophys. Res. Lett.*, **23**, 571, 1996.

Tarasova, L. V., L. N. Khudyakova, T. V. Loiko, and V. A. Tsukerman, Fast electrons and x rays from nanosecond gas discharges at 0.1–760 torr, *Sov. Phys. Tech. Phys.*, **19**, 351, 1974.

*Torii, T. T. Nishijima, Z.-I. Kawasaki, and T. Sugita, Downward emission of runaway electrons and bremsstrahlung photons in thunderstorm electric fields, *Geophys. Res. Lett.*, **31**, L05113, 2004.

Tzeng, Y. and E. E. Kunhardt, Effect of energy partition in ionizing collisions on the electron-velocity distribution, *Phys. Rev. A*, **34**, 2148, 1986.

Valdivia, J.A., G. M. Milikh, and K. Papadopoulos, Red sprites: Lightning as a fractal antenna, *Geophys. Res. Lett*., **24**, 3169-3172, 1997.

* Wescott, E.M., D.D. Sentman, D. L. Osborne, D. L. Hampton, and M. J. Heavner, Preliminary results from the Sprites94 campaign. 2: Blue Jets, *Geophys. Res. Lett.*, **22**, 1210, 1995.

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. Phys.*, **60**, 733, 1998.

Williams, E.R., The positive charge reservoir for sprite-producing lightning. *J. Atmos. Solar-Terr. Phys*., **60**, 689-692, 1998.

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

Winckler, J. R., R. C. Franz, and R. J. Nemzek, Fast low-level light pulses from the night sky observed with the SKYFLASH program, *J. Geophys. Res.*, **98**, 8775, 1993.

Yukhimuk, V., R. Roussel-Dupre, E. M. D. Symbalisty, and Y. Taranenko, Optical characteristics of Red Sprites produced by runaway air breakdown, *J. Geophys. Res.*, **103**, 11473, 1998.

Yukhimuk, V., R. Roussel-Dupre, and E. M. D. Symbalisty, On the temporal evolution of red sprites: Runaway theory versus data, *Geophys. Res. Lett.*, **26,** 679, 1999.

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