Aspen Global Change Institute

June 16, 2010

LIGHTNING-RELATED TRANSIENT LUMINOUS EVENTS AT HIGH ALTITUDE IN THE EARTH'S ATMOSPHERE

Victor Pasko

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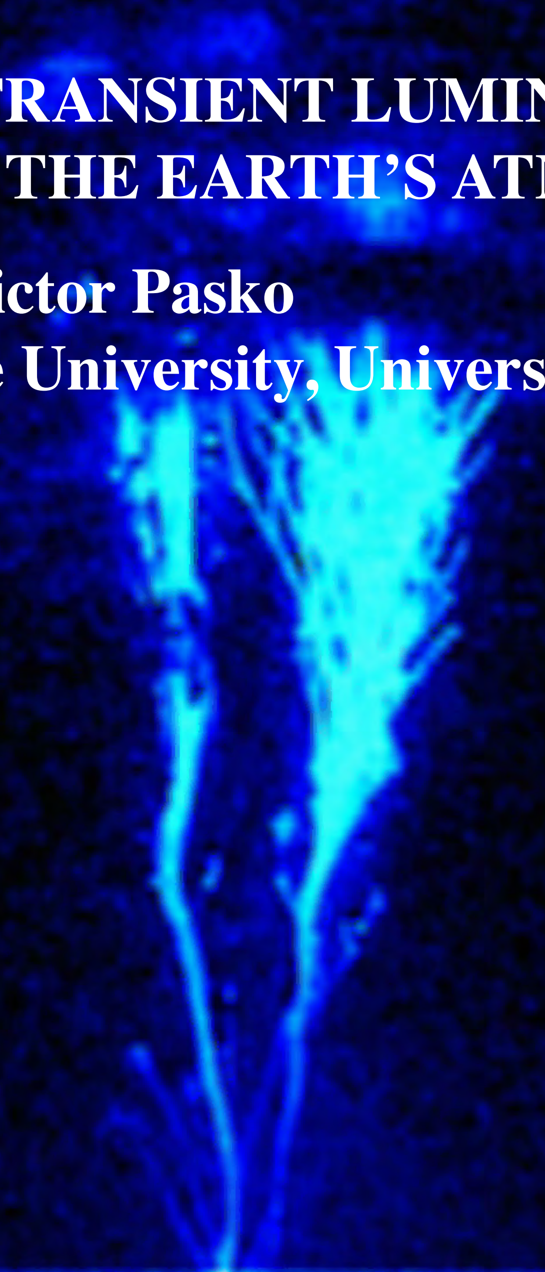

LIGHTNING-RELATED TRANSIENT LUMINOUS EVENTS AT HIGH ALTITUDE IN THE EARTH'S ATMOSPHERE

Victor P. Pasko
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Workshop on Global Change
and Solar-Terrestrial Environment
Aspen Global Change Institute
Aspen, Colorado, USA

12-17 June, 2010

Outline

- Introduction
- Phenomenology and Physical Mechanism of Elves
- Phenomenology and Physical Mechanism of Sprites
- Phenomenology and Physical Mechanism of Blue Jets and Gigantic Jets
- AGU Chapman Conference on Effects of Thunderstorms and Lightning in the Upper Atmosphere

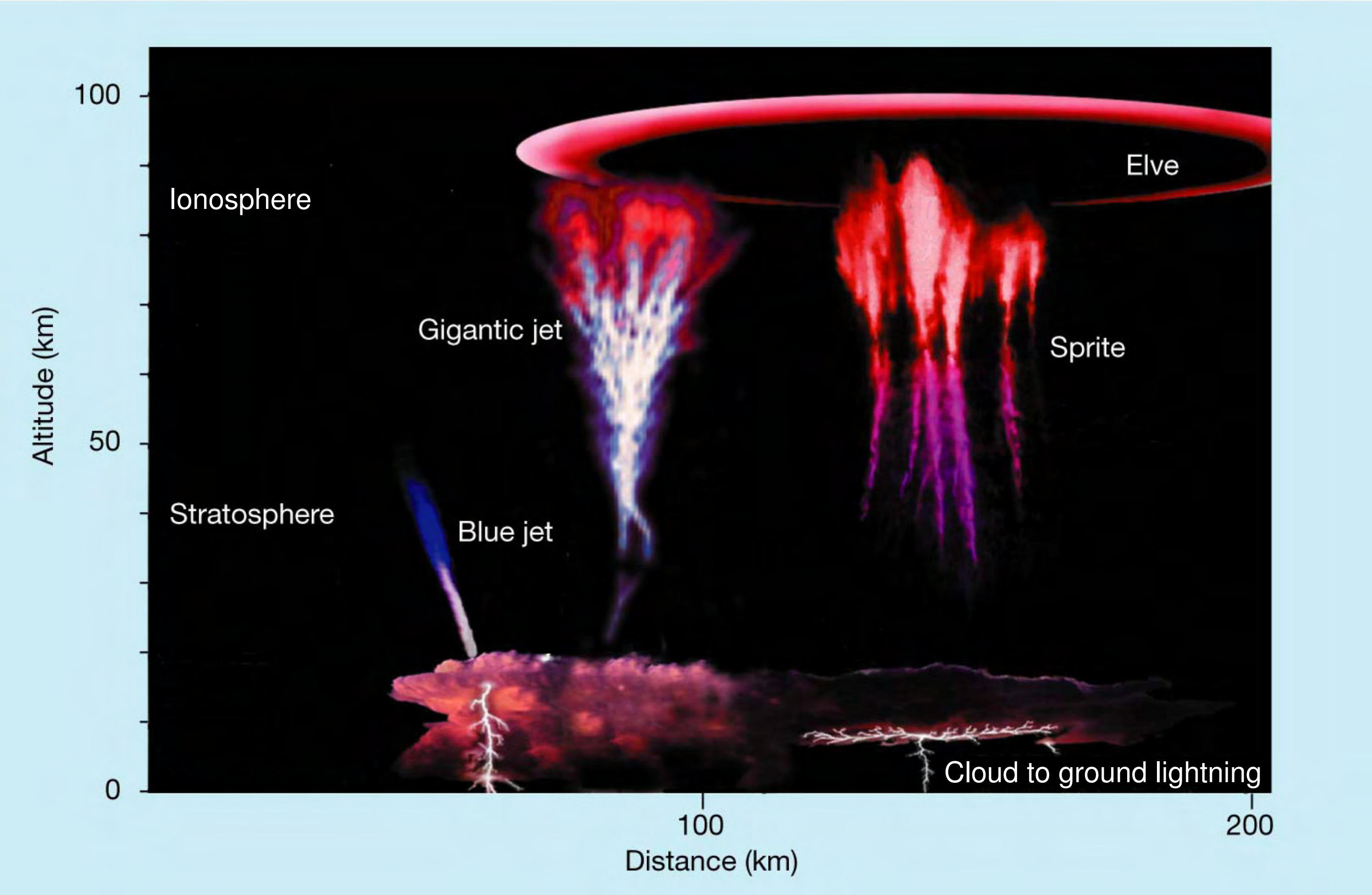
The First TV Image of an Optical Flash Above Thunderstorms

- The first recorded TV image of unusual optical flashes occupying large volumes of space above thunderstorms was obtained serendipitously on July 5, 1989 during a test of a low-light-level TV camera at the O'Brien Observatory of the University of Minnesota near Minneapolis [*Franz et al.*, Science, 249, 48, 1990].

A Sprite Event Recorded on Color Video [*Sentman et al.*, 1995]

- A sprite event (one of the largest) recorded on color video on 4 July 1994 at 0400:20 UT [*Sentman et al.*, Geophys. Res. Lett., 22, 1205, 1995]

Lightning-Related Middle Atmospheric Transient Luminous Events



[Lyons et al., BAMS, 84, 445, 2003; Pasko, Nature, 423, 927, 2003]

The global electric circuit

Bering et al., Physics Today, P. 24-30, October 1998

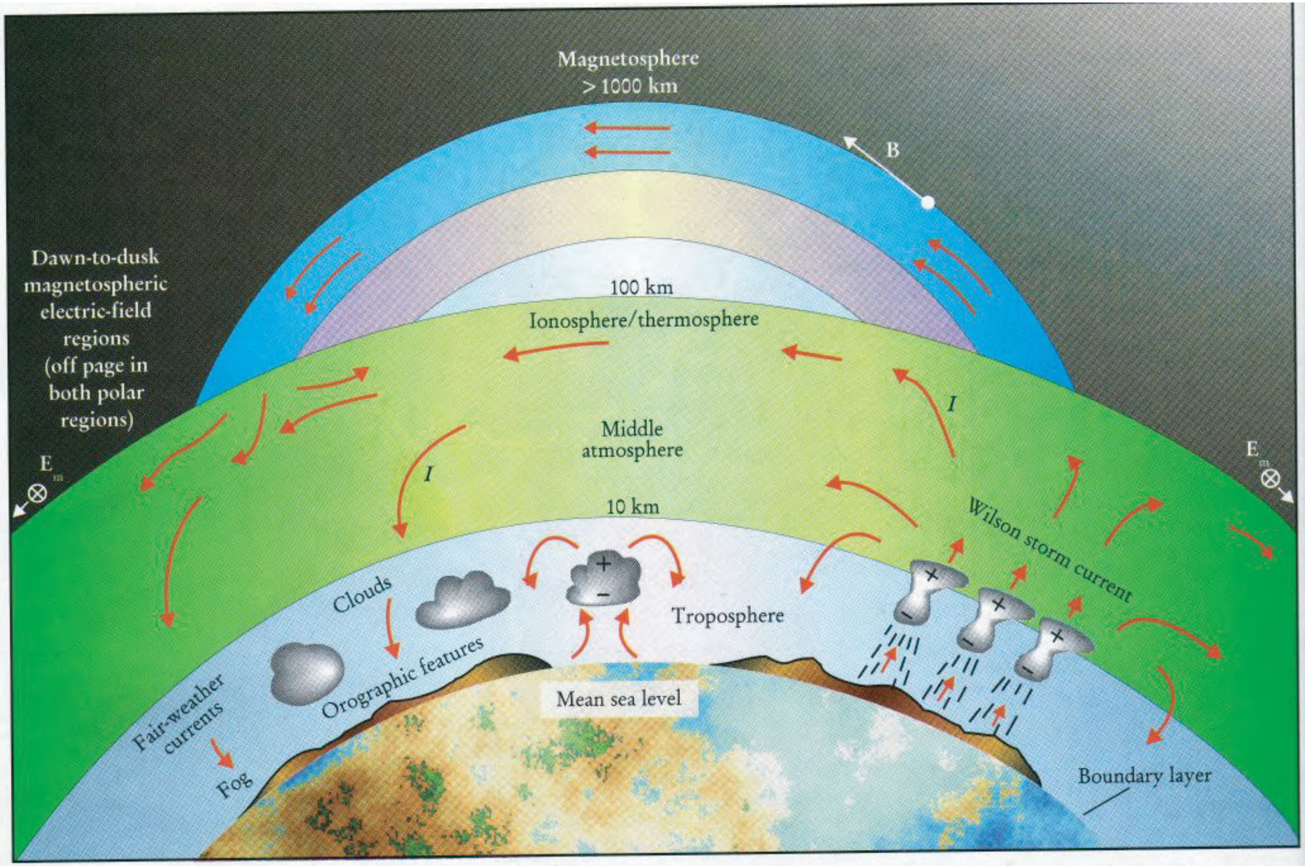
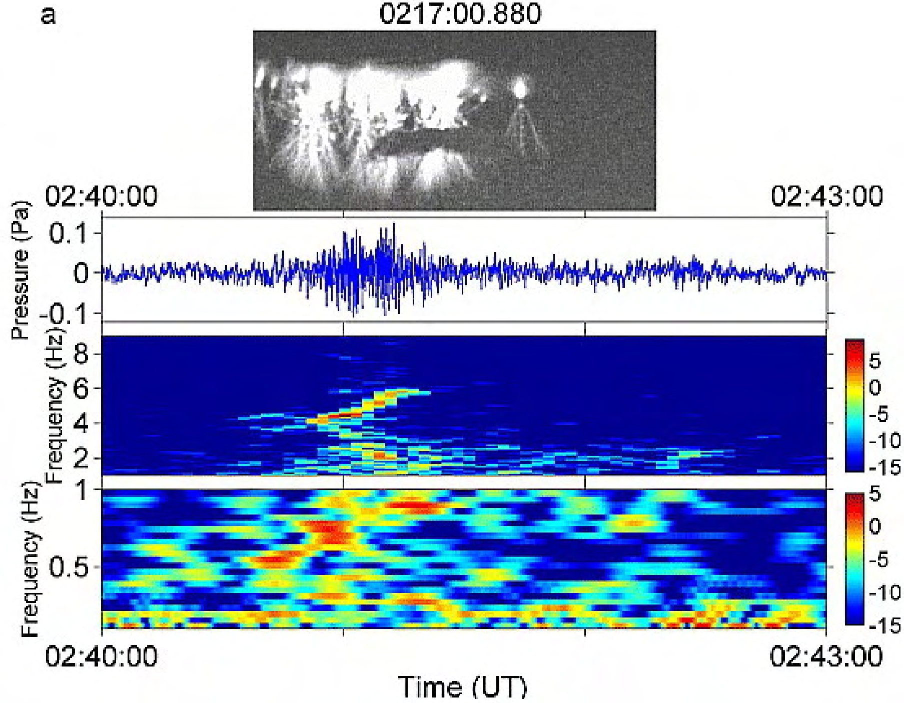


FIGURE 2. FLOW OF ELECTRIC CURRENT in the global circuit. All of the unlabeled arrows represent current flow. The strongest batteries in the circuit are the thunderstorms indicated on the right. They produce the Wilson current. The fair-weather currents are indicated by downward-pointing arrows away from the thunderstorms. (Based on a diagram by Ray G. Roble.)

Identification of Infrasound Produced by Sprites

- Farges et al. [GRL, 32, L13824, 2005] provided first direct correlation of the chirp-like signatures in 0.1-9 Hz range with optical observations of sprites. The sprite correlated infrasound signatures are characterized by arrival of low frequencies before high frequencies and pressure amplitudes on the order 0.01-0.1 Pa at horizontal distances ≃400 km.



X-Rays from Lightning


A BOLT OUT OF THE BLUE

New research shows that lightning is a surprisingly complex and mystifying phenomenon

By Joseph R. Dwyer

NATURE'S X-RAY MACHINE: Recent studies show that lightning emits bursts of x-rays as it carves its jagged conductive channels through the atmosphere. The energies of the x-rays extend to 250,000 electron volts, or about twice the energy of a chest x-ray.

Lightning is a particularly unsettling product of bad weather. It causes more deaths and injuries in the U.S. than either hurricanes or tornadoes do, and it strikes without warning, sometimes with nothing but blue sky overhead. In central Florida, where I live, thunderstorms are a daily occurrence during the summer, and so, ironically, people in the Sunshine State often spend their afternoons indoors to avoid the risk of death from the sky.

Worldwide, lightning flashes about four million times a day, and bolts have even been observed on other planets. Yet despite its familiarity, we still do not know what causes lightning. It is a misconception that Benjamin Franklin solved the puzzle when he conducted his famous kite experiment in 1752.

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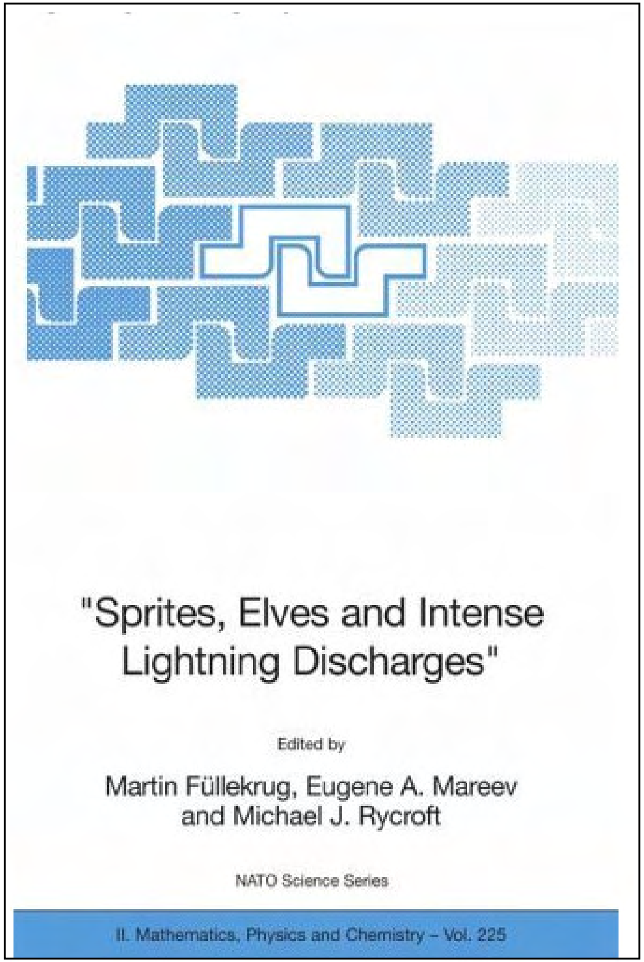
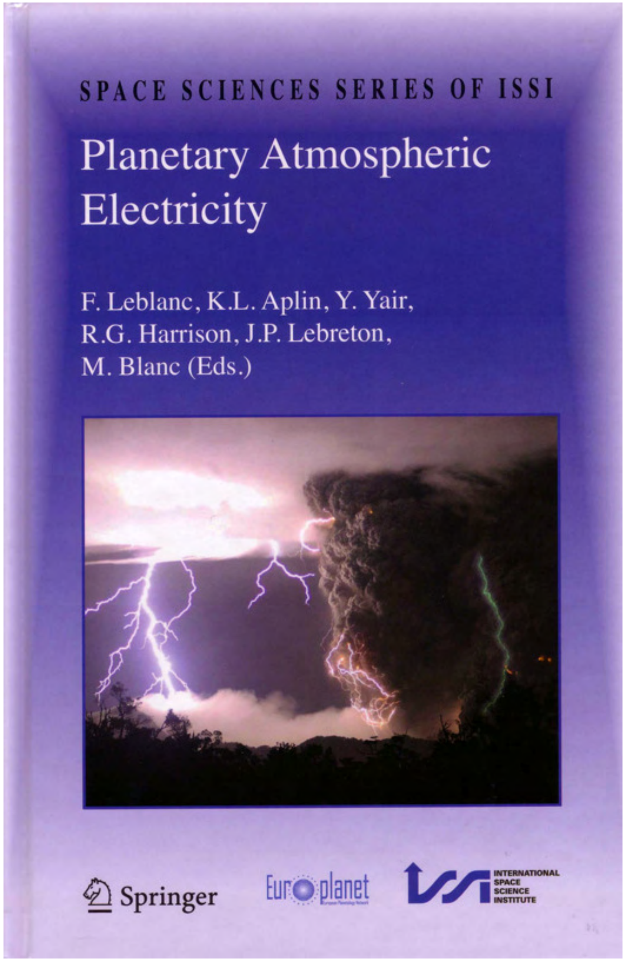
Credit: J. R. Dwyer, Sci. American, May, 2005


Earth's Gamma-Ray Bursts Triggered by Lightning
Credit: NASA, Smith et al., Science, 307, 1085, 2005
http://www.nasa.gov/vision/universe/solarsystem/rhessi_tgf.html

Books on Transient Luminous Events





Recently Published Reviews on Transient Luminous Events

- Ebert, U., and D. Sentman, Editorial Review: Streamers, sprites, leaders, lightning: from micro- to macroscales, *J. Phys. D: Appl. Phys., 41,* 230301, 2008.
- Mishin, E., G. Milikh, Blue jets:Upward lightning, *Space Sci.Rev.,137,*473, 2008.
- Neubert, T., et al., Recent results from studies of electric discharges in the mesosphere, *Surv. Geophys., 29,* 71-137, 2008.
- Pasko, V. P., Topical Review: Red sprite discharges in the atmosphere at high altitude: the molecular physics and the similarity with laboratory discharges, *Plasma Sources Sci. Technol., 16,* S13-S29, 2007.
- Pasko, V. P., Blue jets and gigantic jets: transient luminous events between thunderstorm tops and the lower ionosphere, *Plasma Phys. Control. Fusion, 50,* 124050, 22 pp., 2008.
- Pasko, V. P., Recent advances in theory of transient luminous events, *J. Geophys. Res., 115,* doi:10.1029/2009JA014860, 24 pp., 2010.
- Roussel-Dupre, R., et al., Physical processes related to discharges in planetary atmospheres, *Space Sci. Rev., 137,* 51-82, 2008.

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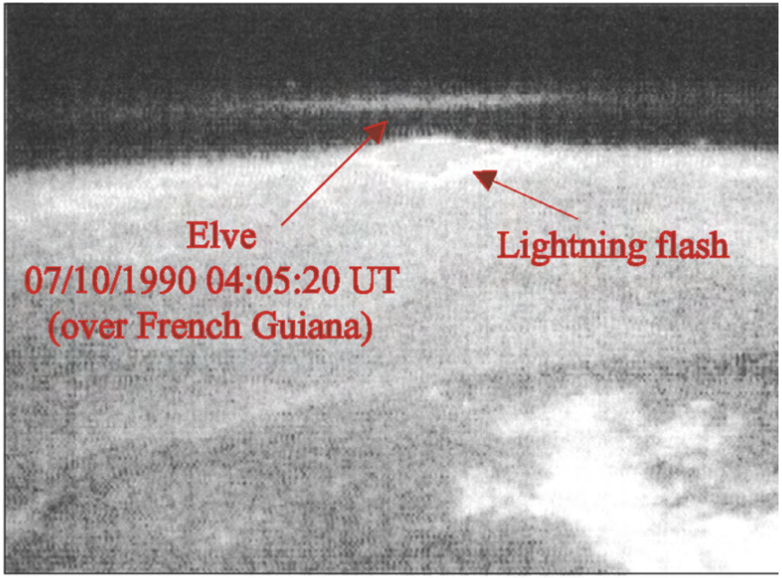
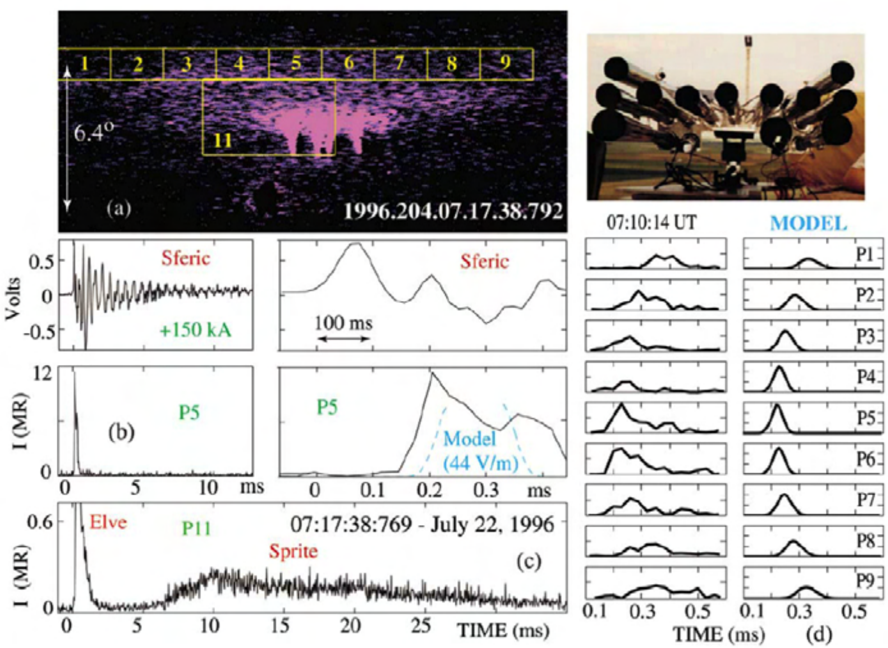
Physical Mechanism of Elves

- *Inan et al.* [GRL, 18, 705, 1991] predicted optical emissions as a result of lightning EMP interaction with the lower ionosphere.
- *Boeck et al.* [GRL, 12, 99, 1992] reported first unambiguous observation of what is now known as 'elves' suggesting the mechanism presented by *Inan et al.* [1991] as explanation:



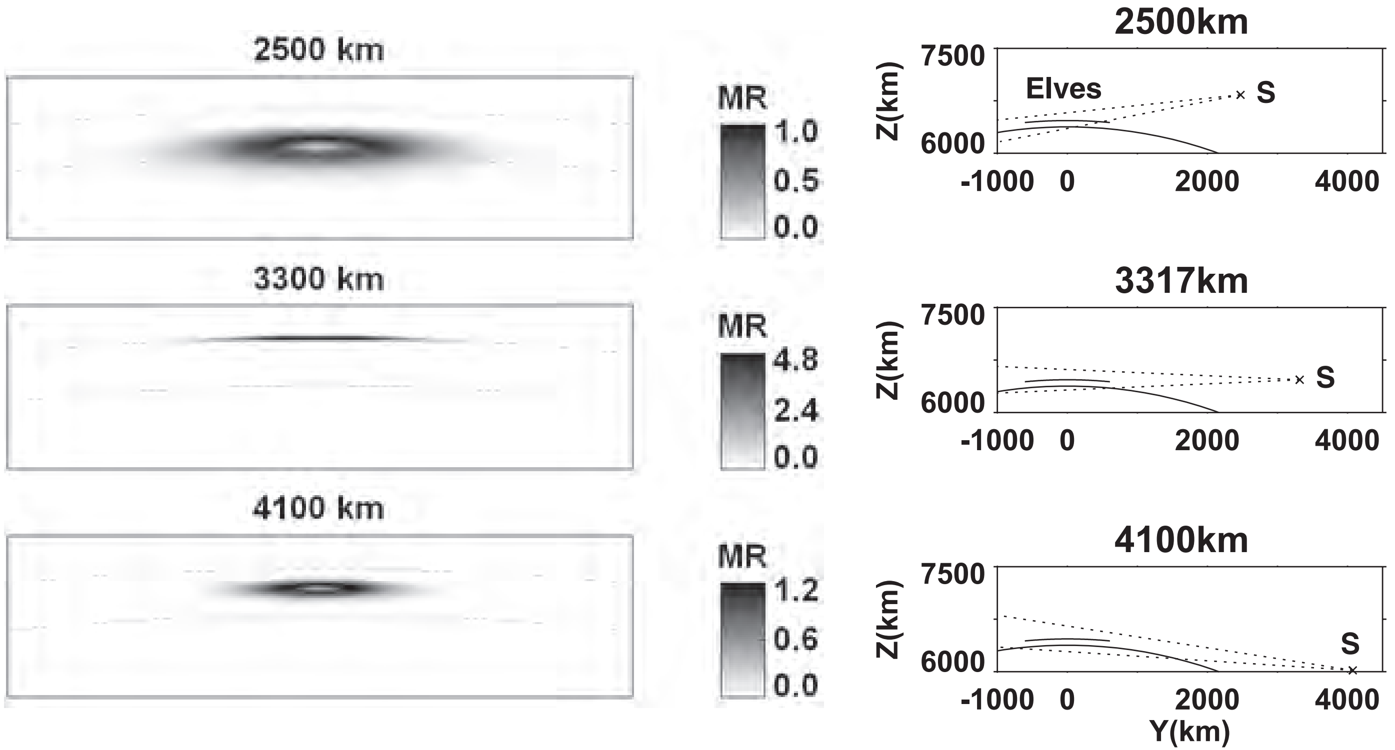
Phenomenology of Elves

- *Fukunishi et al.* [GRL, 16, 2157, 1996] realized first definite observation of elves from the ground using photometers.
- *Inan et al.* [GRL, 24, 583, 1997] used Fly's Eye instrument for definite test of the EMP mechanism:



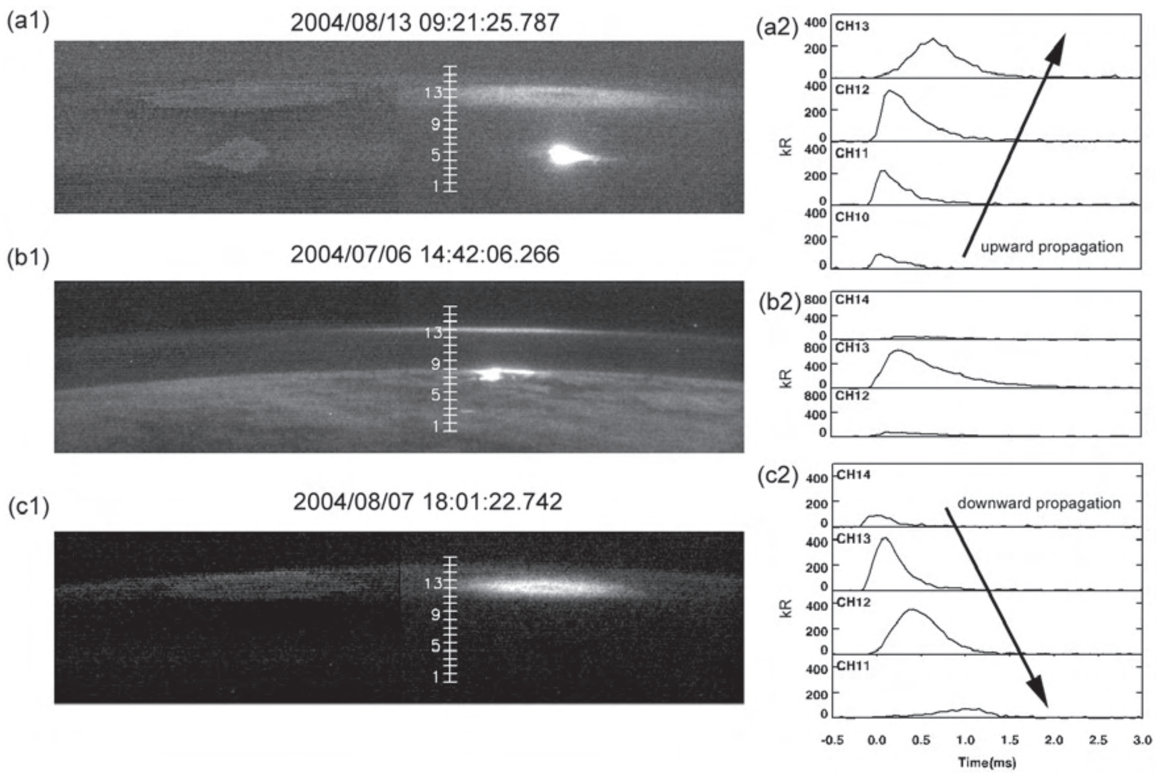
Modeling of Elves Observed by FORMOSAT-2 [*Kuo et al.*, 2007]

- Optical emissions of first positive band system of N_2 of a modeled elve (peak current 280 kA) in front (2500 km), at (3300 km) and behind (4100 km) the limb [*Kuo et al.*, JGR, 112, A11312, 2007]:



Observations of Elves by FORMOSAT-2 Satellite [*Kuo et al.*, 2007]

- ISUAL Imager (a1, b1, c1) and Array Photometer (a2, b2, c2) data for elves occurring in front, at, and behind the limb, respectively [*Kuo et al.*, JGR, 112, A11312, 2007]:



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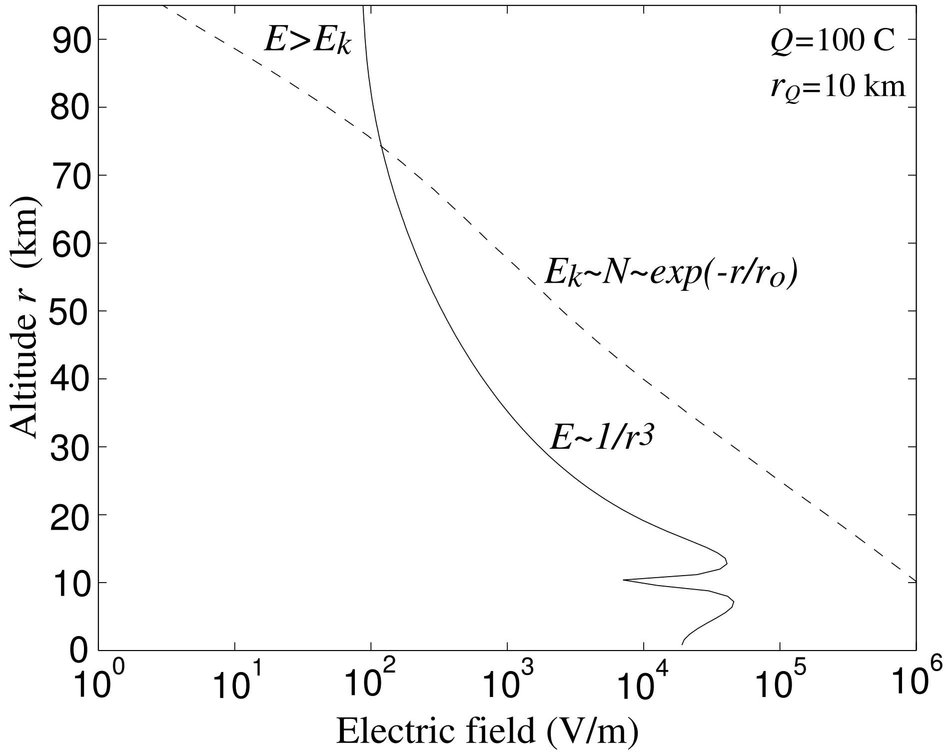
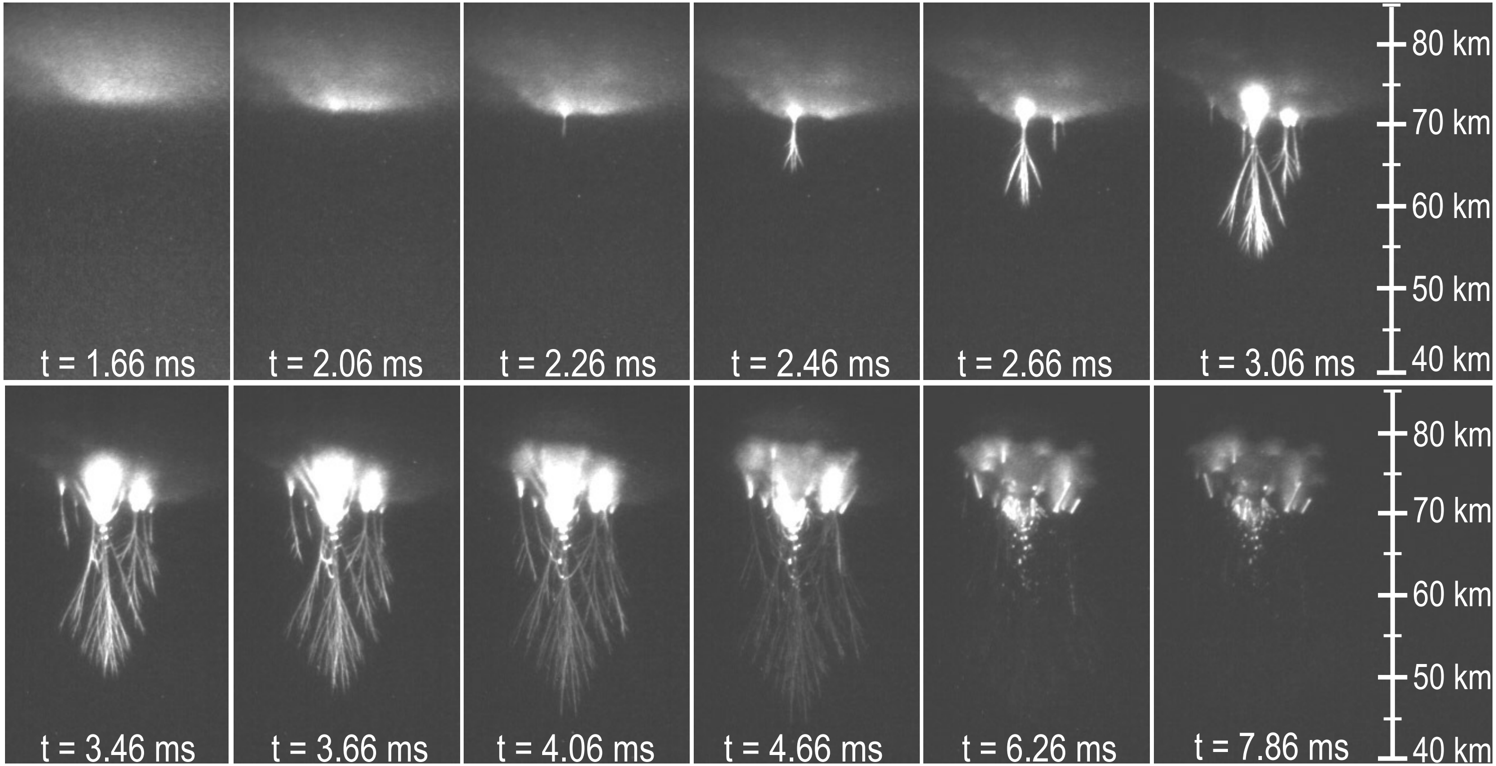
Physical Mechanism of Sprites

"While the electric force due to the thundercloud falls off rapidly as r increase, the electric force required to cause sparking (which for a given composition of the air is proportional to its density) falls off still more rapidly. Thus, if the electric moment of a cloud is not too small, there will be a height above which the electric force due to the cloud exceeds the sparking limit."

C.T.R. Wilson, Proc. Phys. Soc. Lond., Vol. 37, P. 32D, 1925



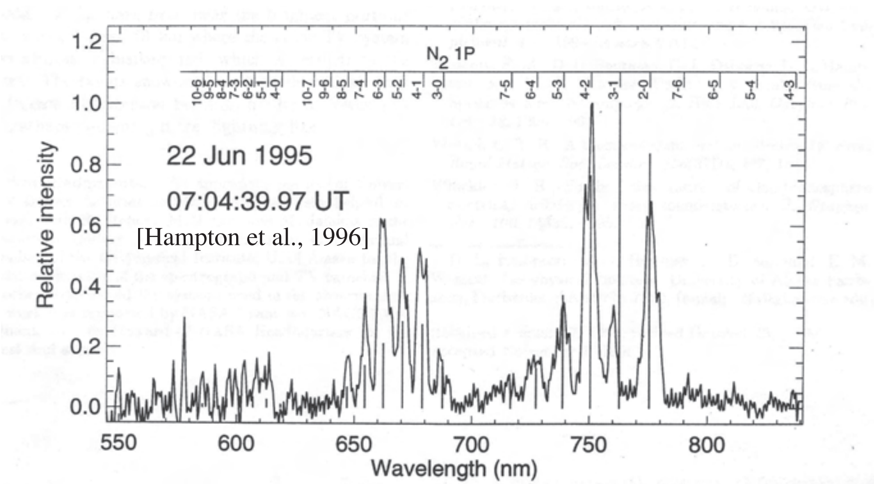
Phenomenology of Sprites



[Cummer et al., Geophys. Res. Lett., 33, L04104, 2006]

Overview of Emissions from Sprites

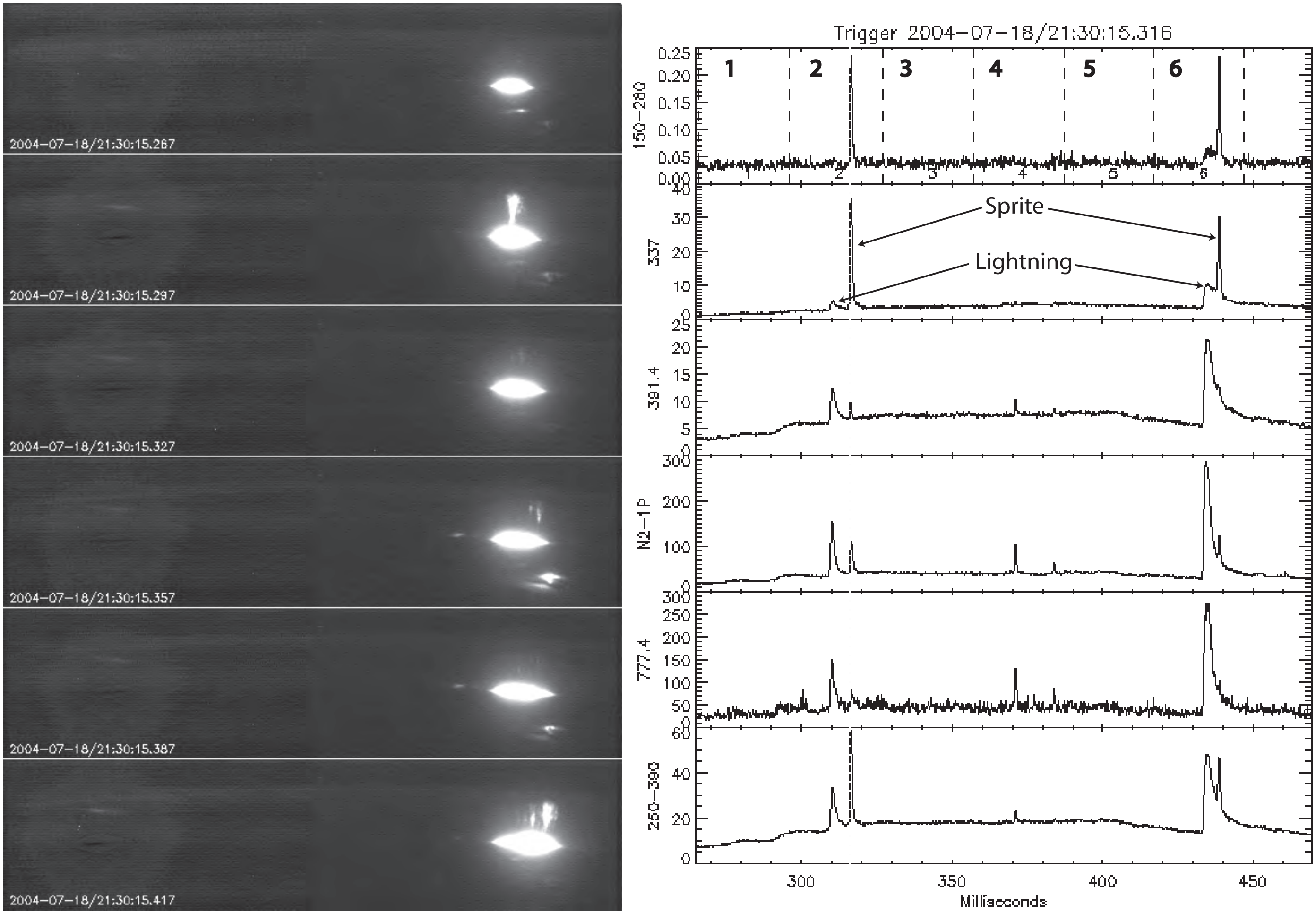
- The time averaged optical emissions in sprites are dominated by red emissions associated with the first positive band system of N_2 [*Mende et al.*, 1995; *Hampton et al.*, 1996; *Morrill et al.*, 1998; *Takahashi et al.*, 2000; *Bucsela et al.*, 2003].



- The narrow band photometric and blue-light video observations of sprites [*Armstrong et al.*, 1998, 2000; *Suszcynsky et al.*, 1998; *Morrill et al.*, 2002] indicate presence of short duration (∼ms) bursts of blue optical emissions associated with the second positive band system of N_2 and the first negative band system of N_2^+ appearing at the initial stage of sprite formation.

- Possible features from the Meinel band system of N_2^+ have been discussed by *Morrill et al.* [1998] and *Bucsela et al.* [2003].

A Sprite Event Observed by the ISUAL on FORMOSAT-2



[*Mende et al.*, 2006]

Summary of Emissions from Sprites

Emission Band System	Transition	Excitation Energy Threshold (eV)	Lifetime at 70 km Alt.	Quenching Alt. (km)
$1PN_2$	$N_2(B^3\Pi_g) \rightarrow N_2(A^3\Sigma_u^+)$	$\sim$7.35	5.4 μs	$\sim$53
$2PN_2$	$N_2(C^3\Pi_u) \rightarrow N_2(B^3\Pi_g)$	$\sim$11	50 ns	$\sim$30
LBH N_2	$N_2(a^1\Pi_g) \rightarrow N_2(X^1\Sigma_g^+)$	$\sim$8.55	14 μs	$\sim$77
$1NN_2^+$	$N_2^+(B^2\Sigma_u^+) \rightarrow N_2^+(X^2\Sigma_g^+)$	$\sim$18.8	69 ns	$\sim$48

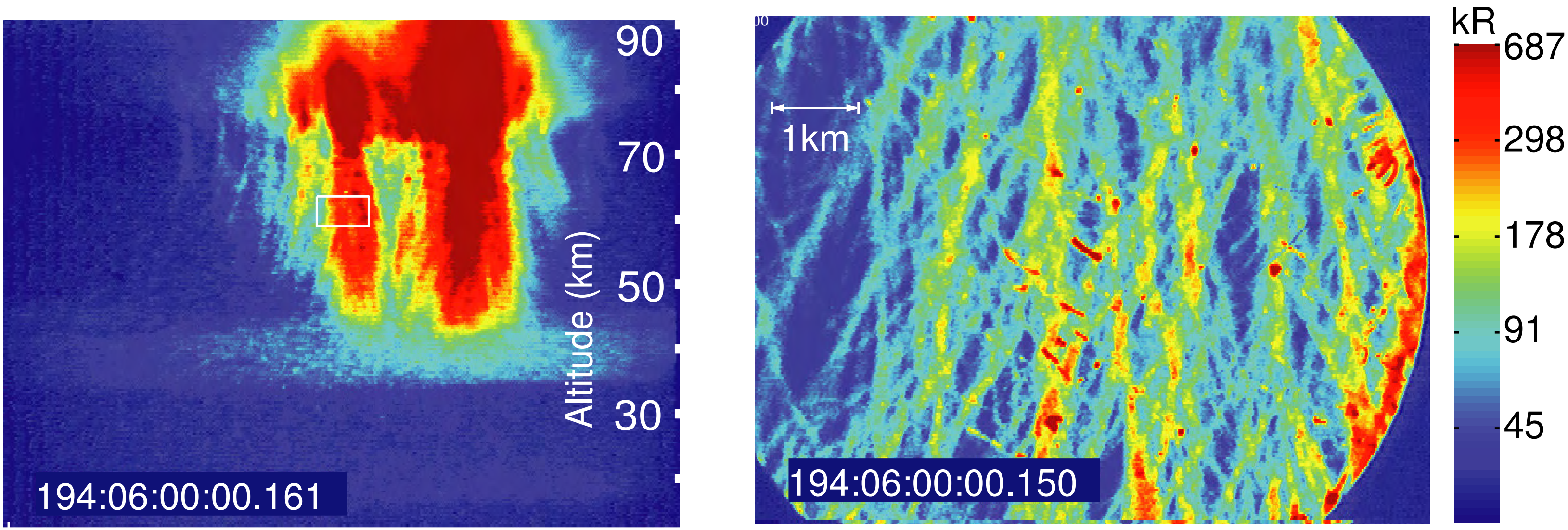
- The $N_2(B^3\Pi_g)$ vibrational distribution obtained in [*Bucsela et al.*, 2003] appeared to be consistent with those observed in laboratory afterglows, indicating an energy transfer process of the form:

$$N_2(A^3\Sigma_u^+, w) + N_2(X^1\Sigma_g^+, v \geq 5) \rightarrow N_2(B^3\Pi_g, w') + N_2(X^1\Sigma_g^+, v' \sim 0) \qquad (1)$$

- The spectroscopic features of sprites are consistent with emissions from pulsed corona discharges in laboratory experiments [*Gallimberti et al.*, 1974; *Teich*, 1993; *Simek et al.*, 1998, 2002; *Kim et al.*, 2003].
- There is a need of further studies of processes related to vibrational excitation of ground state of N_2 molecules, and pooling and resonant energy transfer reactions involving $N_2(A^3\Sigma_u^+)$ metastable species for understanding of emissions originating from $B^3\Pi_g$ and $C^3\Pi_u$ states of N_2, and NO γ-band emissions [e.g., *Simek et al.*, 1998, and references therein], during both, initial and post-discharge stages of sprite discharge.

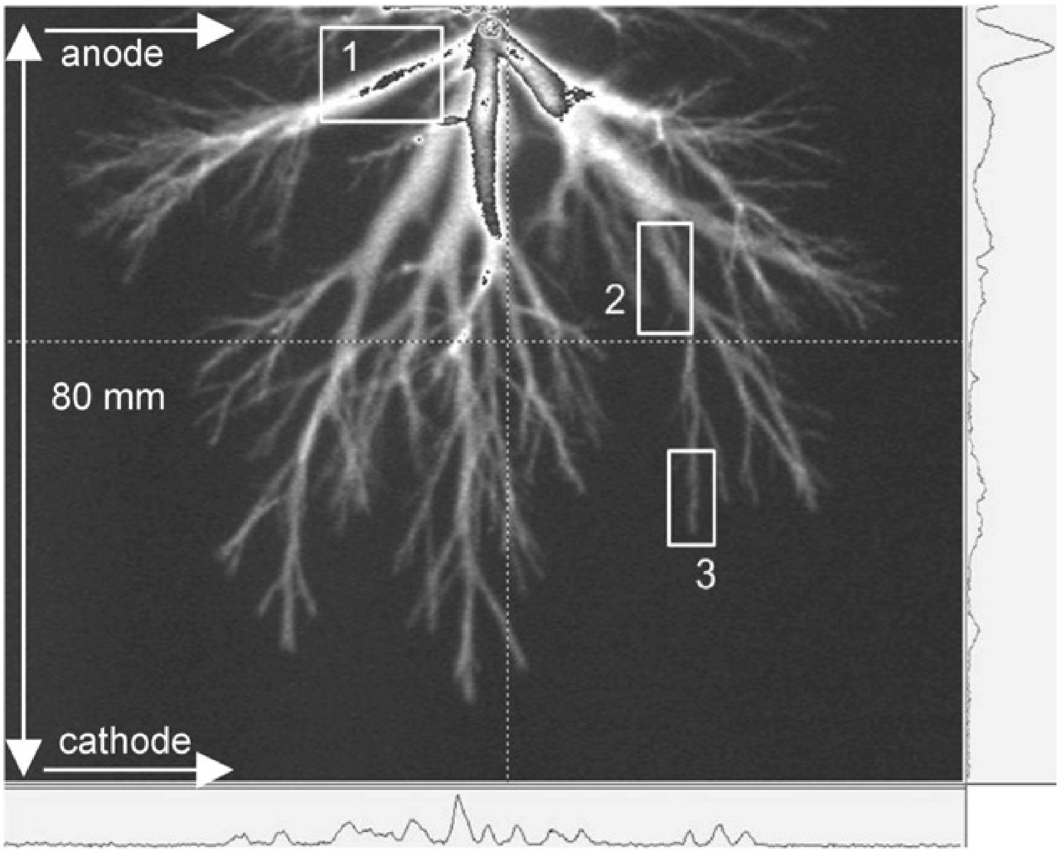
Telescopic Imaging of Sprites

- 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].

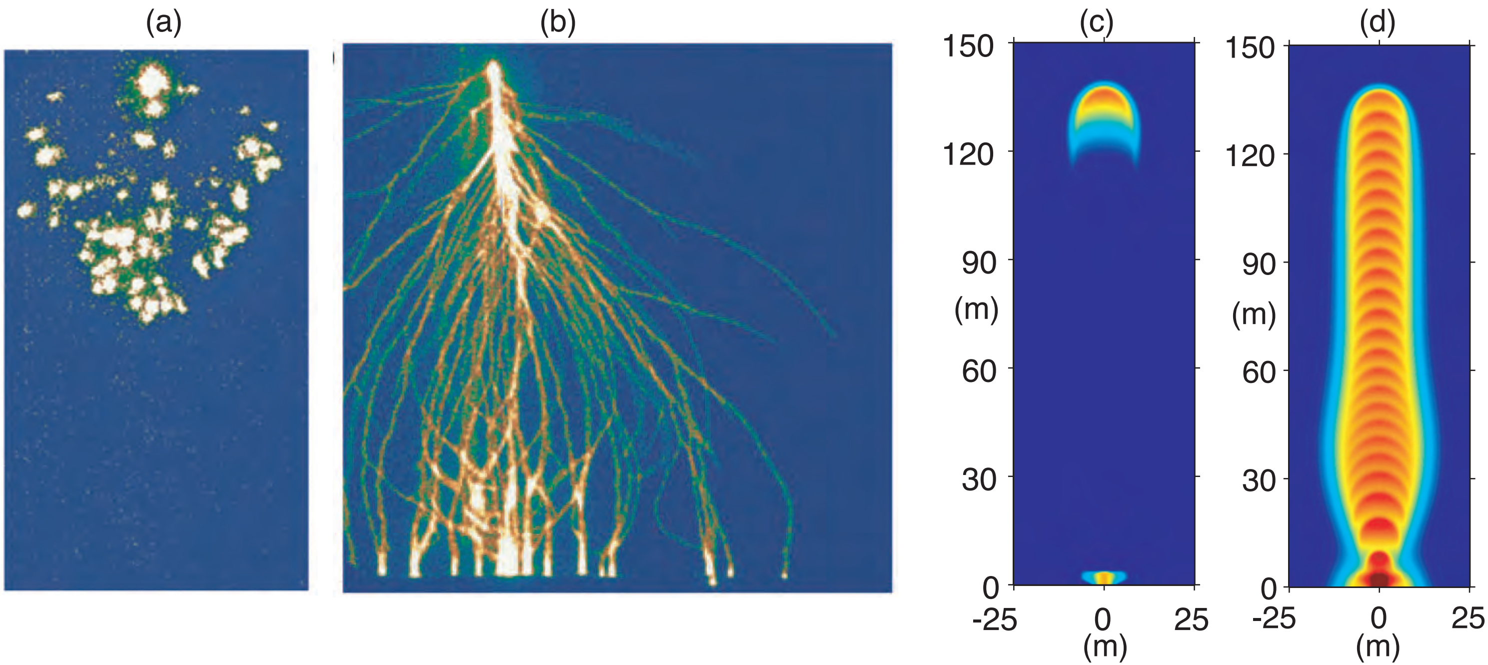
Recent Laboratory Experiments on Streamers



- Streamers in a 80 mm gap imaged with optical gate ∼80 ns [*Briels et al.*, 2006]

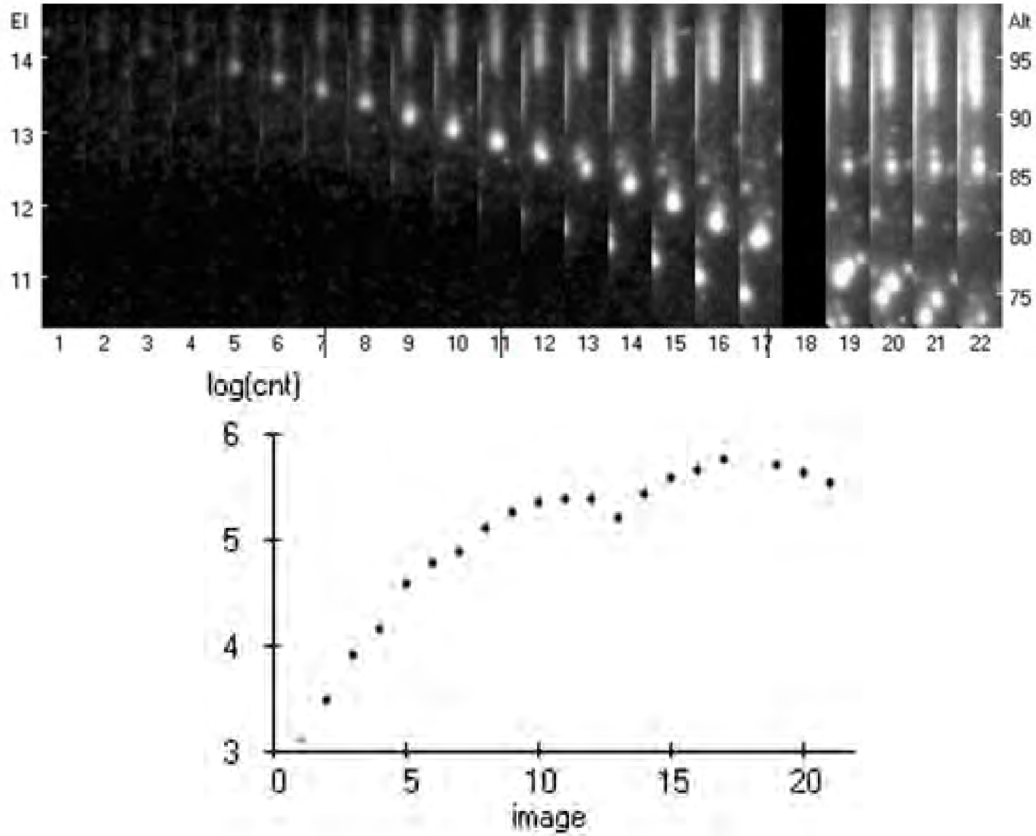
Illustration of Time-Integrated Effects

- CCD photos of streamers in a 25 mm point-wire gap at ground pressure in air using an optical gate of (a) 0.8 ns and (b) 5 μs [*van Veldhuizen and Rutgers*, 2002].
- Modeling results of $1PN_2$ streamer emissions at 70 km altitude at the moment of time 530 μs (c), and a series of moments of time between 0 μs and 530 μs (d) [*Liu and Pasko*, 2004].



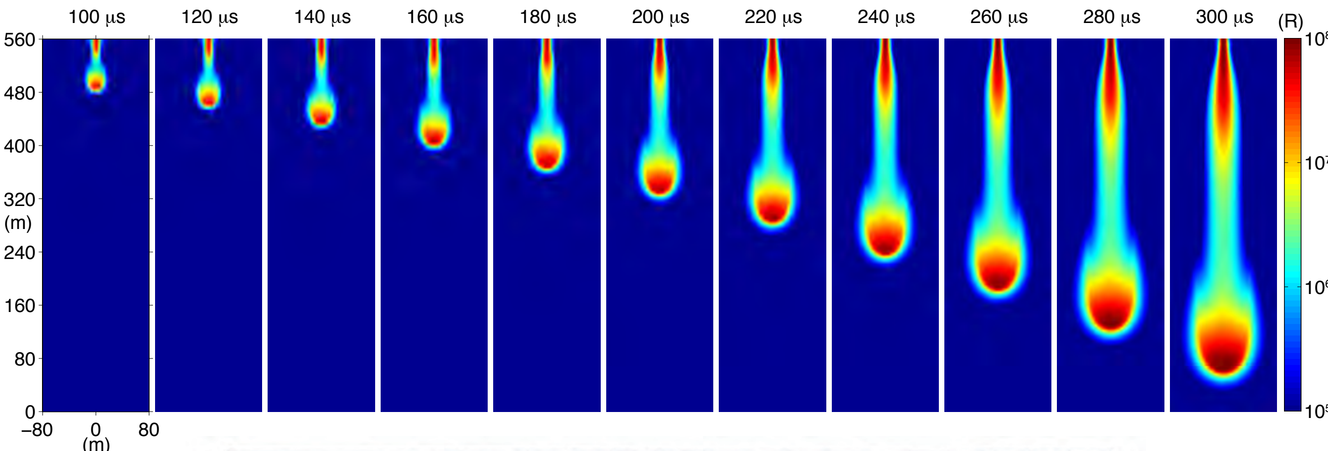
Positive Streamers in Sprites Are Initiated Before Negative Ones

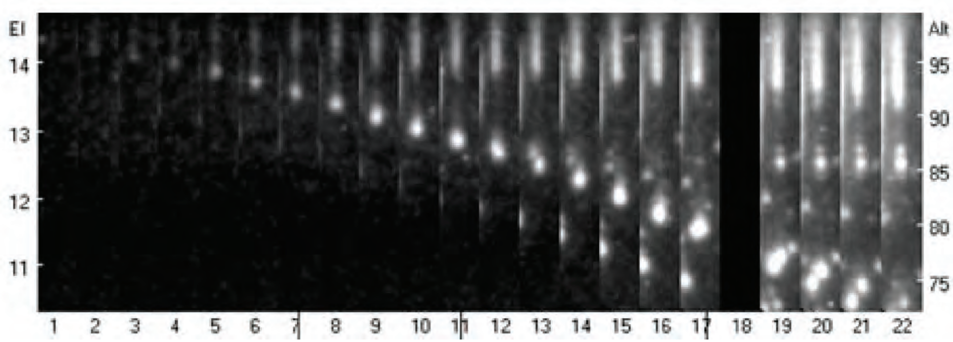
- Sprite images recorded at 10,000 fps with 50 μs exposure time [*McHarg et al.*, 2007; *Stenbaek-Nielsen et al.*, 2007]:



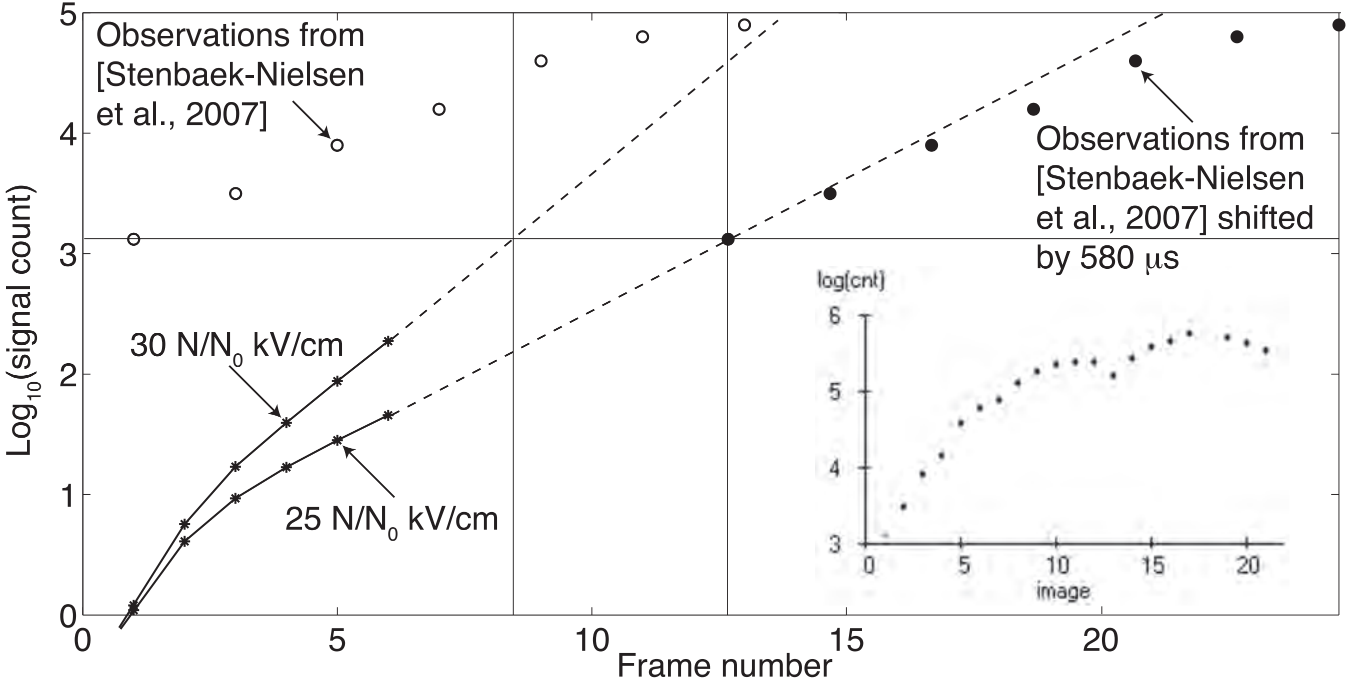
Acceleration of the Model Streamer [*Liu et al.*, 2009]

- A time sequence of the intensity distribution of $1PN_2$ for the downward propagating model positive streamer at 75 km altitude [*Liu et al.*, JGR, 114, A00E03, 2009].





Exponential Increase of the Brightness of a Streamer Head



- The model streamer corresponds to the initial stage of the observed streamer.
- The exponential growth rate depends on the external field, and its measurement can be used for remote sensing of electric fields driving sprites [*Liu et al.*, 2009].

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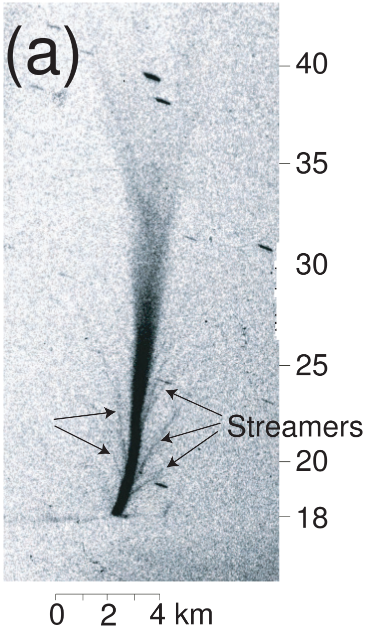
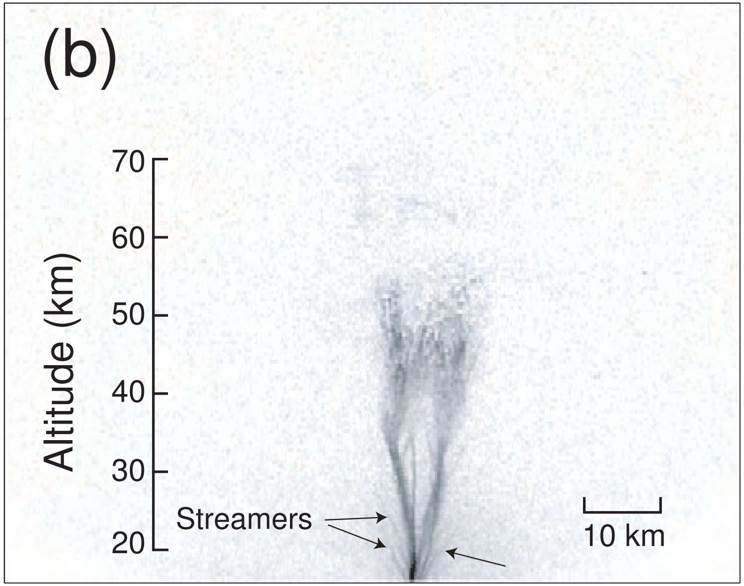
Physical Mechanism of Blue Jets and Gigantic Jets

- *Petrov and Petrova* [Tech. Phys., 44, 472, 1999] have suggested that blue jets correspond qualitatively to the development of the streamer zone of a positive leader and therefore should be filled with a branching structure of streamer channels.

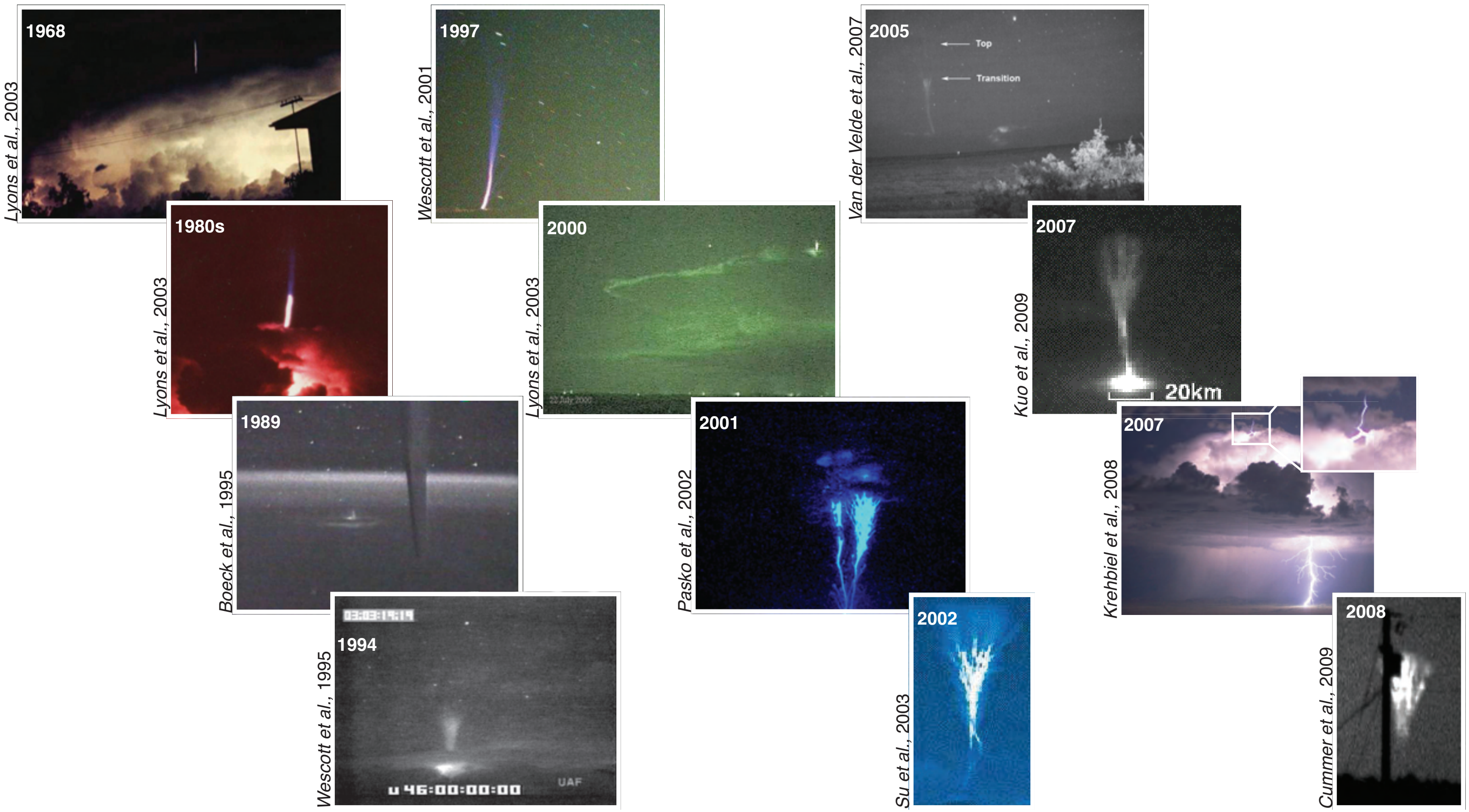


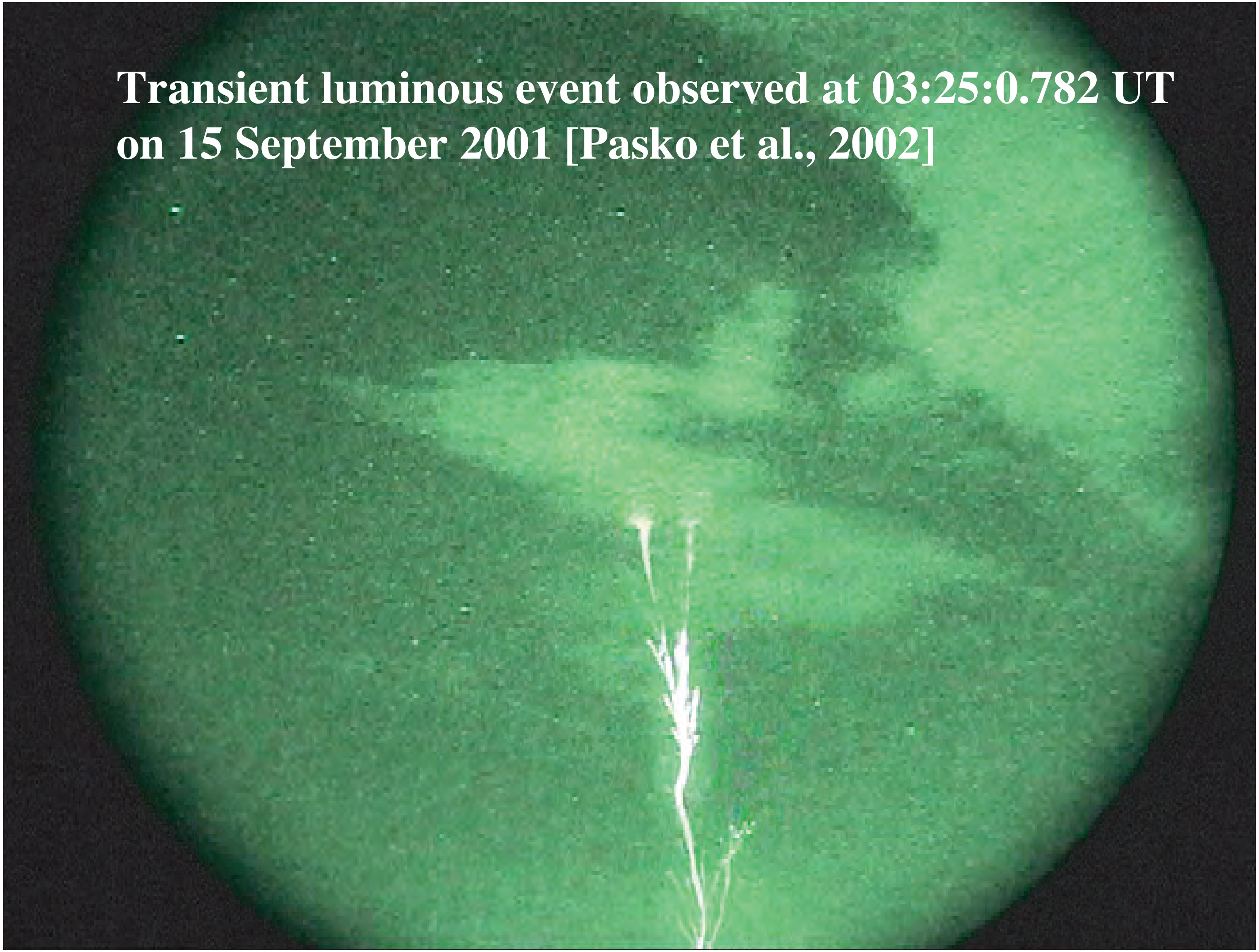
(a) A black and white image of a 2-min time exposure of a blue jet [Wescott et al., JGR, 106, 21549, 2001]

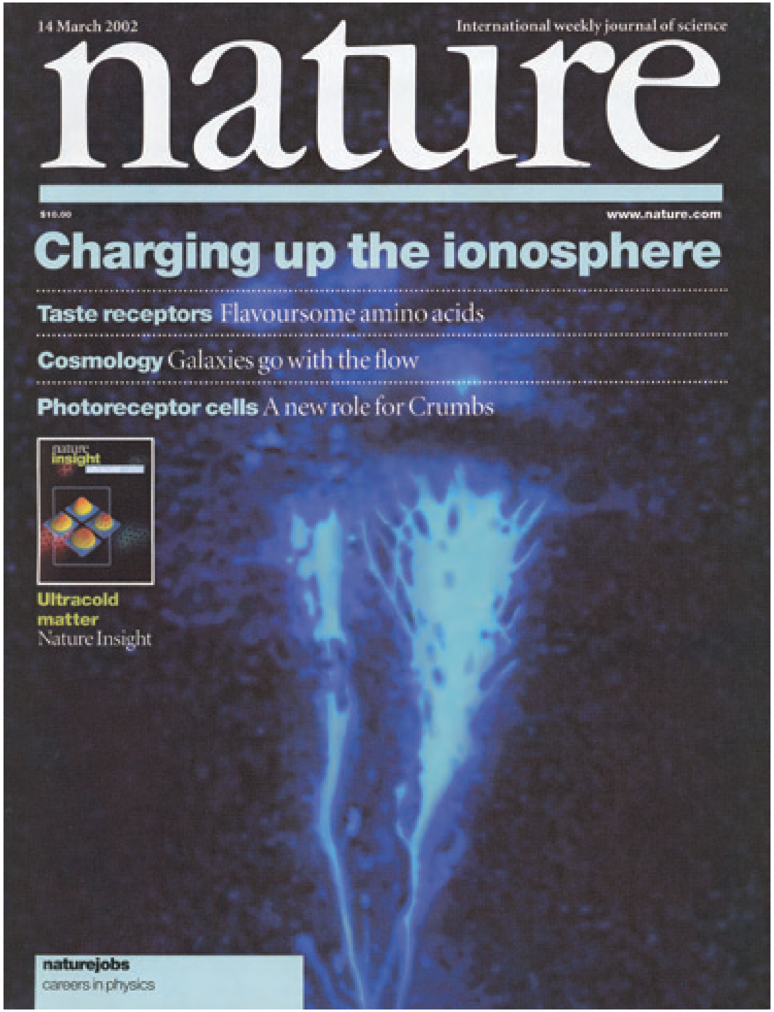


(b) Processed image obtained by averaging the sequence of video fields from [Pasko et al., Nature, 416, 152, 2002; http://pasko.ee.psu.edu/Nature/].

Phenomenology of Blue Jets and Gigantic Jets




Transient luminous event observed at 03:25:0.782 UT
on 15 September 2001 [Pasko et al., 2002]



Supplementary information is available at http://pasko.ee.psu.edu/Nature/

Upward Electrical Discharges From Thunderstorms

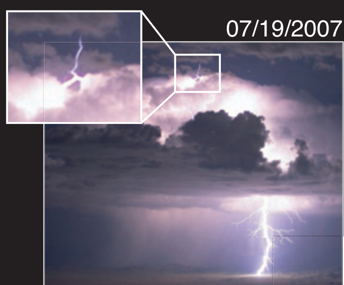
New Mexico Tech

PennState

Paul R. Krehbiel, Jeremy A. Riousset, Victor P. Pasko, Ronald J. Thomas, William Rison, Mark A. Stanley & Harald E. Edens

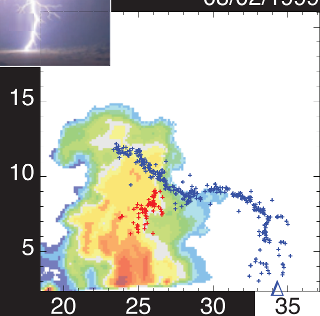
Nature Geoscience, Vol 1, No 4, April, 2008

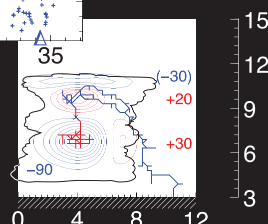
07/19/2007



H. E. Edens

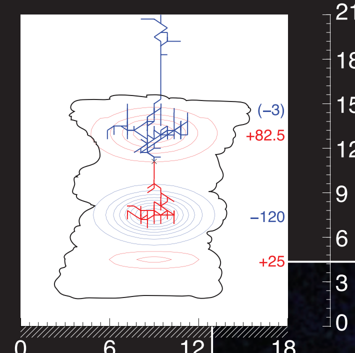
08/02/1999



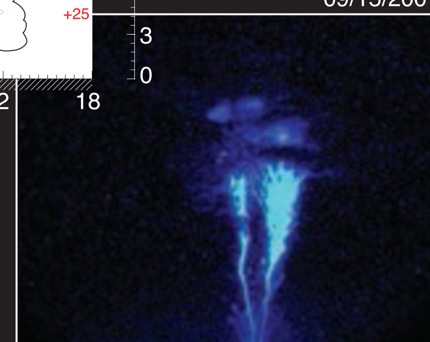


From Bolt-from-the-Blue...

... to Gigantic Jet



09/15/2001



Pasko et al., Nature, 416, 152, 2002

Upward Electrical Discharges From Thunderstorms

New Mexico Tech
PennState

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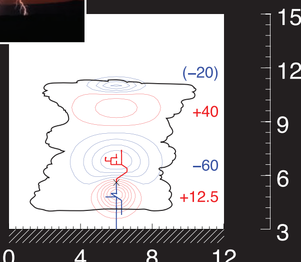
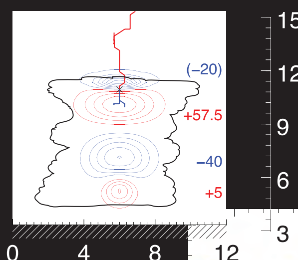
Nature Geoscience, Vol 1, No 4, April, 2008

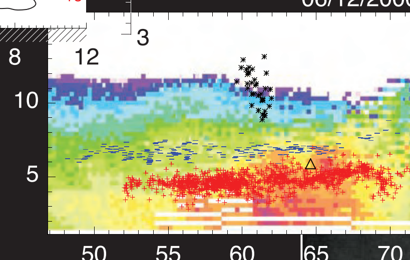
… to Upward Blue Jet

H. E. Edens

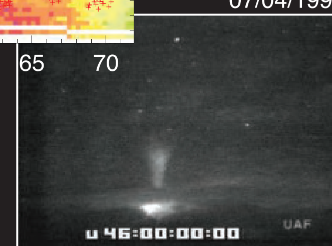




06/12/2000



07/04/1994



Wescott et al., GRL, 22(10), 1209, 1995

From Downward Cloud-to-Ground Lightning…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geoscience
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Bacterial metal acquisition
YOUNGER DRYAS
Radiocarbon reconstruction
MEDITERRANEAN EARTHQUAKES
Recurrence on a hidden fault
Lightning revealed

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Chapman Conference on the Effects of Thunderstorms and Lightning in the Upper Atmosphere

Penn State University, State College, PA, USA
May 10–14, 2009

Image Courtesy of Hans Stenbaek-Nielsen

Topics:

- Observations of Transient Luminous Events
- Theory of Transient Luminous Events
- ELF/VLF Effects of Lightning and Transient Luminous Events
- Energetic Radiation from Lightning and Terrestrial Gamma Ray Flashes

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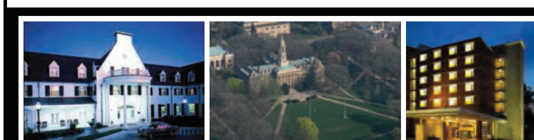

Conveners:

Davis Sentman,
Univ. Alaska, Fairbanks, USA
Victor Pasko,
Penn State Univ., USA
Jeff Morrill,
NRL, USA

Chapman Conference Facts

- Total number of participants: 110
- Total number of students: 30
- Total number of participants receiving financial support: 41
- Total number of represented countries: 16 (Brazil, Canada, Denmark, France, Fiji, Greece, Israel, Italy, Japan, the Netherlands, Norway, Russia, Spain, Taiwan, United Kingdom and United States)

JGR-Space Special Section - 58 Papers Accepted (by June 10, 2010)

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Effects of Thunderstorms and Lightning in the Upper Atmosphere

Journal of Geophysical Research, vol. 114, no. , 2009

Journal of Geophysical Research, vol. 115, no. , 2010

Guest Editor(s): D. Sentman

Description: This Special Section of the Journal of Geophysical Research, Space Physics, includes papers presented at the AGU Chapman Conference "Effects of Thunderstorms and Lightning in the Upper Atmosphere" 10–14 May 2009 at Penn State University, as well as papers relevant to the subject of the conference recently published in JGR Space Physics. The Special Section covers topics across the full spectrum of disciplines relevant to the subject, ranging from the underlying meteorology of sprite-associated lightning, gas breakdown and discharge processes, electromagnetic effects, energetic processes, and photochemical, kinetic and transport mechanisms.

Babich, L. P., E. I. Bochkov, I. M. Kutsyk, and R. A. Roussel-Dupré
Localization of the source of terrestrial neutron bursts detected in thunderstorm atmosphere
J. Geophys. Res., 115, A00E28, doi:10.1029/2009JA014750
7 pages, 7 figures, 1 table
22 May 2010 [Abstract] [Full Article] [Print Version]

Carlson, B. E., N. G. Lehtinen, and U. S. Inan
Terrestrial gamma ray flash production by lightning current pulses
J. Geophys. Res., 114, A00E08, doi:10.1029/2009JA014531
6 pages, 1 figure, 2 tables
19 December 2009 [Abstract] [Full Article] [Print Version]

Carlson, B. E., N. G. Lehtinen, and U. S. Inan
Neutron production in terrestrial gamma ray flashes
J. Geophys. Res., 115, A00E19, doi:10.1029/2009JA014696
6 pages, 4 figures, 2 tables
21 April 2010 [Abstract] [Full Article] [Print Version]

Chang, S.-C., C. L. Kuo, L.-J. Lee, A. B. Chen, H.-T. Su, R.-R. Hsu, H. U. Frey, S. B. Mende, Y. Takahashi, and L. C. Lee
ISUAL far-ultraviolet events, elves, and lightning current
J. Geophys. Res., doi:10.1029/2009JA014861, in press.
[PDF] (accepted 3 March 2010)

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