On Physics of High Altitude Lightning

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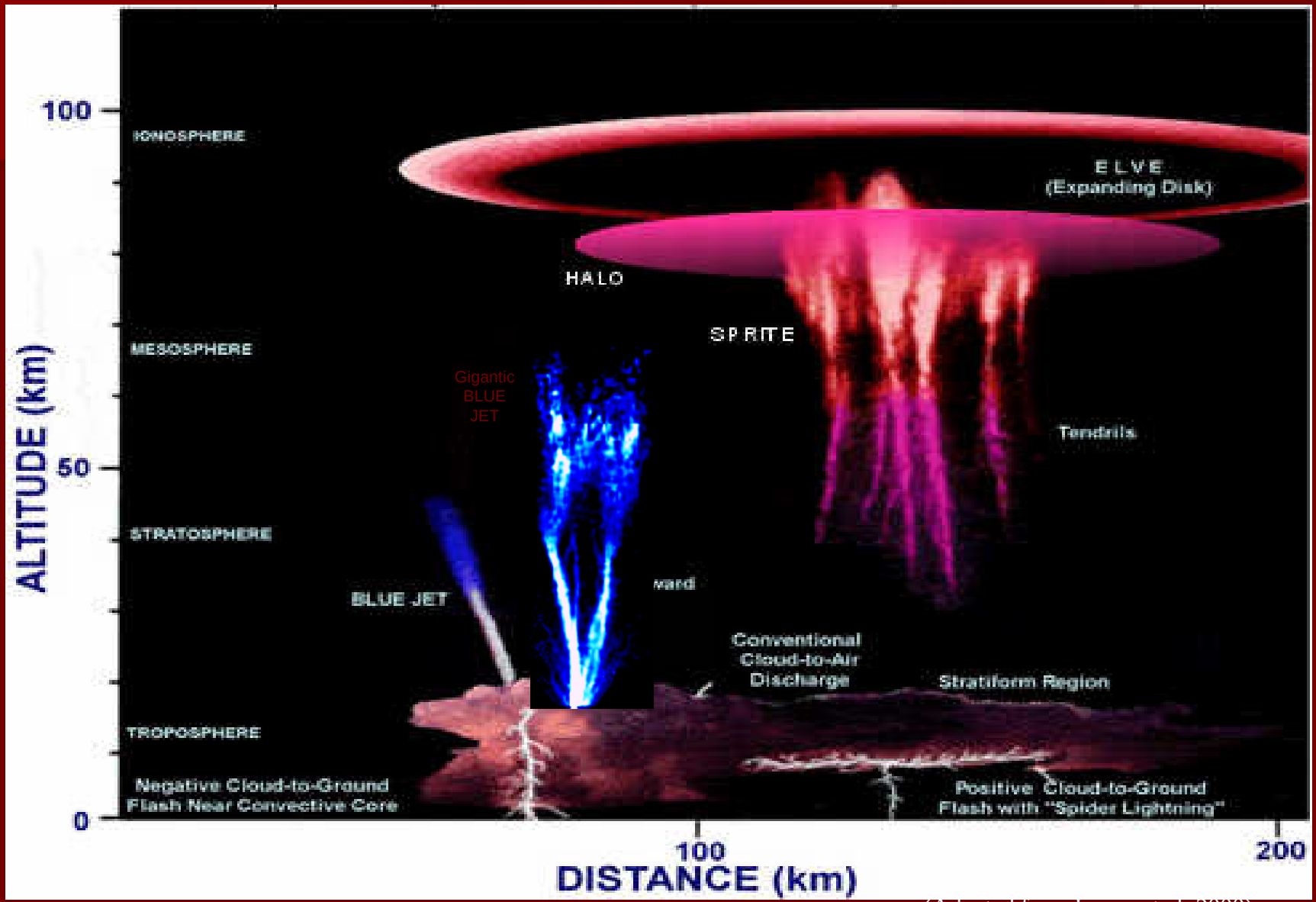
Outline

- Discovery of High Altitude Lightning
- Phenomenology of High Altitude Lightning
  - Red Sprites
  - Blue Jets
  - Elves
- Theoretical Models
  - Generation Mechanisms of Transient Luminous Events
  - Sprites optical spectrum
  - Streamer structure of sprites

Discovery of High Altitude Lightning

- The first recording of luminous phenomena above cloud tops was serendipitously obtained in 1989 by Franz et al. while testing a new long-light video system.
- Sentman and Wescott [1993] flue two jets above the top of a thundercloud. They recorded two phenomenon later termed as sprites and jets, and obtained their altitude.

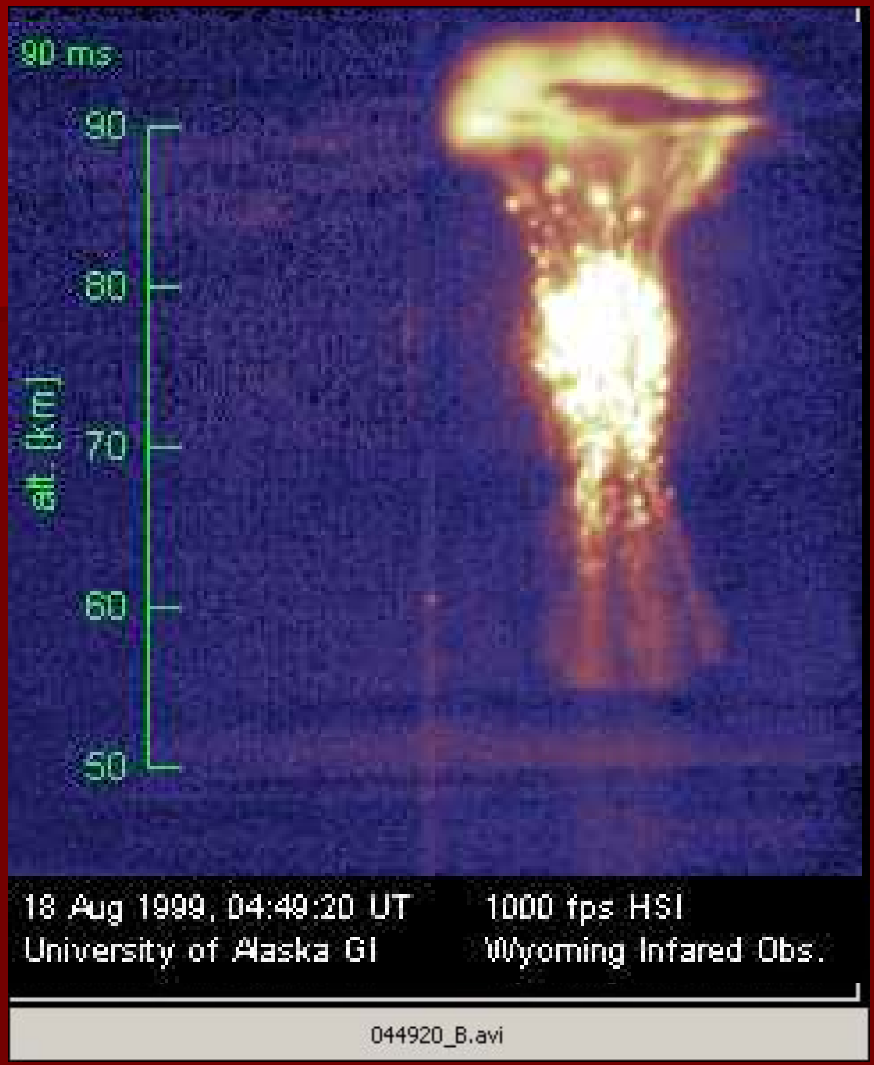
Forms of High Altitude Lightning (Transient Luminous Events)



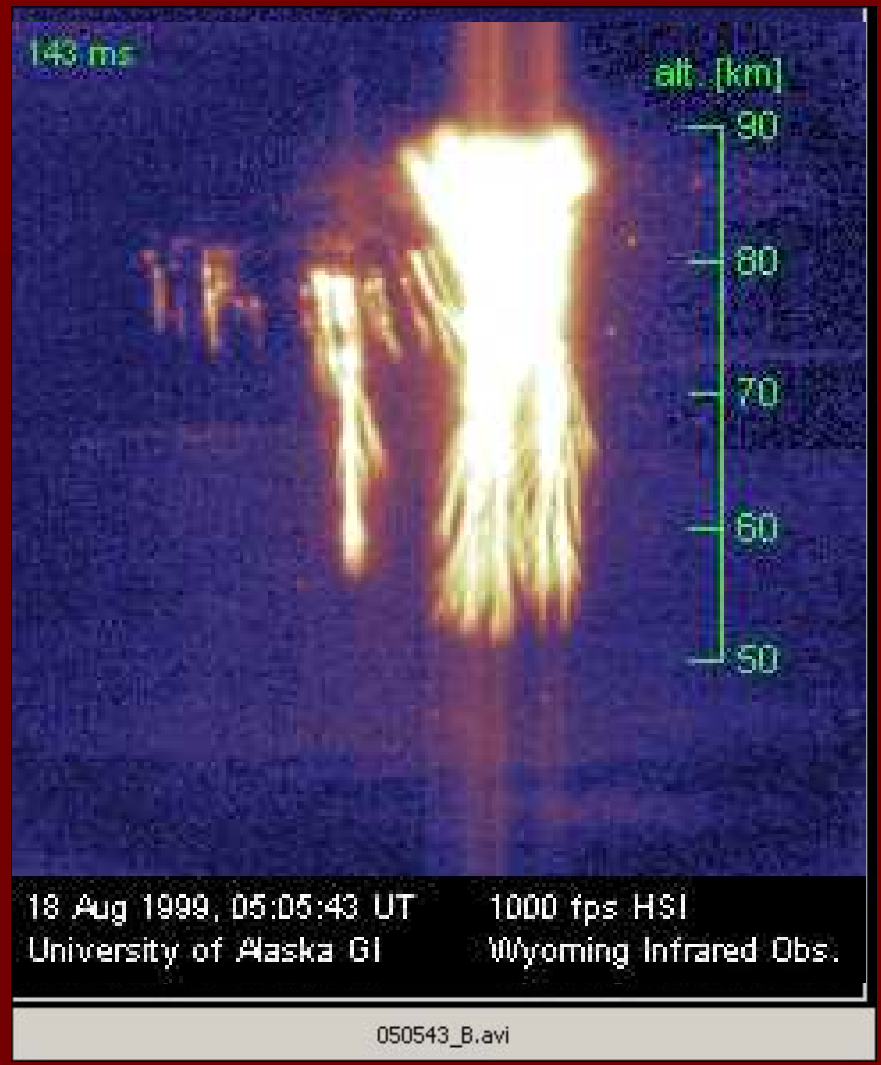
(Adapted from Lyons et al. 2000)

Images of Red Sprites

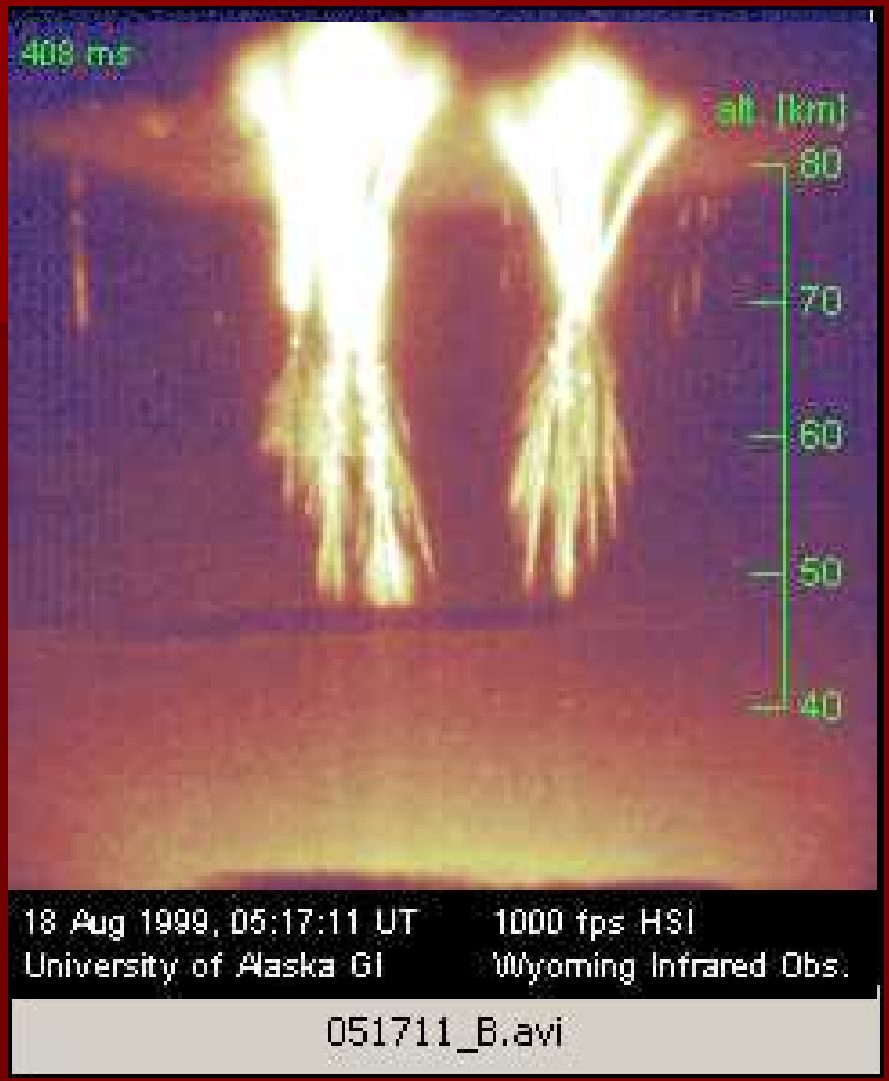
- The following three slides show selected frames from images of sprites obtained 08/18/99. The observations were made from the Wyoming Infrared Observatory on Jelm Mountain, WY. [Courtesy of Dave Sentman].



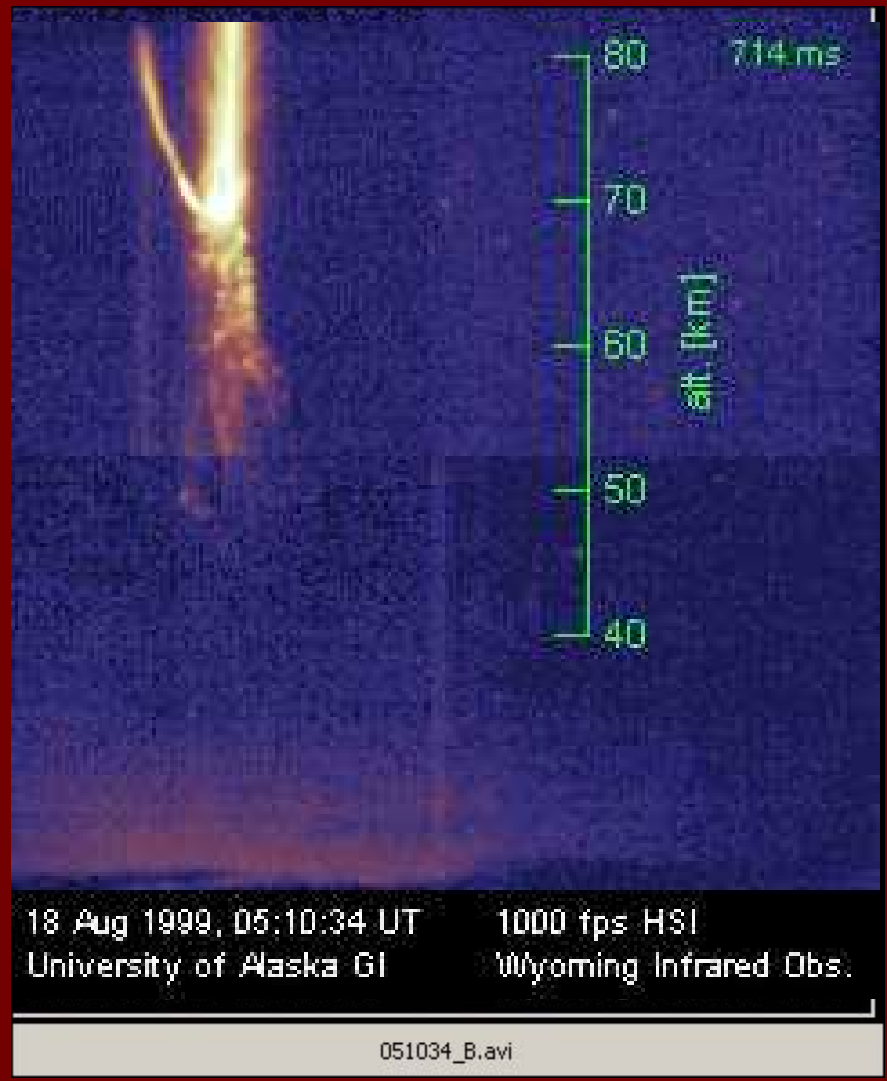
Halo followed by offset double sprites, weak downward “smoke” billows (false color) [Selected frame from video clip]



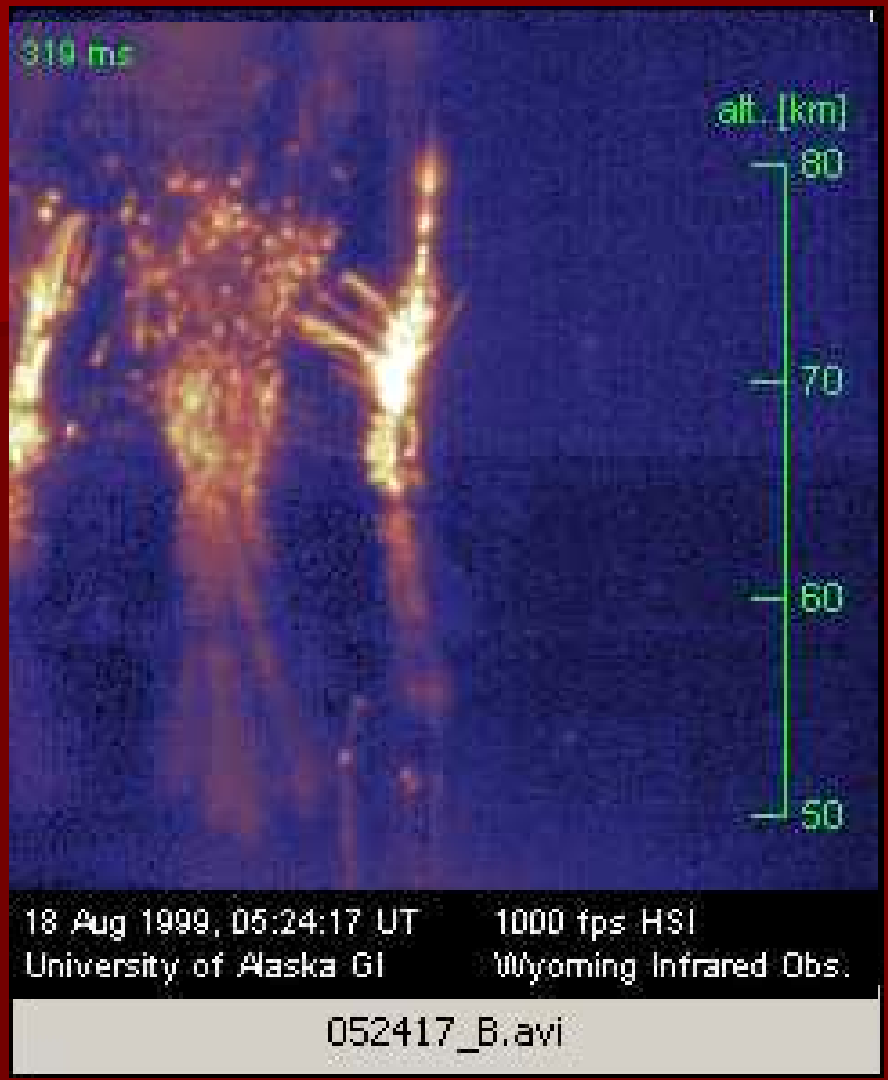
Halo, sprites, downward “smoke” billows (false color) [Selected frame from video clip]



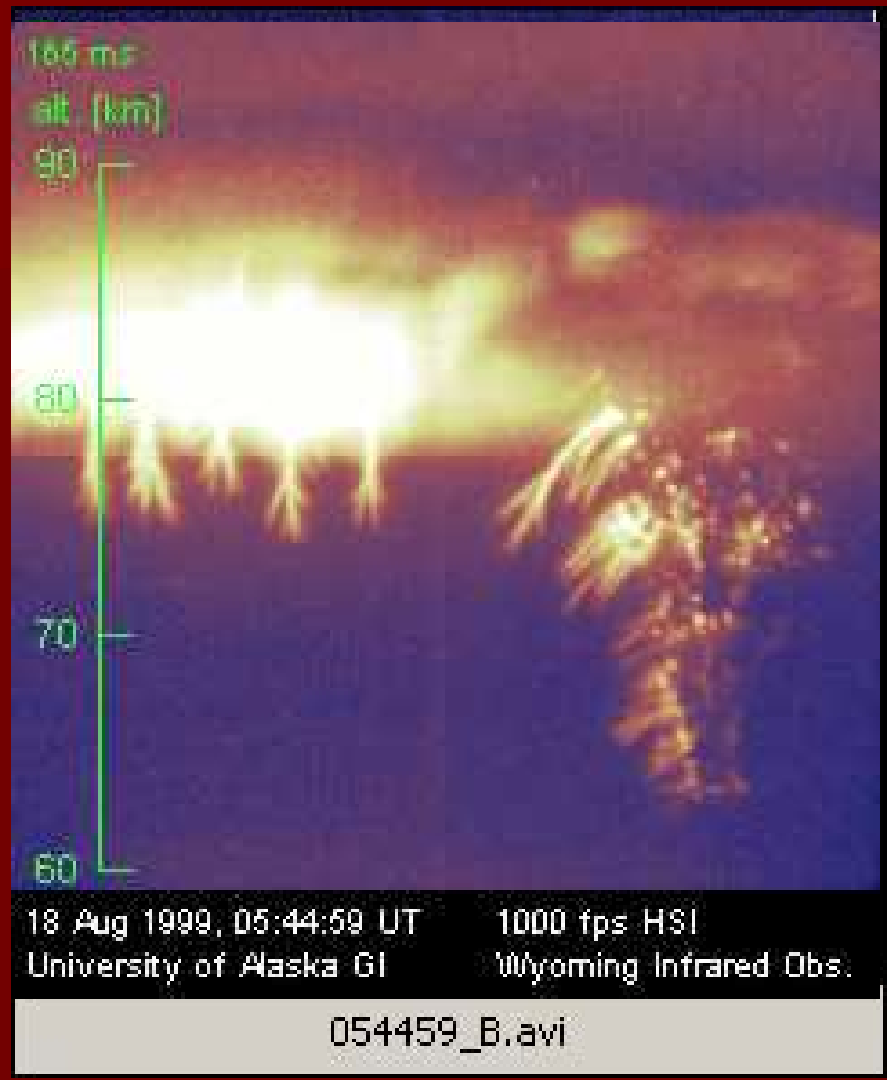
Sprites, persistent ascending “embers” in tendrils (false color) [Selected frame from video clip]



Sprites, ascending “embers,” second sprite and rebrightening, weak “smoke” billows (false color) [Selected frame from video clip]

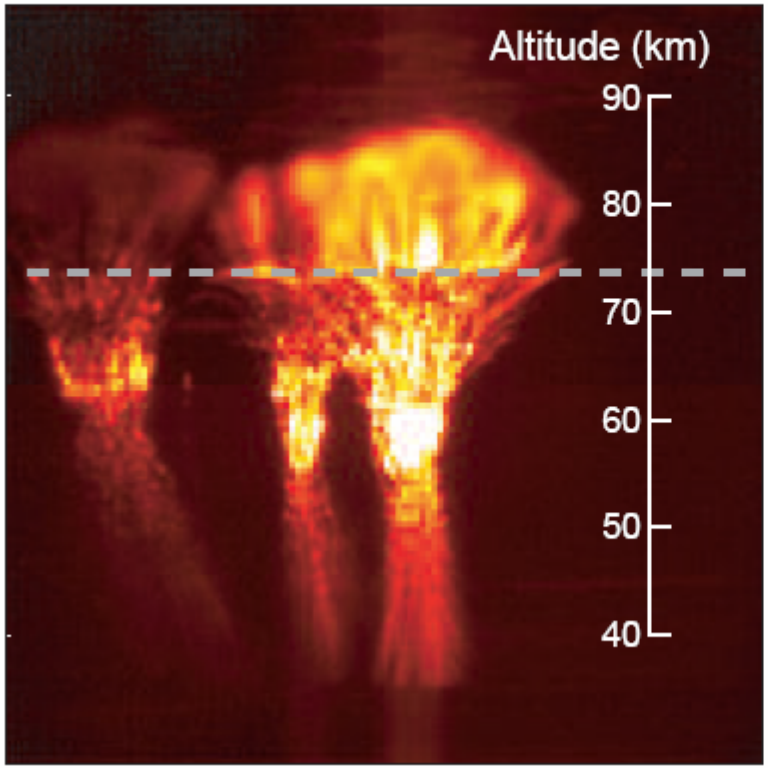


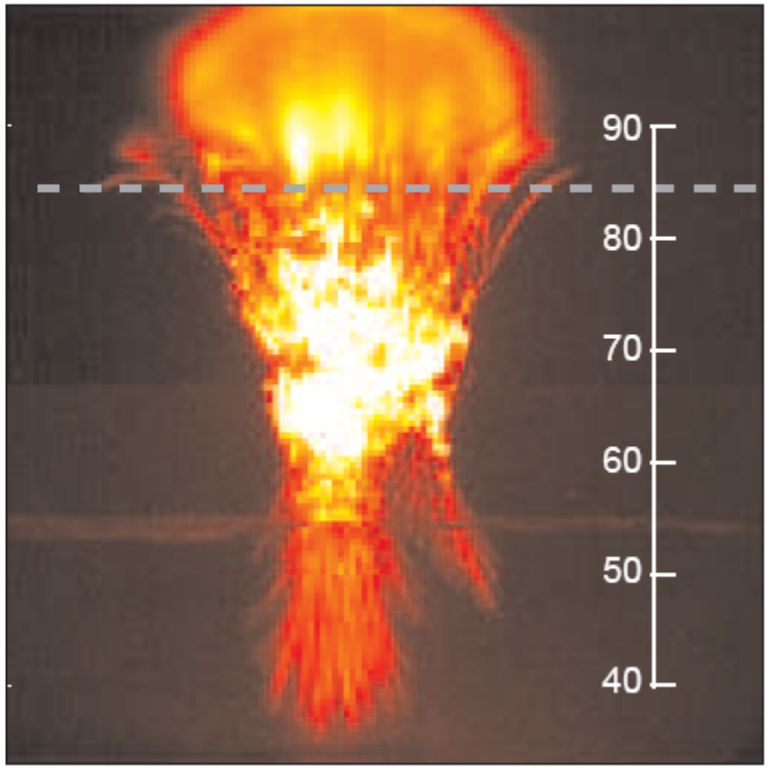
Complex sprite followed by “palm tree” ascending from below, sideways discharges, “smoke” billows (false color) [Selected frame from video clip]



Fast downward precursor streamer preceding sprite, second upward precursor (false color) [Selected frame from video clip]

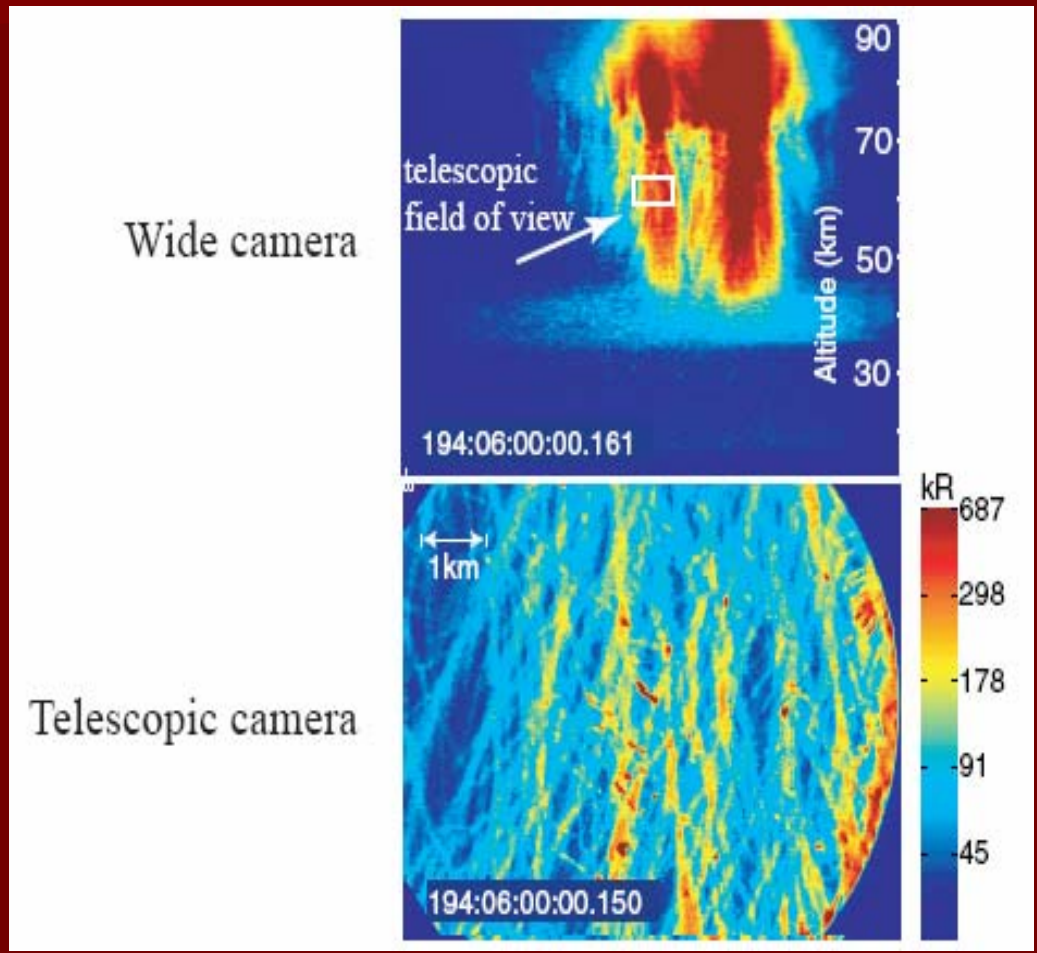
- The images illustrating the altitude transition between diffuse and streamer regions in sprites [*Stenbaek-Nielsen et al.*, GRL, 27, 3827, 2000]:





Fine structure of sprites

Observations made by Elizabeth Gerken by using an optical telescopic camera [Gerken and Inan, GRL, 2000]



Characteristics of Sprites

1. Associated with large (~1000 C-km) cloud-to-ground lightning discharges that induce large scale electrical breakdown in the mesosphere across volumes that can exceed 10^4 km^3.

2. Vertical extent spans the full height of the mesosphere ~40-90 km.

3. Duration of events is typically a few ms.

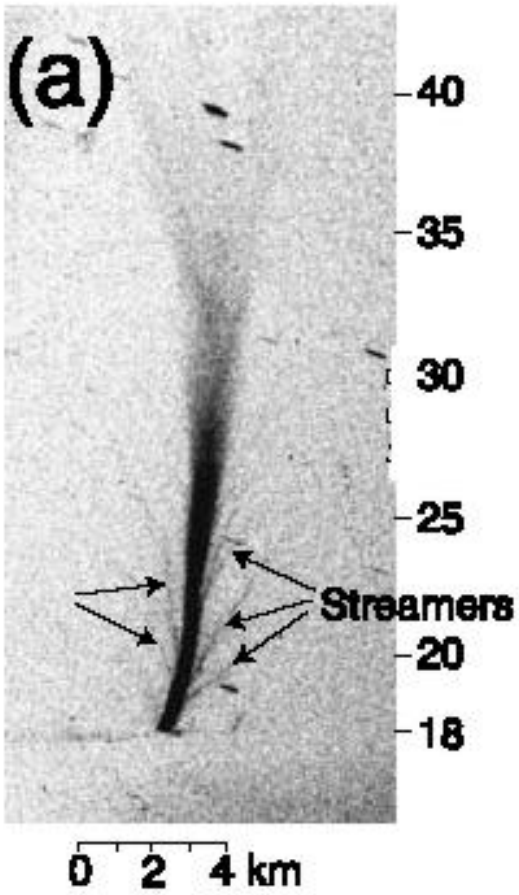
4. Optical emissions are primarily from $N_2(1P)$ and $N_2(2P)$ electronic states.

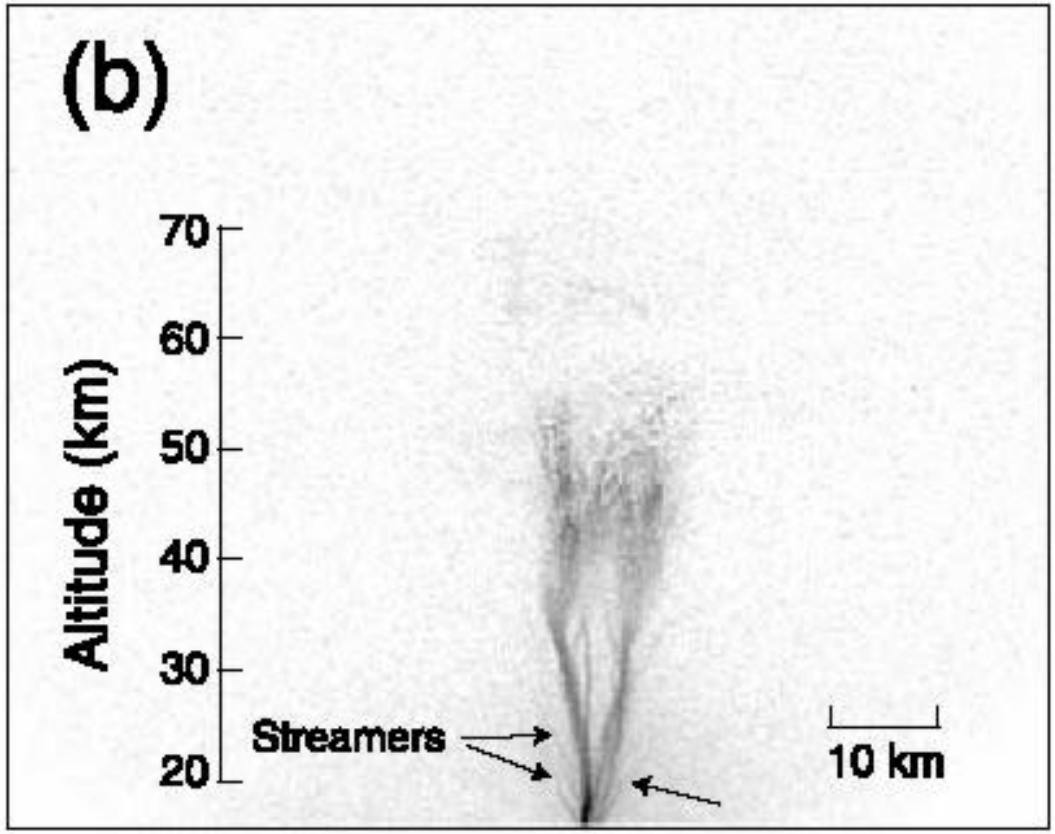
5. Internal currents are on the order of a few kA.

6. Total energy deposition in the mesosphere is ~1-10 MJ .

Images of a Blue Jet & Gigantic Jet

Blue Jets emanate from Cloud Tops





Wescott et al. 1999

Pasko et al. 2000

Characteristics of Blue Jets/Blue Starters

1. Emanate from the tops of the electrical core of thunderstorms as faint blue cones of light that propagate upwards at speeds of ~100 km/sec .

2. Termination altitude is ~50 km (jets), ~30 km (starters), several events reach to the ionosphere (gigantic jets).

3. Are not associated with cloud-to-ground lightning discharges.

3. Occur much less frequently than sprites, although sampling bias may play a role in this assessment since observations are more difficult.

Principal Types of Transient Luminous Events in the Upper Atmosphere Associated with Thunderstorms/Lightning

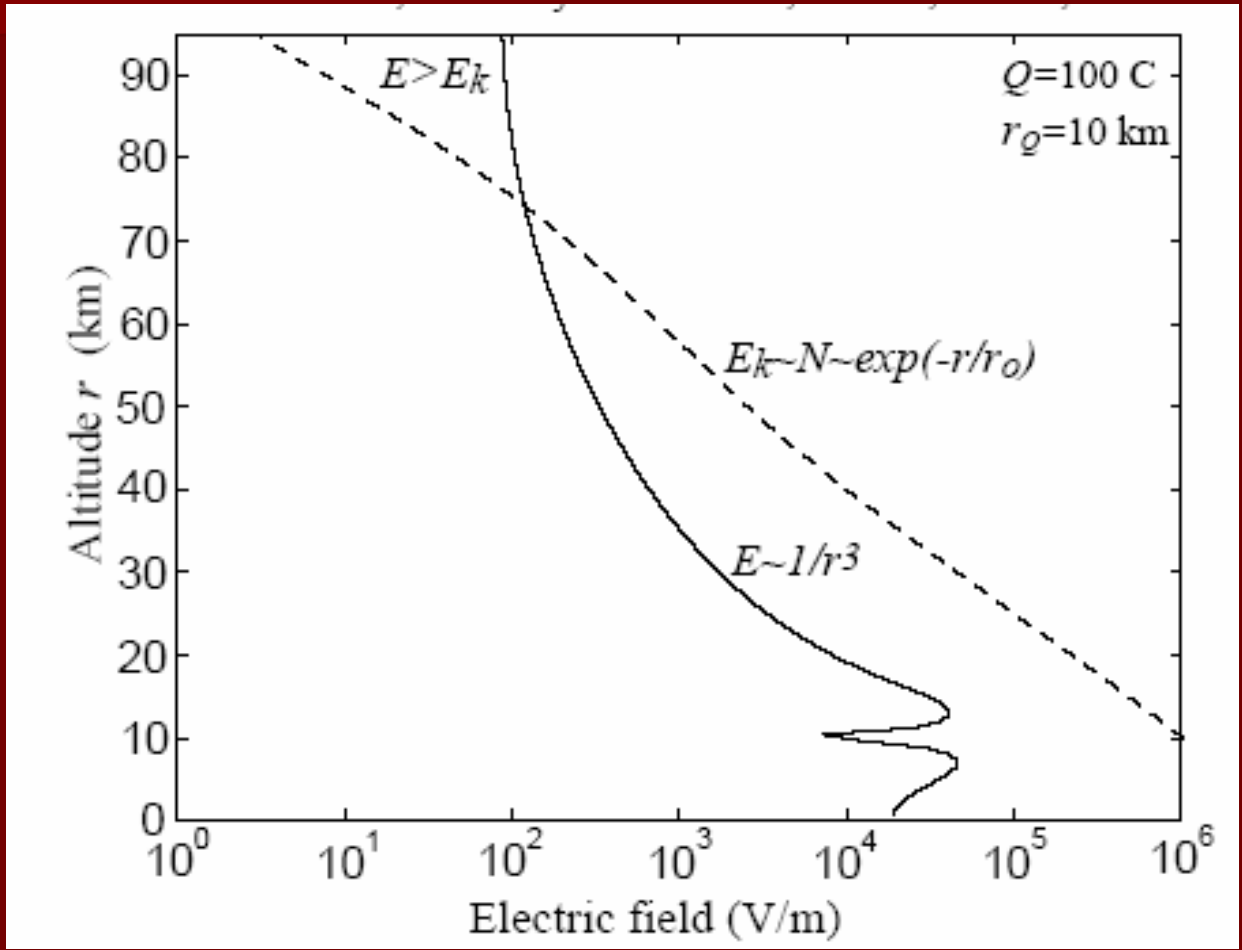
Type of TLE	Altitude Regime	Transverse Dimensions	Spatial Characteristics	Apparent Motion	Duration	Inventory of Observations (est.)
Sprites	~ 50-90 km	~1-20 km	Top (>80 km) diffuse Bottom (<70 km) structured	Top-upward Bottom-downward	few ms	>10,000
Elves	~ 100 km	> 100 km	Diffuse	Lateral Expansion	few ms	>10,000
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	>10,000
Trolls	~ 60-70 km	~ kms	Structured	Upward (Within decaying sprite tendrils)	100s ms	100s

Mechanisms of Generation of Transient Luminous Events

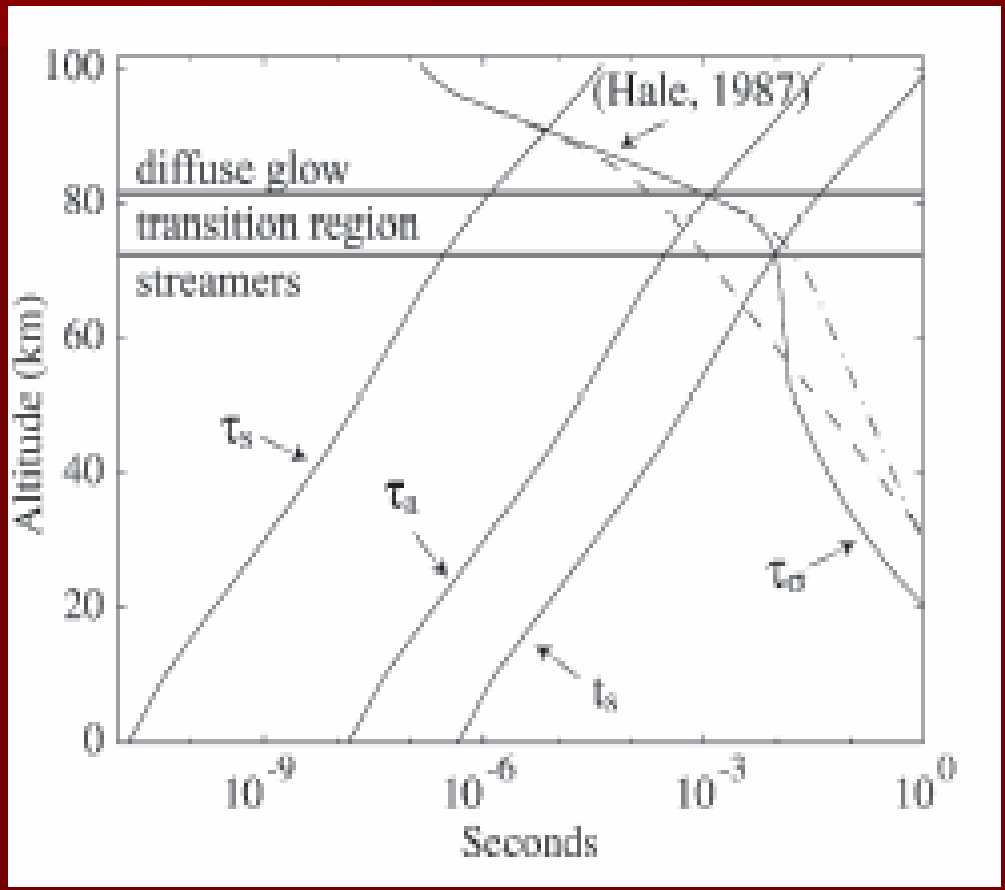
- Electrostatic fields caused by unbalanced charge following cloud-to-ground lightning (sprites)
- Transient radiation fields caused by CG lightning (elves)
- Transient radiation fields caused by intracloud lightning (sprites)
- Beam of runaway electrons caused by unbalanced charge following CG lightning (sprites)
- Streamer zone of a leader (jets)

Electrostatic Mechanisms of Sprite Generation

Electric field caused by a CG lightning leaving behind an unbalanced charged cloud [Pasko et al., 1996]

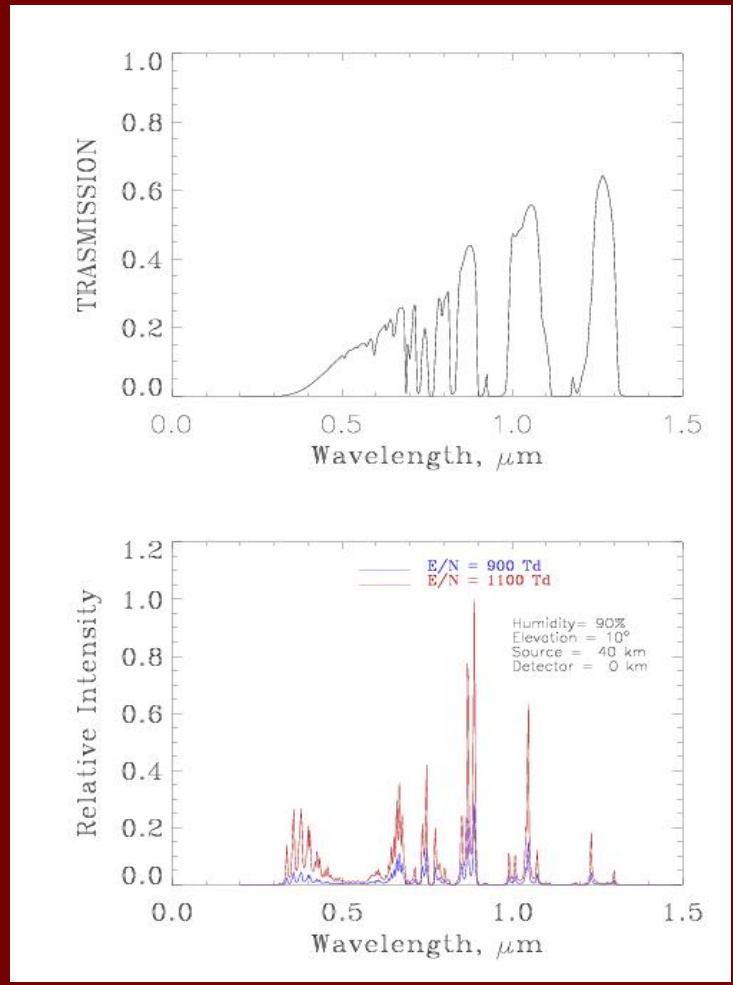


Timescales of related processes



Model of Sprite optical spectra

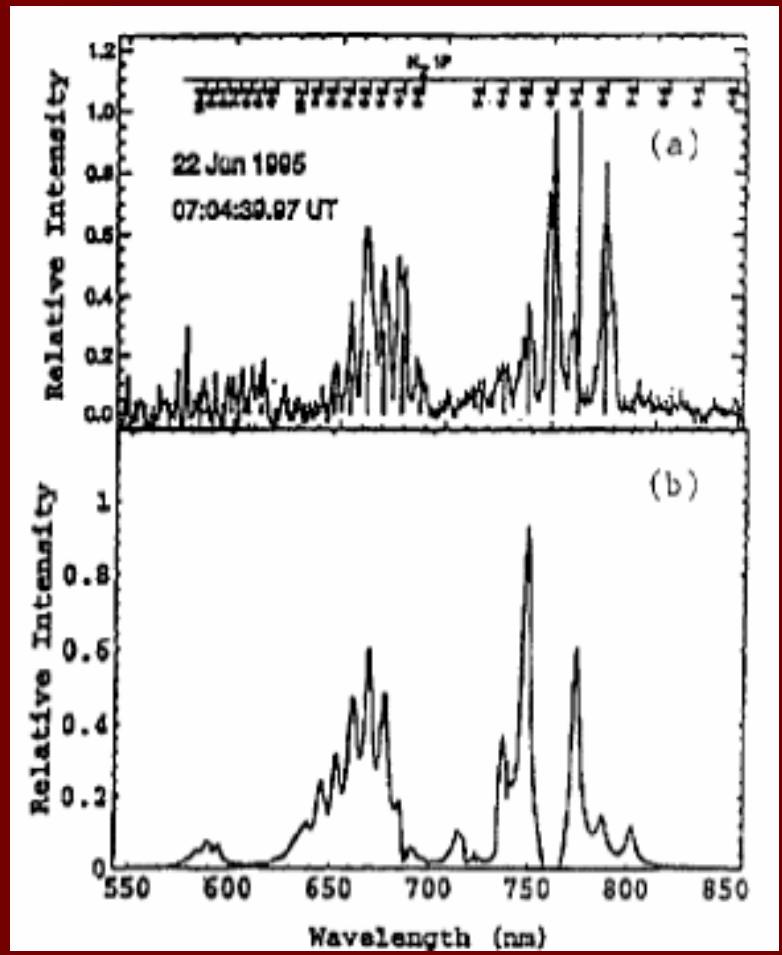
- For a given electric field amplitude E(z)
- Find the EDF by solving Boltzmann equation numerically
- Compute N_2 excitation rates versus E/N
- Compute the collisional quenching
- Compute the radiative intensity
- Find atmospheric transmission
- Obtain spectrum as observed by a ground- based detector.



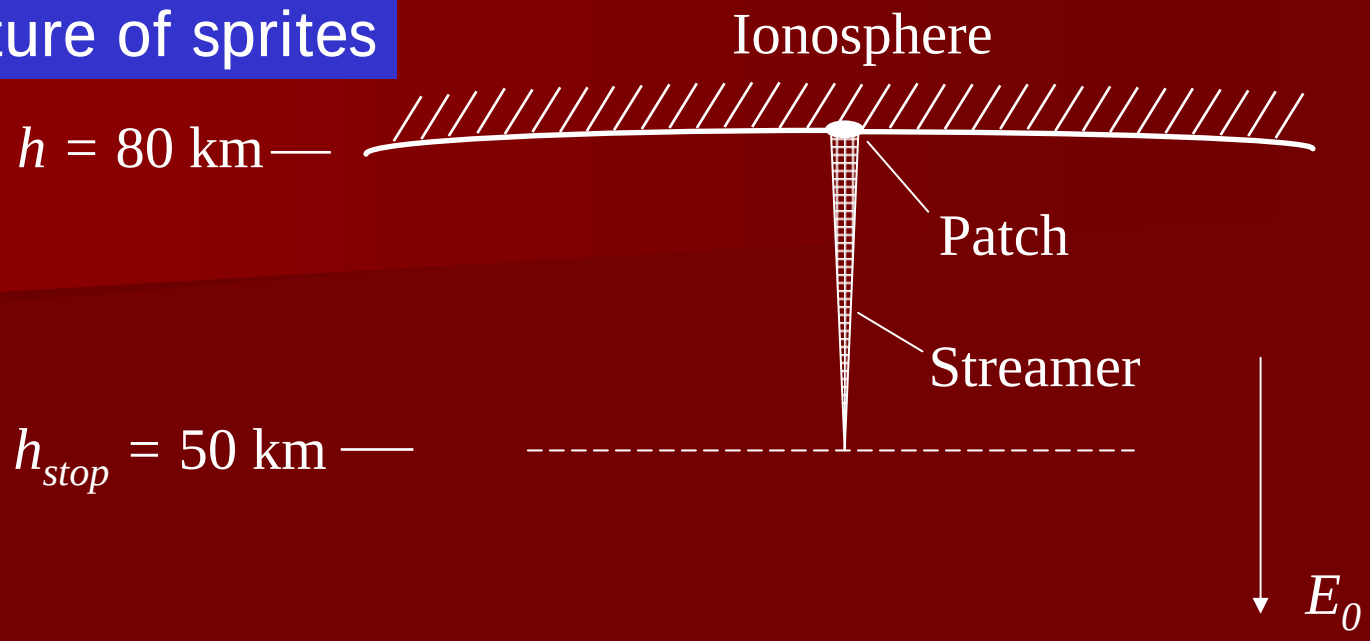
Spectrum of Red Sprites

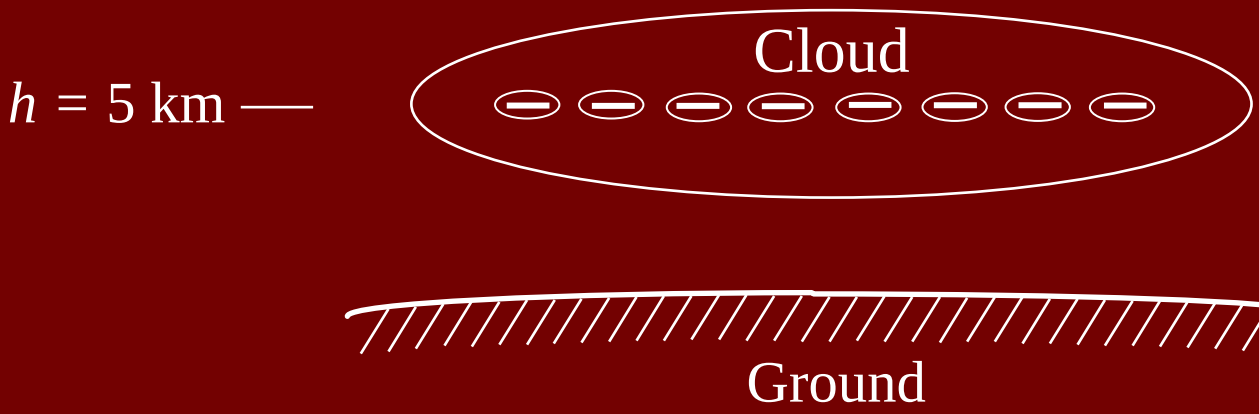
The top plate: the spectrum measured by Hampton et al [1996] at 4.3 km above the sea level at zenith angle of 80^{o}.

The bottom plate: the spectrum modeled by Milikh et al. [1998] under similar conditions.



Model of streamer structure of sprites





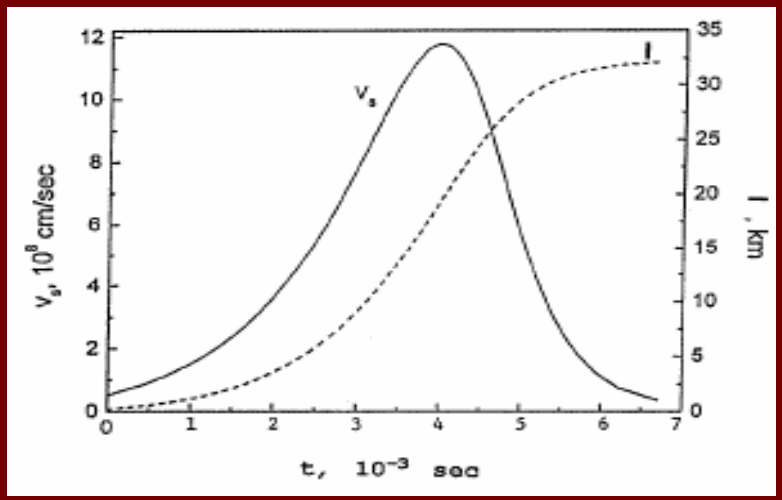
Streamer Triggering Conditions

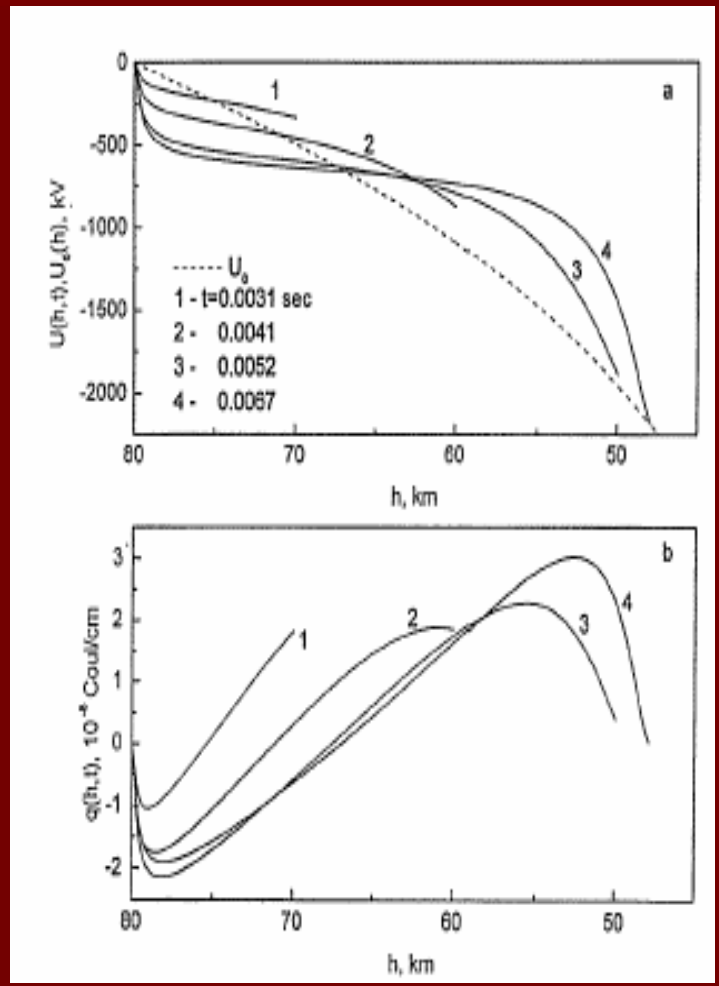
- Electric field exceeds the ionization threshold
- Plasma patches exist

  ($r>60m$, $n_e>150cm^{-3}$ at 80 km, and scale as $r\sim1/N$, $n_e\sim N^2$)
- Free ionospheric electrons start the ionization ahead of the streamer's front.

Streamer growth in the exponential atmosphere

- 1D numerical model of streamer growth [Raizer, Milikh, Shneider, 1998]





Instead of Conclusions

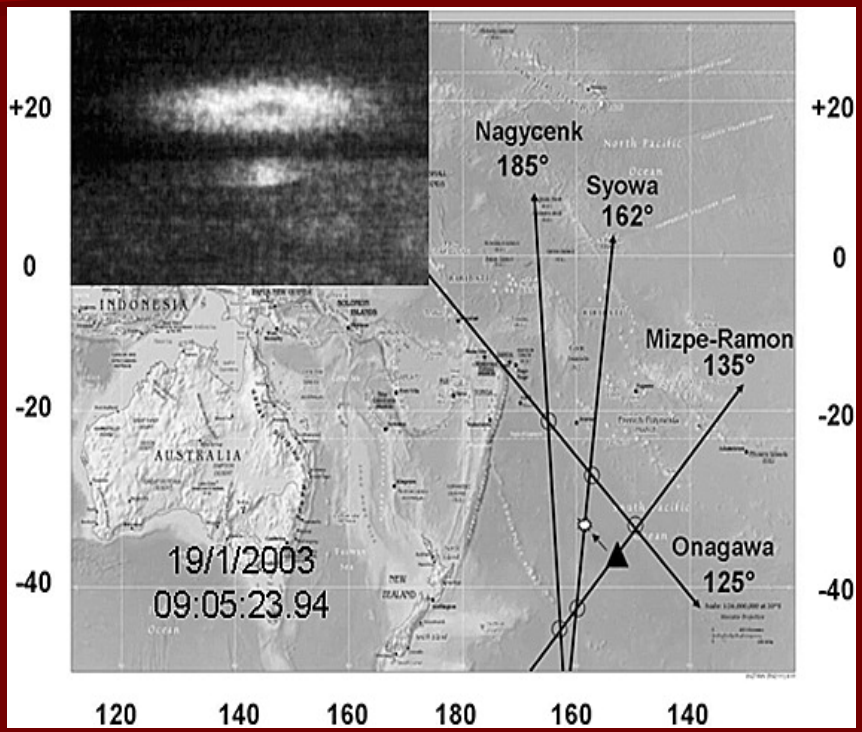
During the 2003 space flight of Shuttle Columbia astronaut Ilan Ramon agreed to look for sprites and elves.

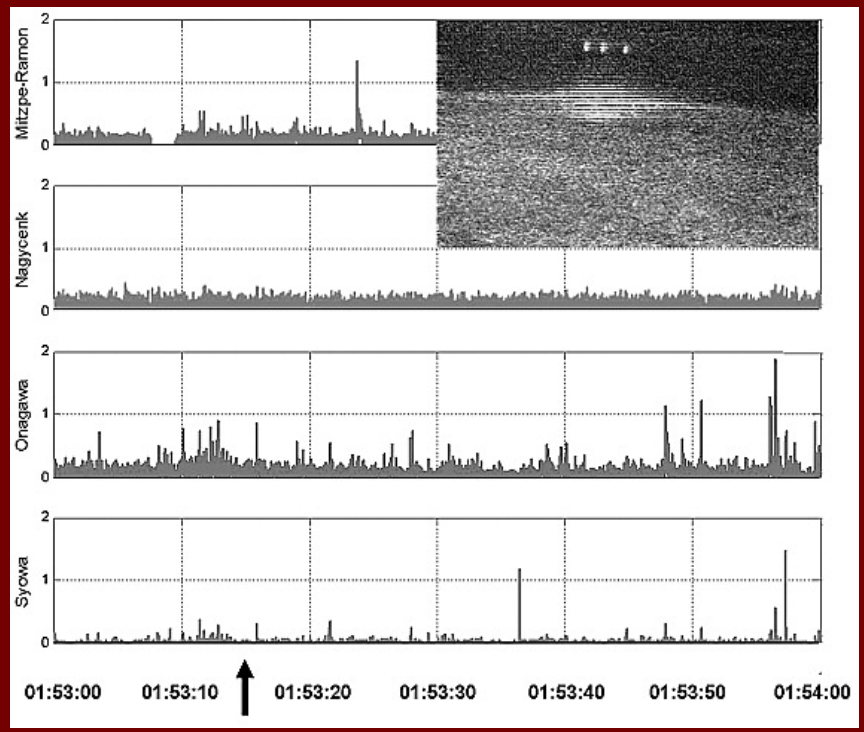
Soon the whole crew was involved in sprite hunting catching tens of events. It was 24 min of pre-assigned time for TLE observations, while 580 min were actually spent.

Simultaneously Israeli scientists detected locations of the parent lightning [Price et al. 2004].

Some of the images were send to the ground, some recorded on a device found in the Shuttle debris.

Observations made by the Space Shuttle Columbia in mission STS-107





Left plate, elve observed in the Pacific. Right plate, triple sprite observed over Africa.

You have seen the last message sent from the Shuttle Columbia to the rest of the humanity.

Symbolically it was an image of a sprite.

In a memory of the crew of the Shuttle Columbia.