

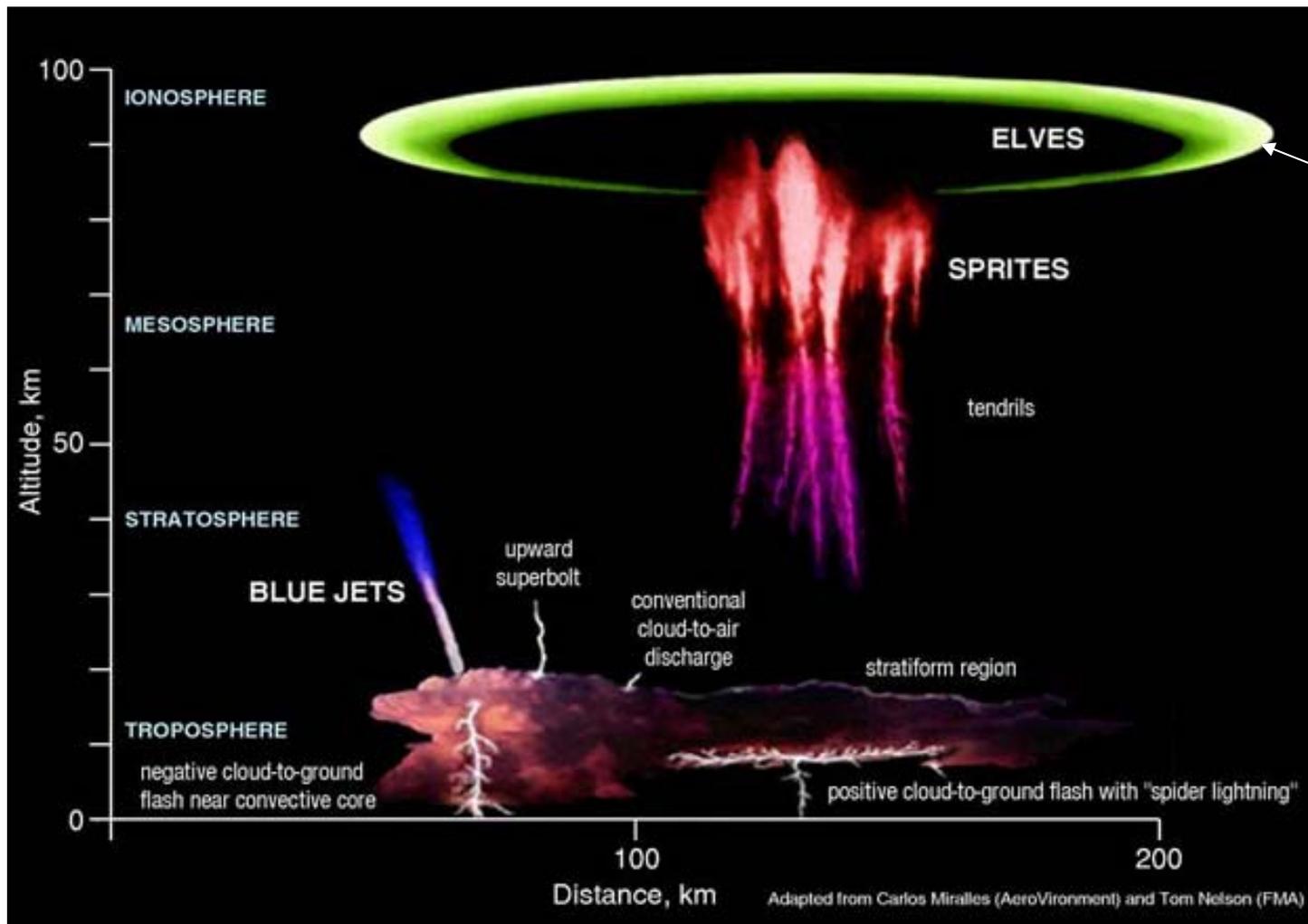


# **Молниевые электромагнитные эффекты в атмосфере: переходные световые явления (TLEs, Transient Luminous Events) и геоактивные гамма вспышки (TGFs, Terrestrial Gamma Flashes)**

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ННГУ им. Лобачевского, 5 октября 2010 г.  
(based on Nikolai G. Lehtinen, Robert Newsome and Brant E. Carlson's  
VLF Group Seminar given on August 3, 2010)**



# Переходные световые явления (TLE, Transient Luminous Events)



(not actually green)



# Two parts:

- I. QES (Quasi-ElectroStatic) field effects (эфффекты квази-электростатического поля)**
- II. EMP (ElectroMagnetic Pulse) effects (эфффекты электромагнитного импульса)**



# I. QES (Quasi-ElectroStatic) field effects

- **Development of a QES field above a thundersorm**
- **Red Sprites (Спрайты) and Halos**
- **Blue Jets (джеты) and Gigantic Jets**
- **QES theory of TGF (Terrestrial Gamma-Ray) production (one of several theories)**

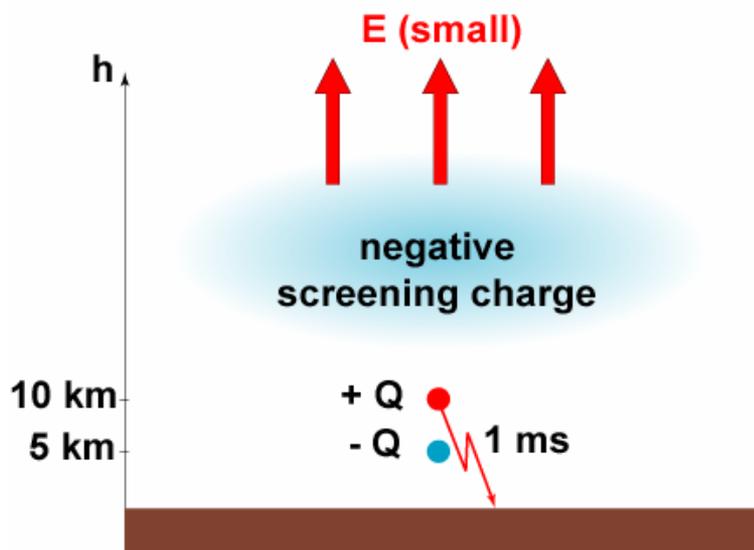


# Development of QES field above a thunderstorm

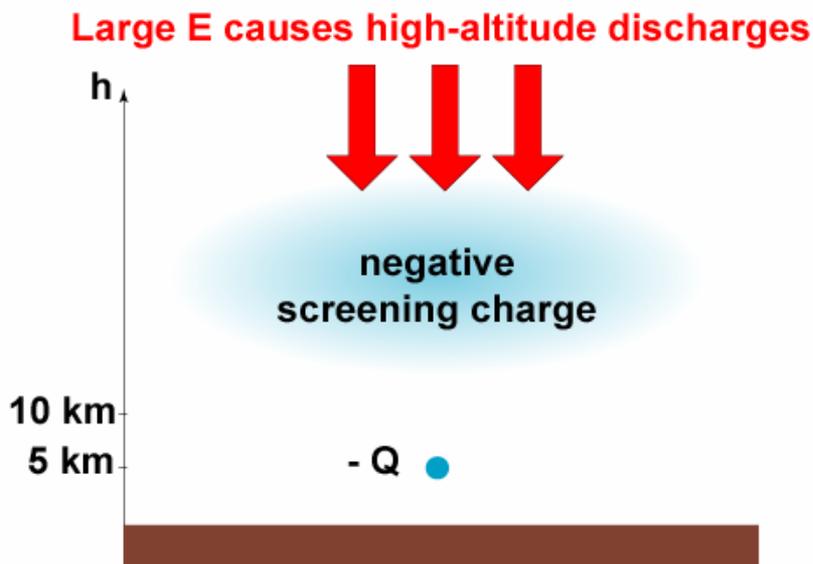


# QES (Quasi-ElectroStatic) field above a thundercloud

## BEFORE DISCHARGE



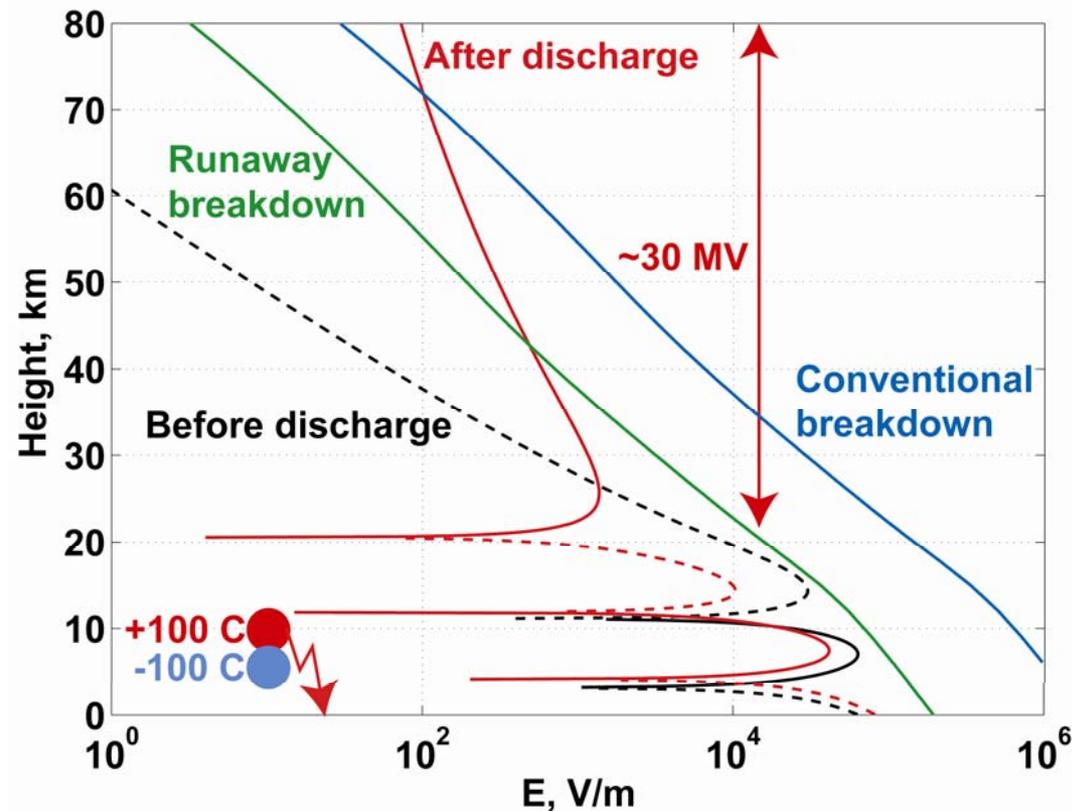
## AFTER DISCHARGE





# QES field exceeds breakdown thresholds

- The breakdown field values in “townsends” (1Td is defined as  $E/N=10^{-21} \text{ V m}^2$ ):
  - $E^+ = 18 \text{ Td}$  (positive streamers)
  - $E^- = 50 \text{ Td}$  (negative streamers)
  - $E_k = 80 \text{ Td}$  (conventional breakdown)
  - $E_t = 8 \text{ Td}$  (relativistic runaway breakdown)



There is an analytical formula for the QES potential for an exponential conductivity profile  $\sim \exp(z/H)$ :

$$\Phi_{\text{disch}} = \frac{Q}{4\pi\epsilon_0} \frac{\exp[-(r+z)/2H] - 1}{r}$$

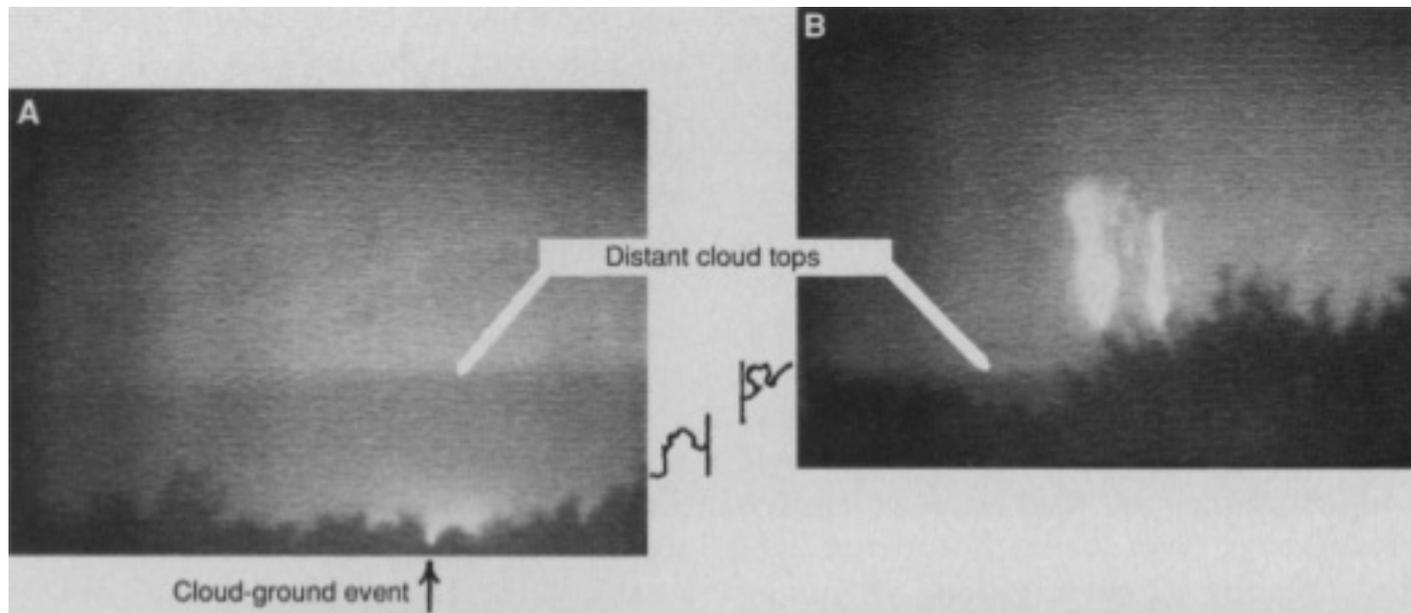


# Red Sprites and Halos



# Discovery of Red Sprites

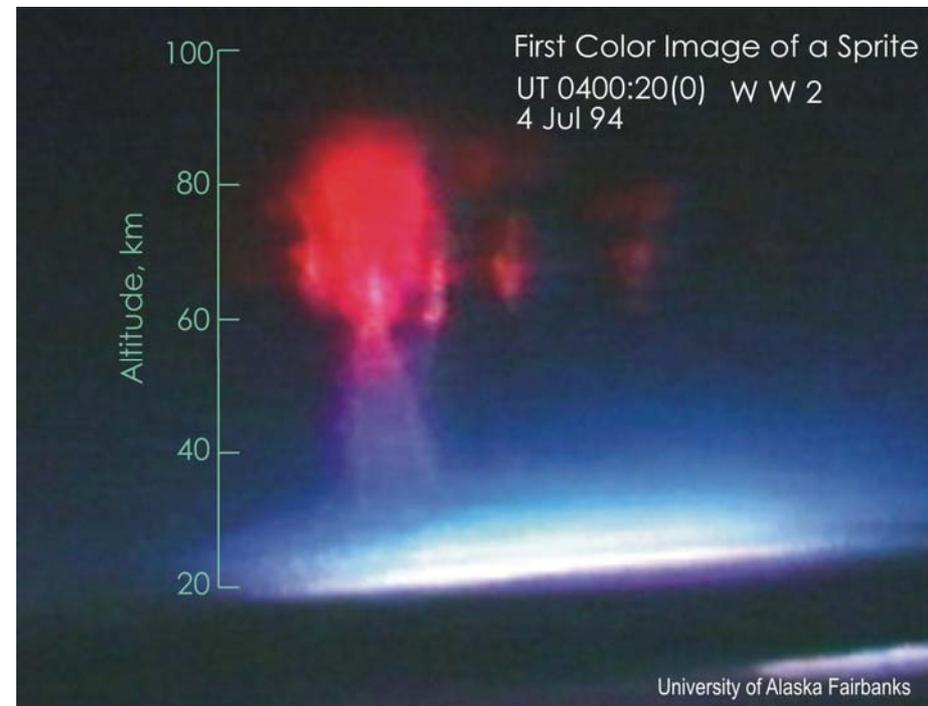
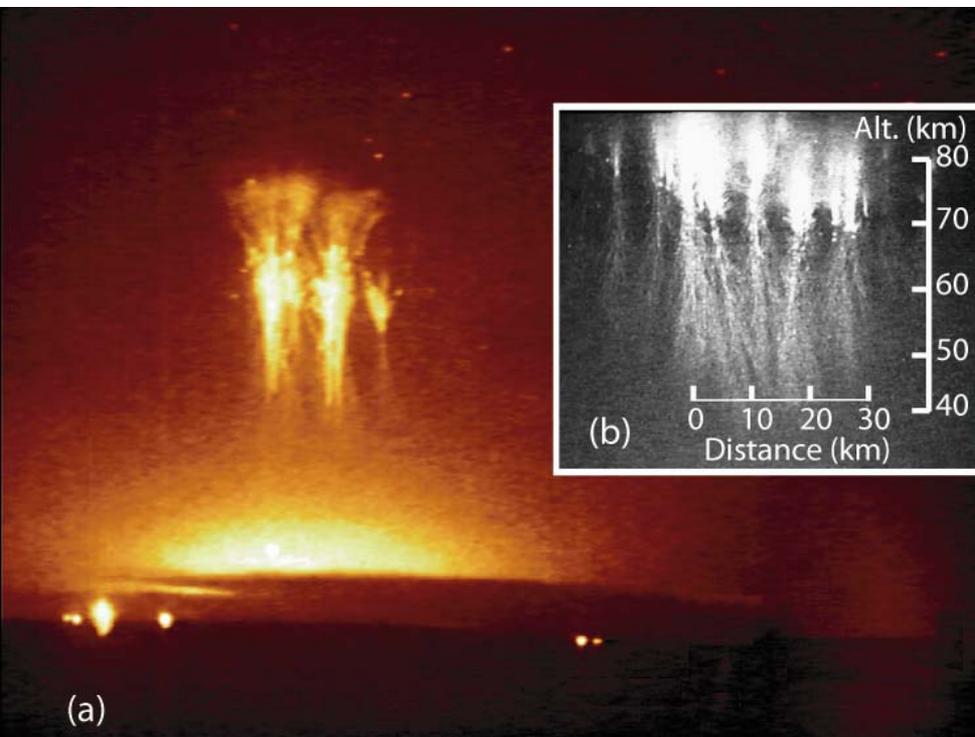
- **First TLE (a sprite) documented in 1989**
  - Sprites theoretically predicted in 1929 by C.T.R. Wilson
  - Occasional reports of high-altitude flashes by pilots
  - First photographed accidentally in 1989
    - And then published



# Characteristics of Red Sprites



- Sprites occur at altitudes  $\sim 40 - 90$  km (initiate at 75 km) following +CG discharges
- May be delayed from +CG up to  $\sim 200$  ms, and last only a few ms





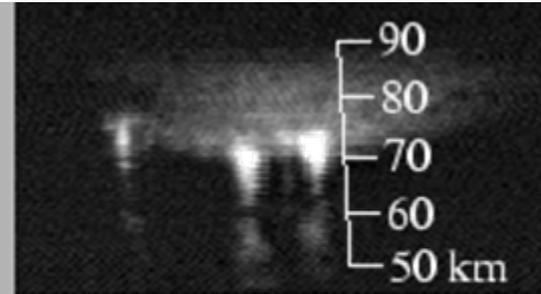
# Sprite Halos: created by QES heating

From: Barrington-Leigh [2000]



1997-239-05:13:00 UT

One 17 ms field of normal video.



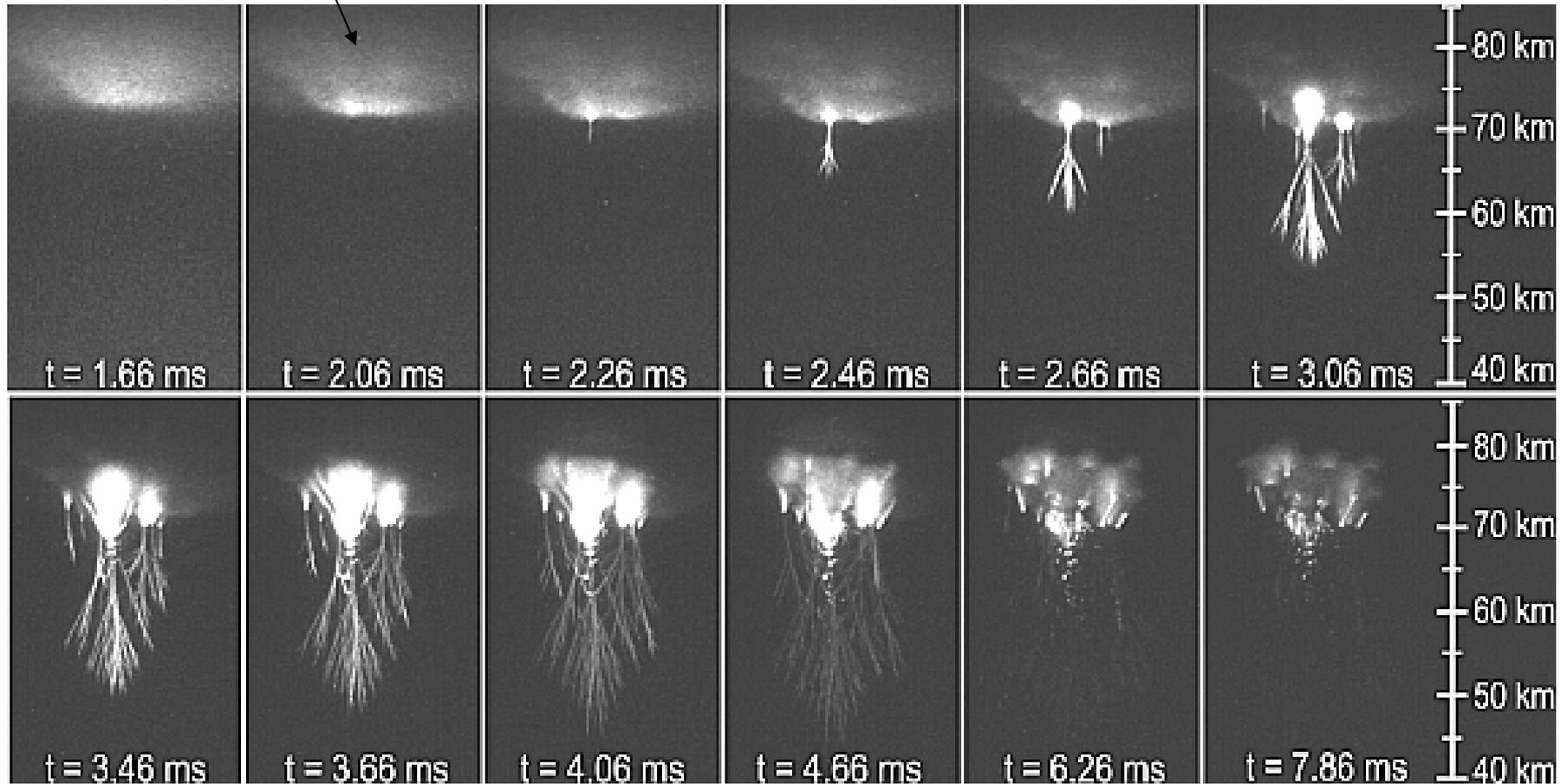
High speed video frames integrated over 2 ms.

[eurosprite.blogspot.com](http://eurosprite.blogspot.com)



# Fast Imaging of Sprites

Sprite halo

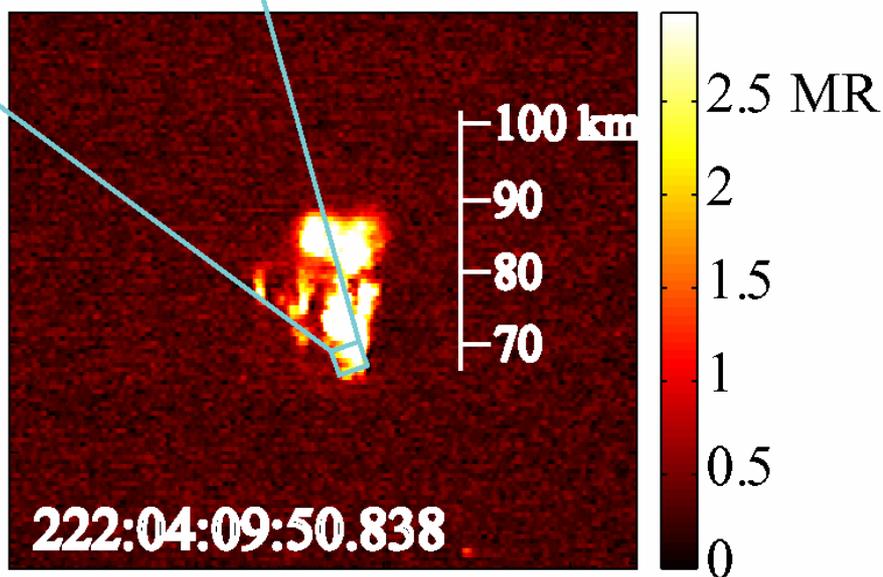
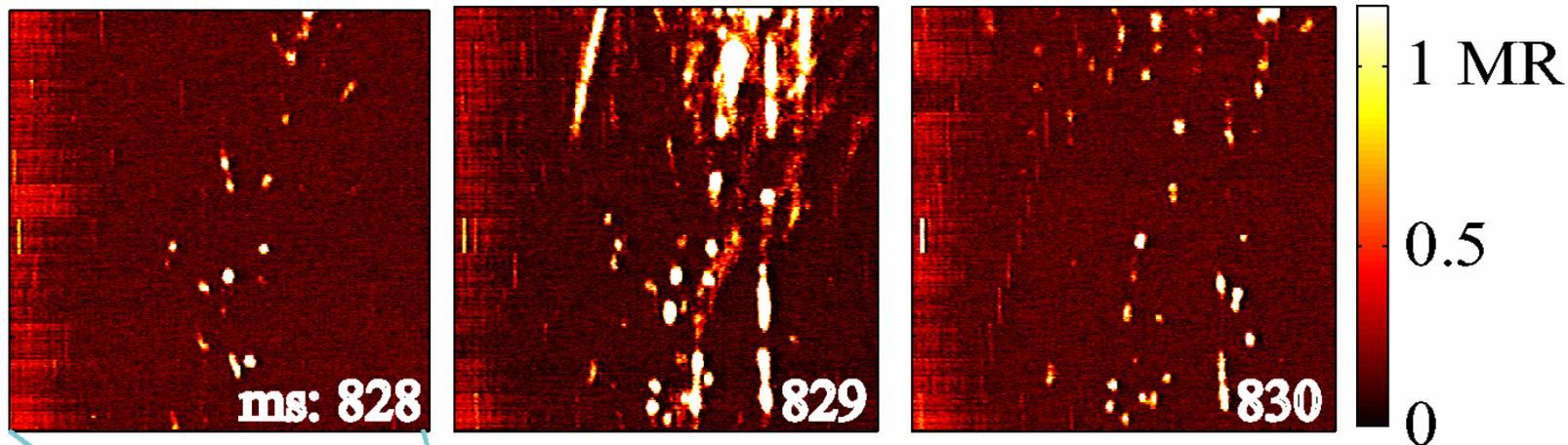


*Cummer et al [2006]*



# Fine structure of Red Sprites: the role of streamers

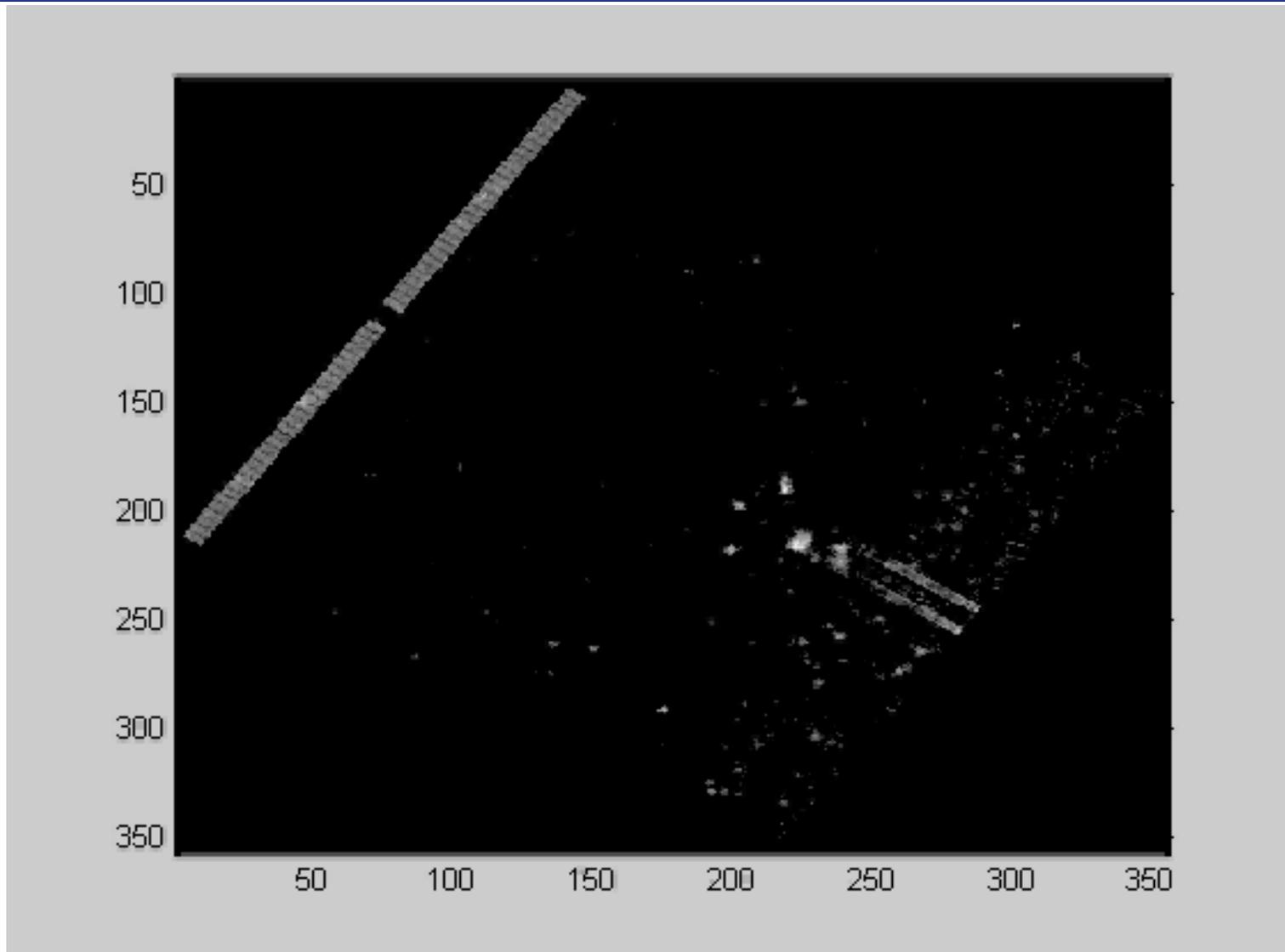
- Note that the threshold for conventional breakdown is higher than that for streamer breakdown ( $E^+/E_k \sim 0.25$ ,  $E^-/E_k \sim 0.6$ )



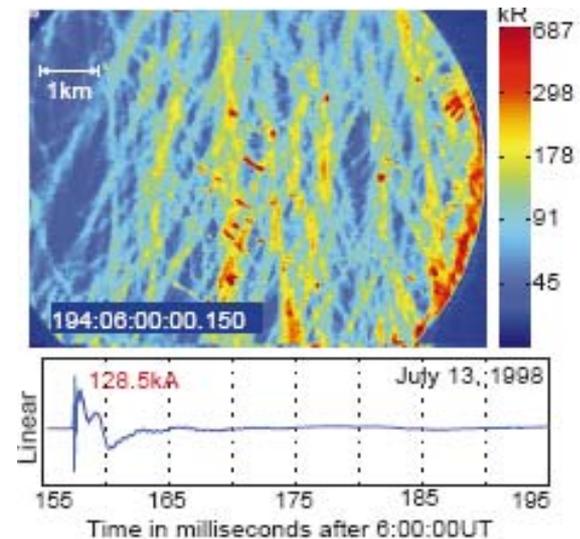
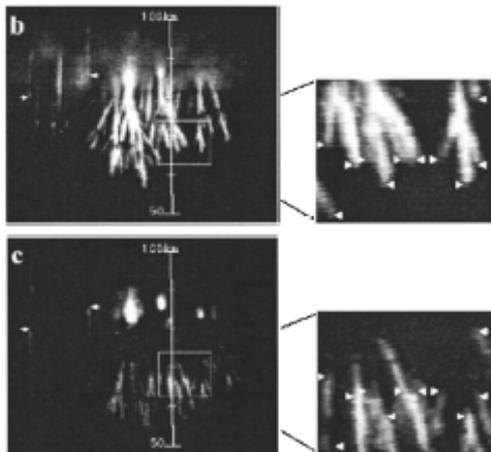
**стример (streamer) -  
нить электрического  
разряда**



# Sprite movie [Harg et al, 2007]



- **1925: C.T.R. Wilson** predicts that electric fields above thunderstorms could cause breakdown and “sparks”
- **Winckler [1989]** made the first recording of a sprite by accident from an airborne platform
- **Coordinated campaigns 1994-2000** were conducted every summer in the US, capturing thousands of sprites
- **Stanley et al [1999]** made the first high-speed observations (1000 fps)
- **Gerken et al [2000]** made the first telescopic observations, discovering features of 10 m scale





# Blue jets and Gigantic jets



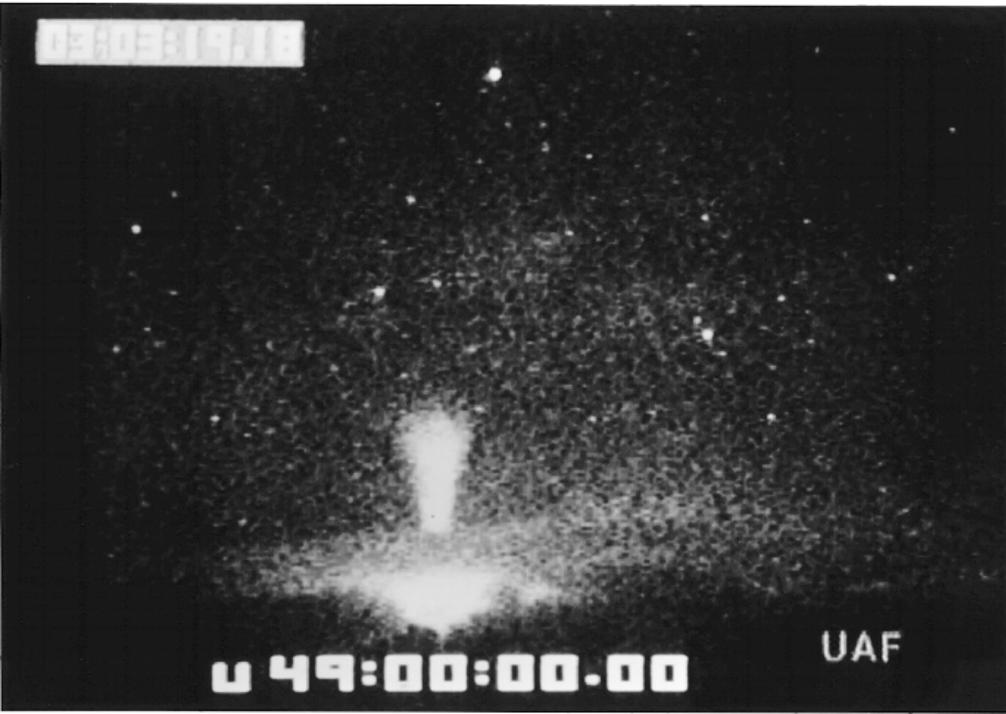
# Blue Jets

- Propagate upwards from the tops of thunderclouds to altitudes of ~40 km
- Are blue in color
- Propagate with speed 20-100 km/s

NASA National Aeronautics and Space Administration

[umbra.nascom.nasa.gov](http://umbra.nascom.nasa.gov)

Headquarters  
Washington, D.C.



Wescott et al [1995]





# Gigantic Jets

- **Connect the thundercloud tops with ionosphere**

Pasko et al [2002]



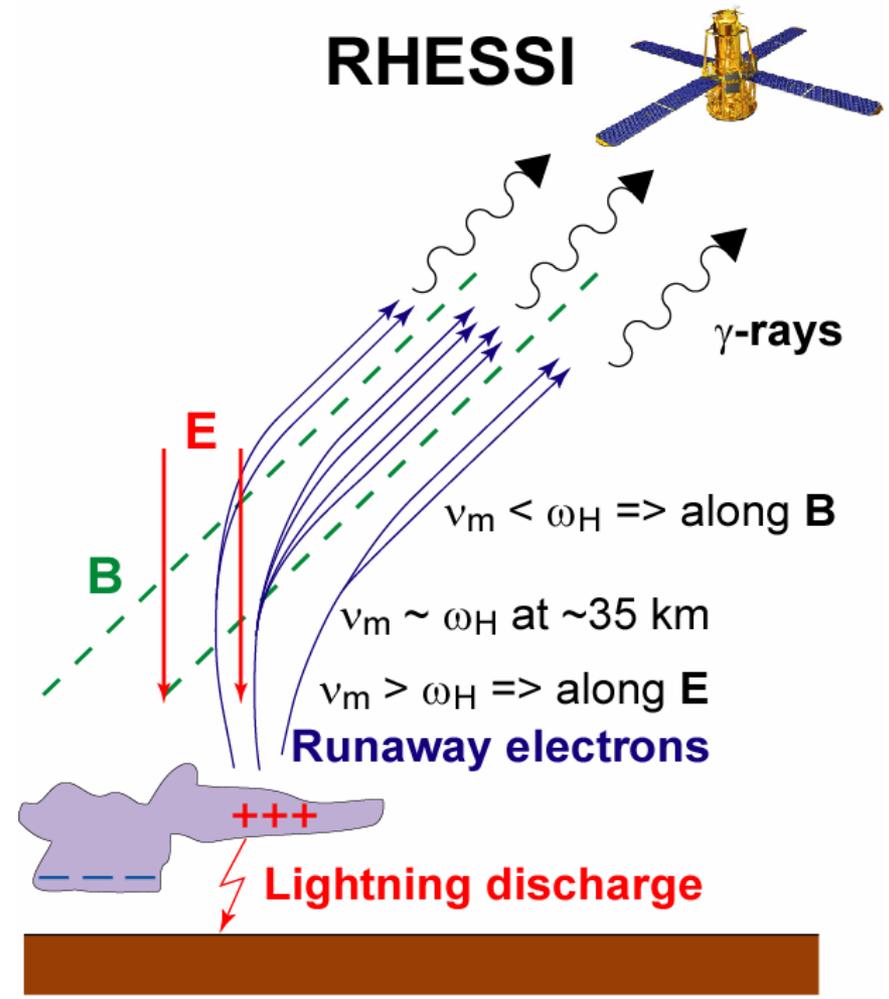


# QES theory of TGF (Terrestrial Gamma Flashes)



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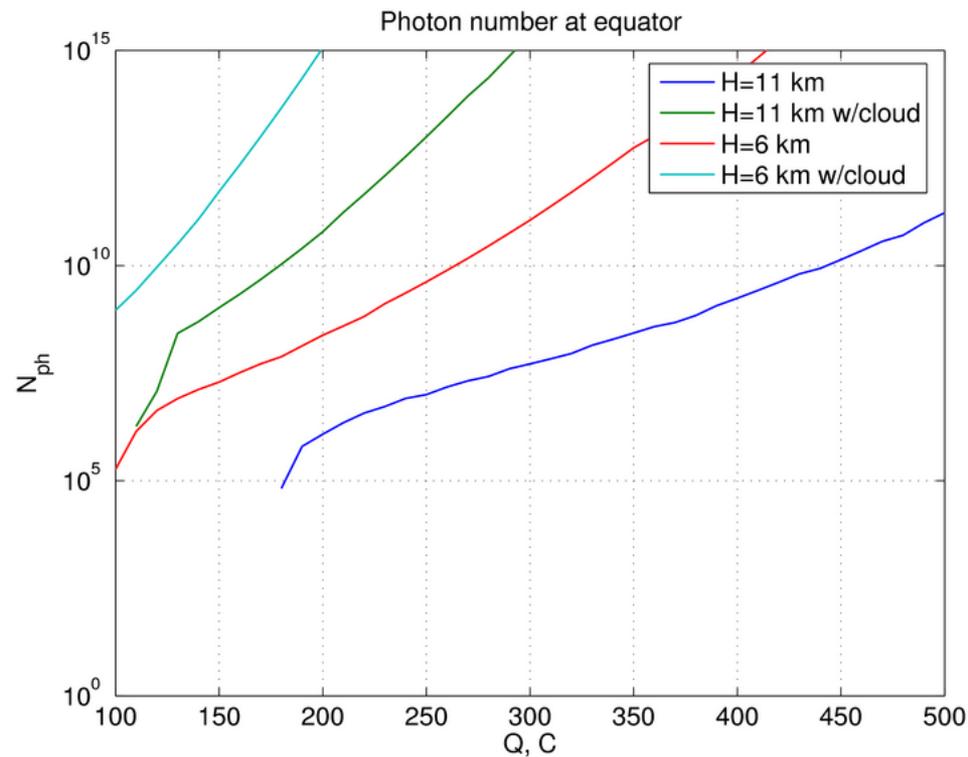
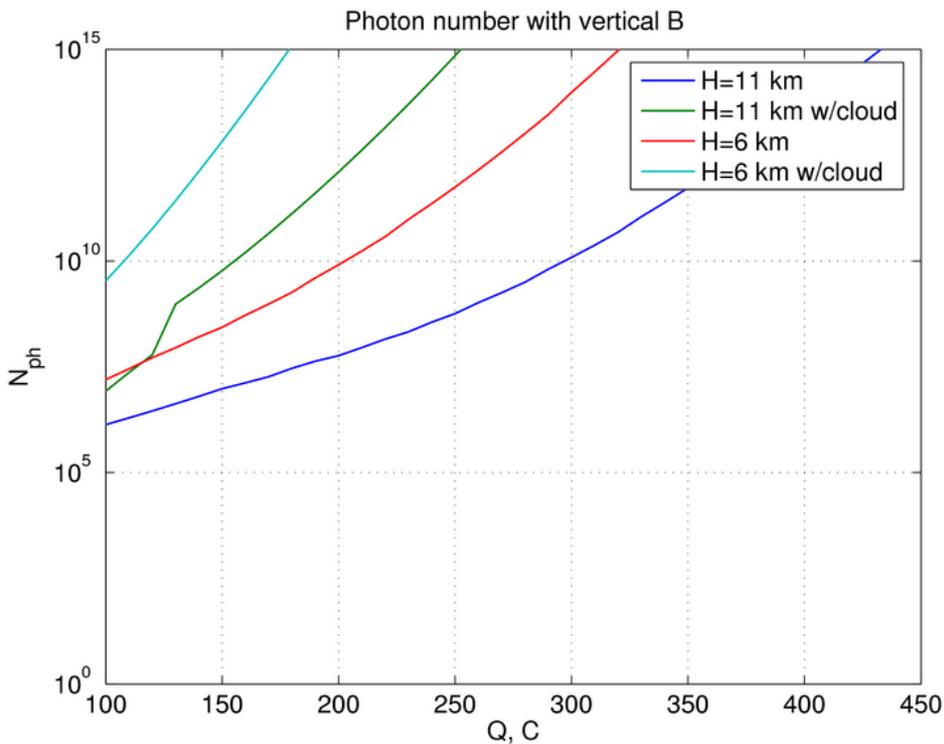
- **Runaway electrons** (убегающие электроны) are avalanching in a QES E field following a +CG discharge
- **Electron motion at >35km altitude is determined by geomagnetic field  $B_E$**
- **If  $B_E$  is non-horizontal, the electrons are predicted to leave the atmosphere.**





# Difficulty with QES model of TGF: too much charge required

- +CG discharge from 18 km [Gurevich et al, 2001]
- The observed photon number is  $\sim 3 \times 10^{15}$  [Smith et al, 2005], corresponding to the upper boundary of these graphs
- Required charge (varies depending on the ambient conductivity profile):
  - $\sim 175$  to  $\sim 450$  C for vertical  $B_E$
  - $\sim 200$  to  $>500$  C for horizontal  $B_E$  (equator)





## II. EMP (ElectroMagnetic Pulse) effects

- **Elves (эльфы)**
- **EMP theory of TGF (Terrestrial Gamma Flashes)**



- **Summary of TGF theories**



# Elves

(singular is “elve”!)

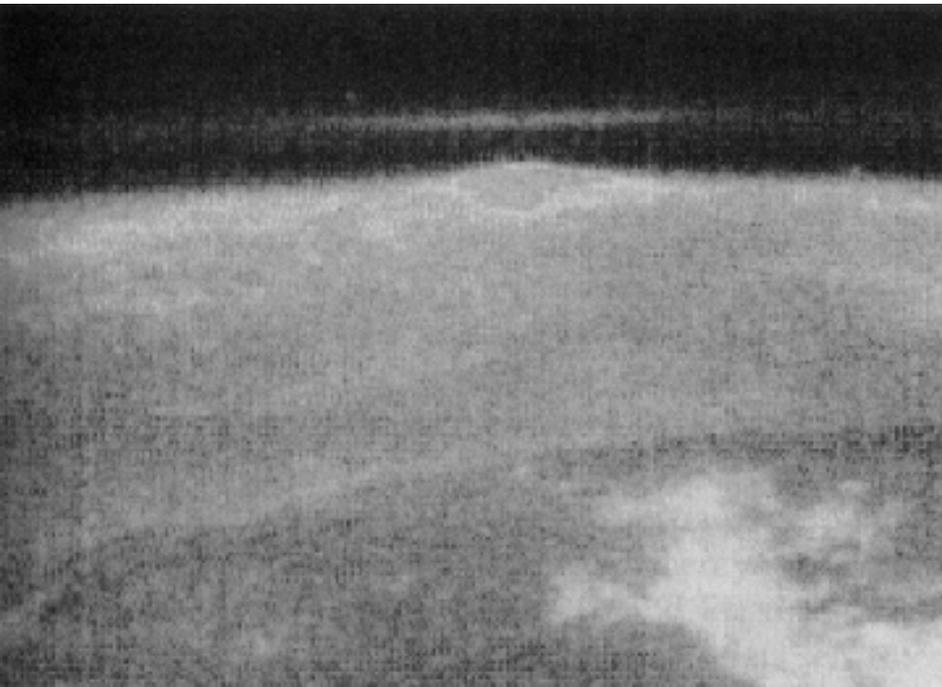
“*Emissions of Light and VLF perturbations due to EMP Sources*”



# Elve Observations

- Look similar to sprite halos (but caused by different mechanism!)
- Unlike sprites, elves are extremely bright ( $\sim 1\text{MR}$ ) but short ( $\sim 1\text{ms}$ ), and cannot be observed by naked eye.

First elve observation from Space Shuttle



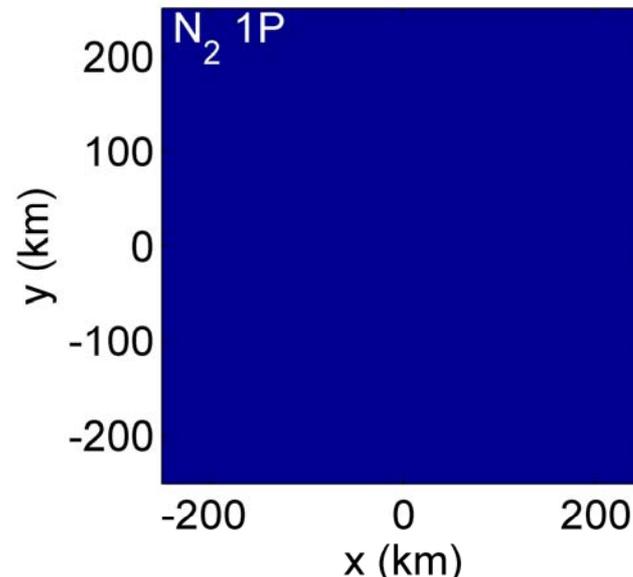
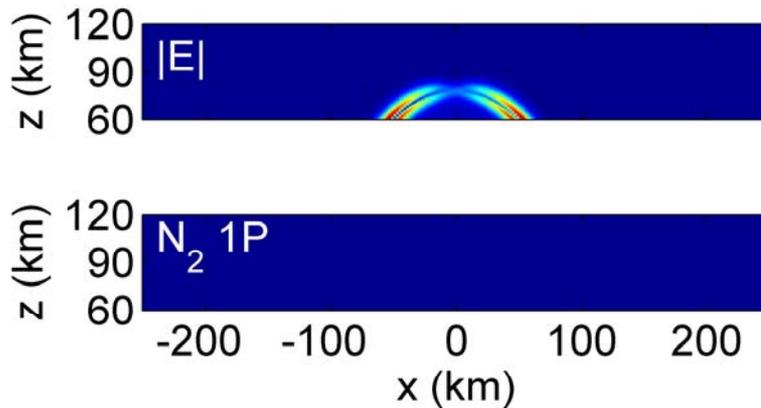
Ground-based observation  
[Taylor and Gardner, 1999]



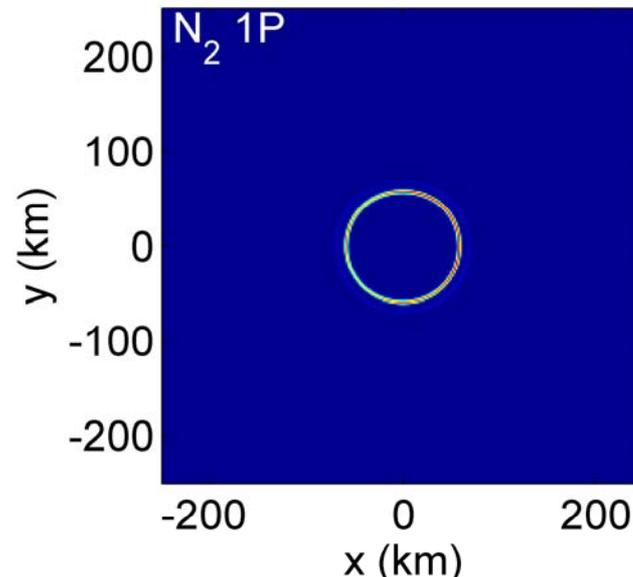
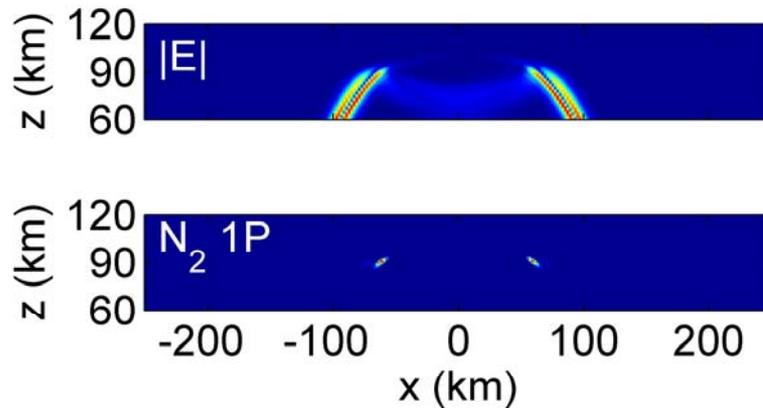


# Elves

- **Elves: “Emissions of Light and VLF perturbations due to EMP Sources”**
- **Theoretically predicted in 1991 by U.S. Inan**
- **Due to EMP heating of D-region ionospheric electrons**
- **For a vertical CG return stroke, an elve looks like a luminous ring “expanding” faster than the speed of light**



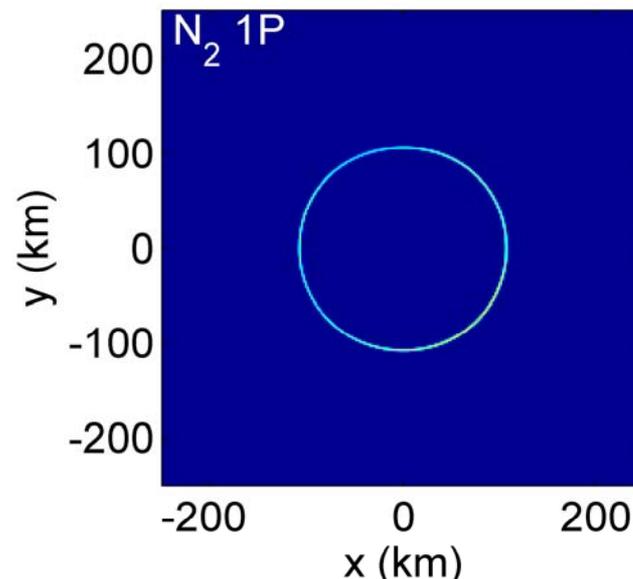
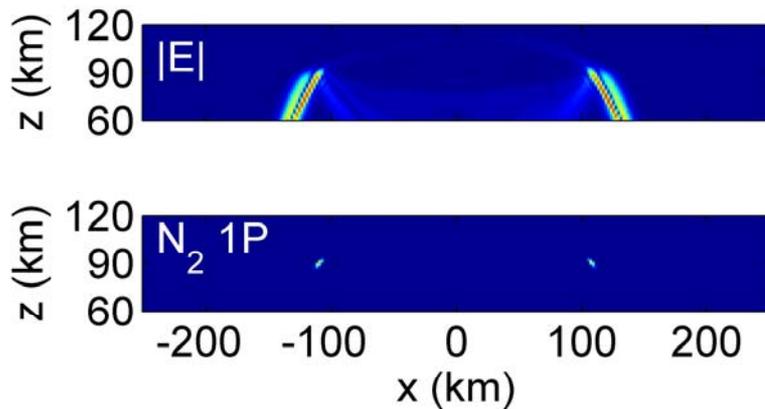
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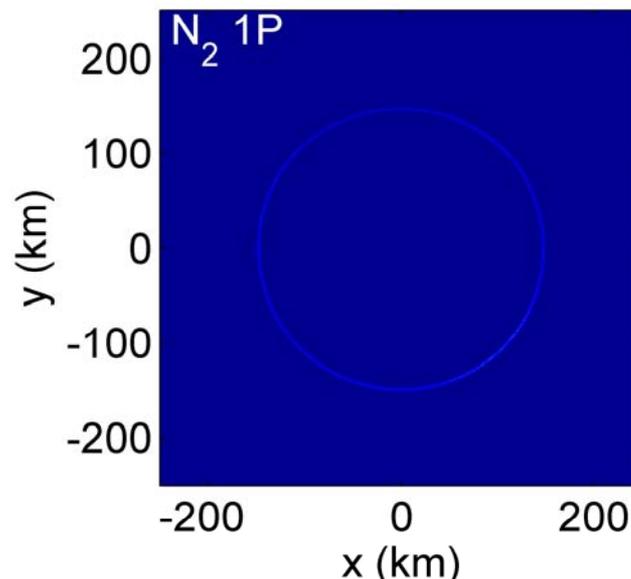
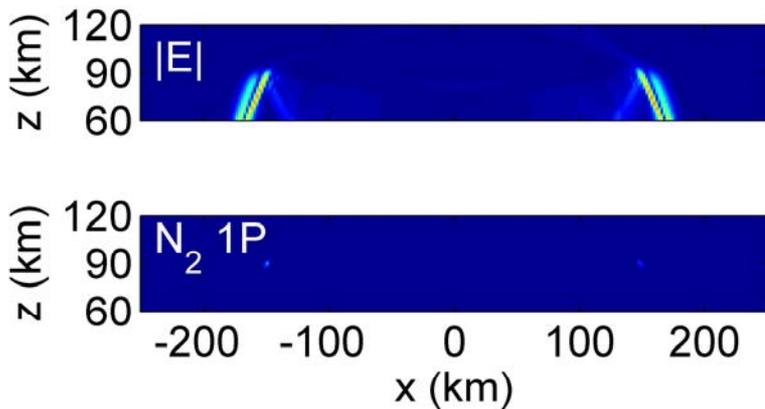
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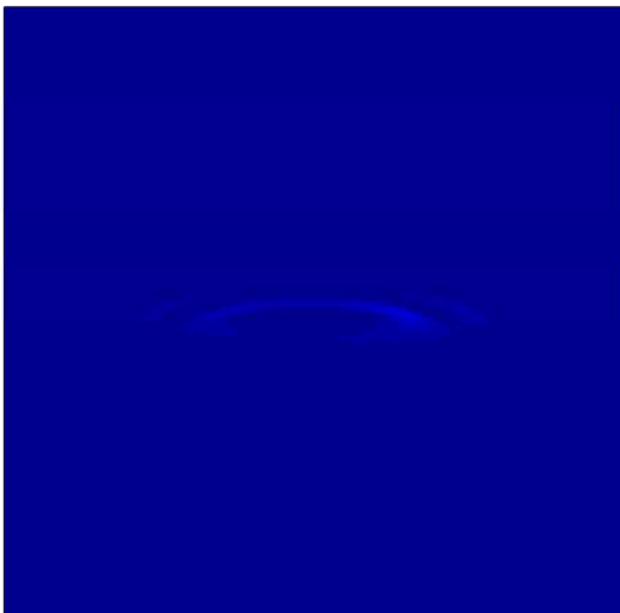




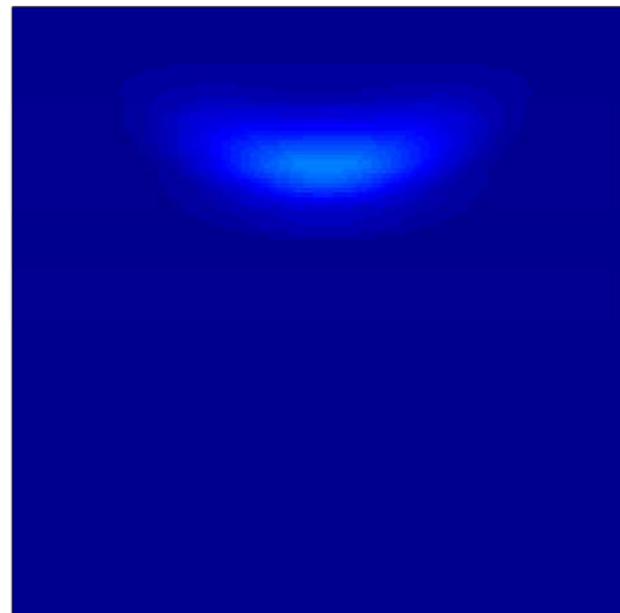
# Imaging Elves at High Speed

- At high speeds (defined as sub-ms temporal resolution):
  - Instrument view does not look like what you might expect
  - Due to out-of-order photon arrival times

Expected view:  $t = 361 \mu\text{s}$



Actual view:  $t = 1083 \mu\text{s}$

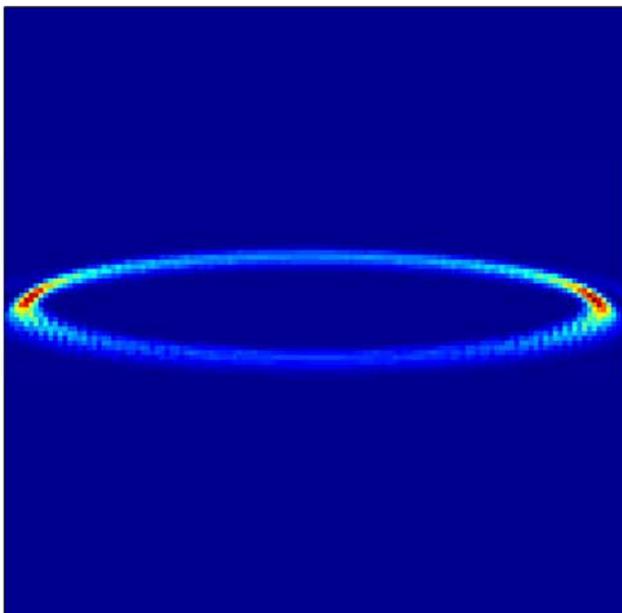




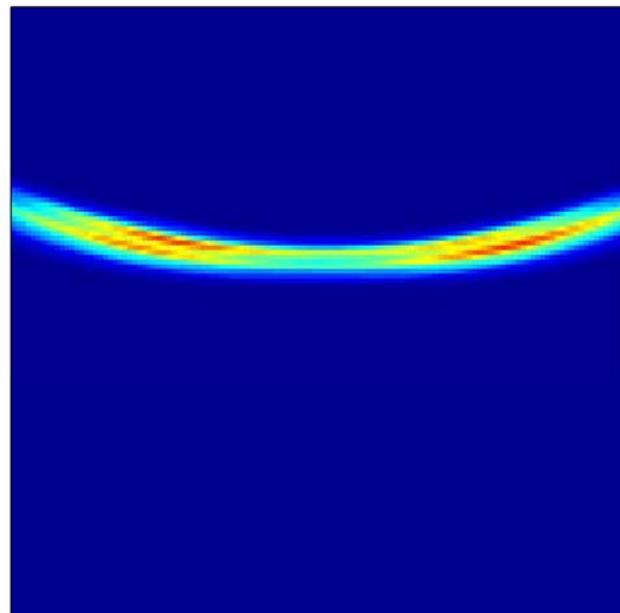
# Imaging Elves at High Speed

- At high speeds (defined as sub-ms temporal resolution):
  - Instrument view does not look like what you might expect
  - Due to out-of-order photon arrival times

Expected view:  $t = 444 \mu\text{s}$



Actual view:  $t = 1167 \mu\text{s}$

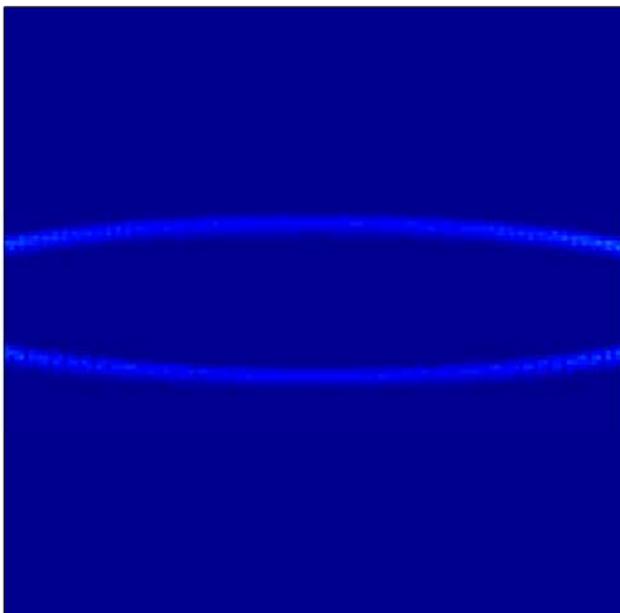




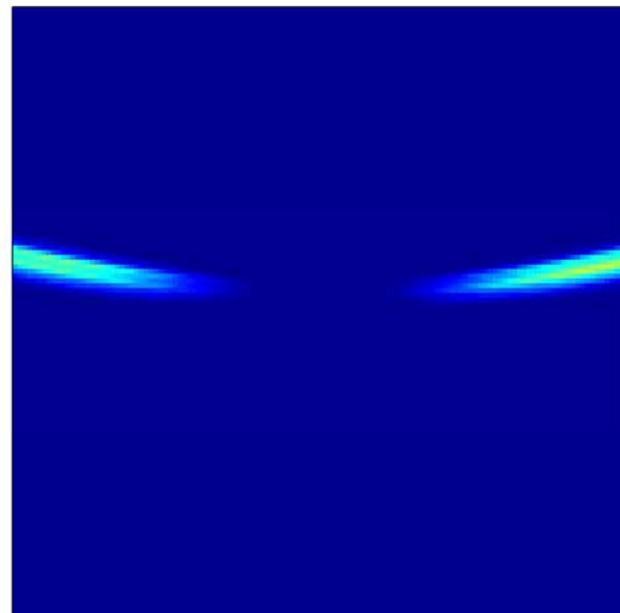
# Imaging Elves at High Speed

- At high speeds (defined as sub-ms temporal resolution):
  - Instrument view does not look like what you might expect
  - Due to out-of-order photon arrival times

Expected view:  $t = 528 \mu\text{s}$



Actual view:  $t = 1250 \mu\text{s}$

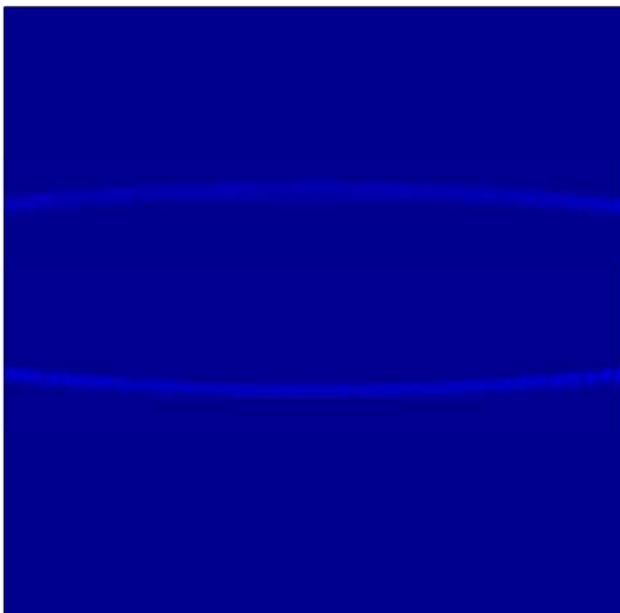




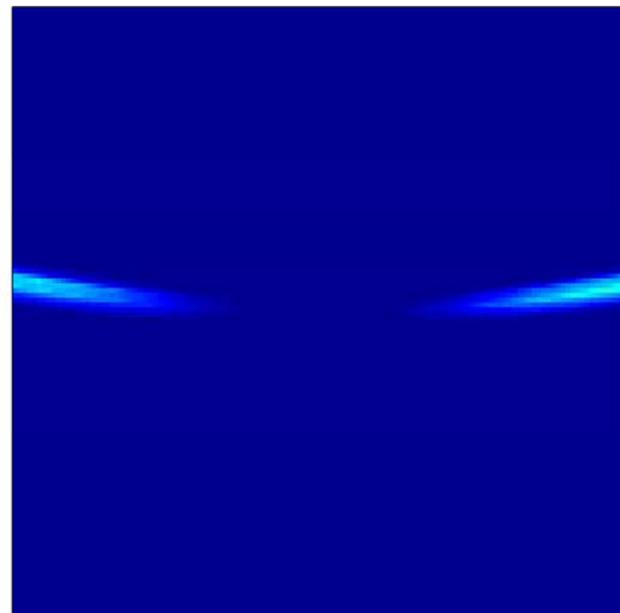
# Imaging Elves at High Speed

- At high speeds (defined as sub-ms temporal resolution):
  - Instrument view does not look like what you might expect
  - Due to out-of-order photon arrival times

Expected view:  $t = 611 \mu\text{s}$



Actual view:  $t = 1333 \mu\text{s}$

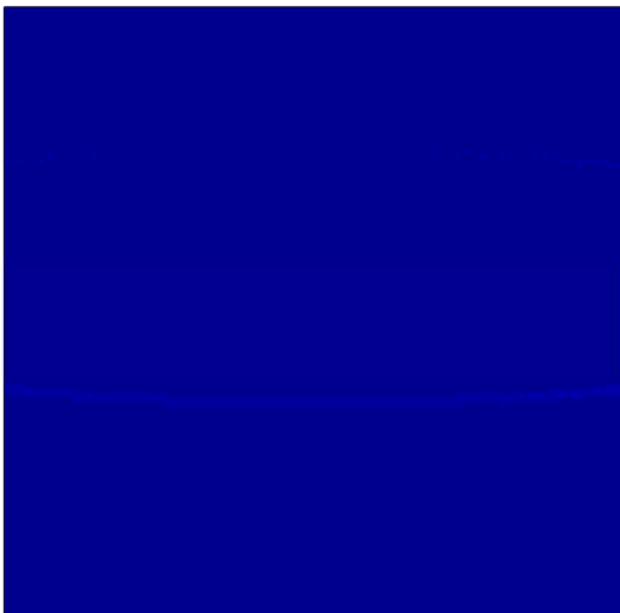




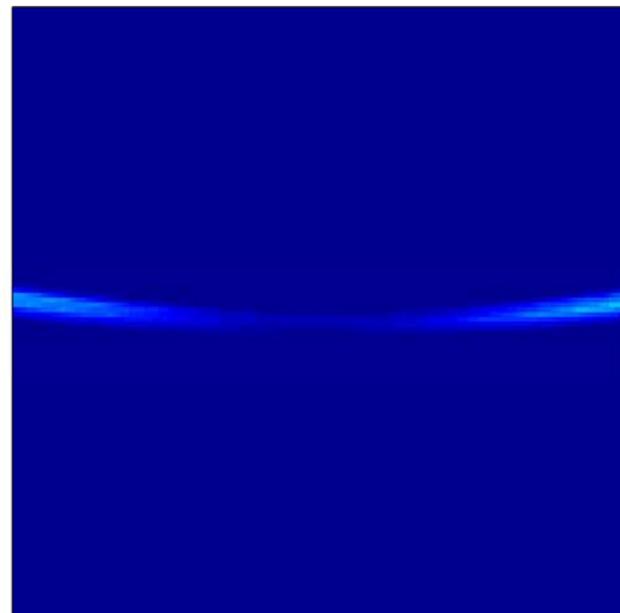
# Imaging Elves at High Speed

- At high speeds (defined as sub-ms temporal resolution):
  - Instrument view does not look like what you might expect
  - Due to out-of-order photon arrival times

Expected view:  $t = 694 \mu\text{s}$



Actual view:  $t = 1417 \mu\text{s}$

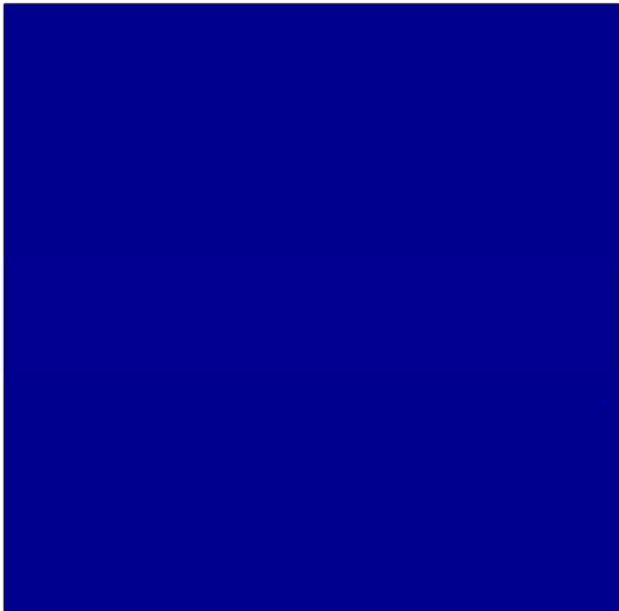




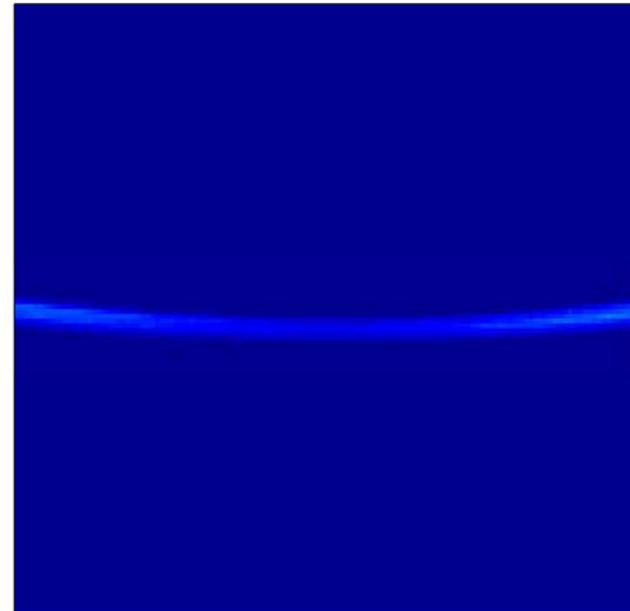
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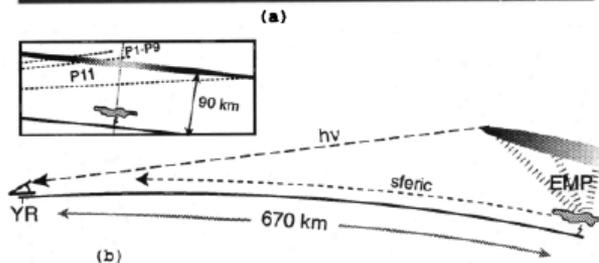
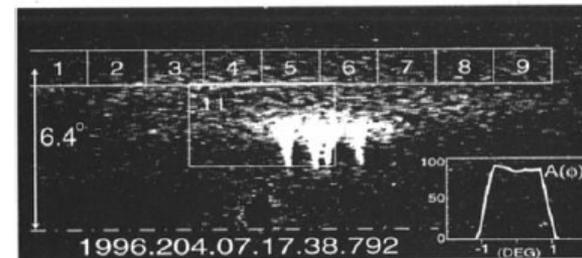
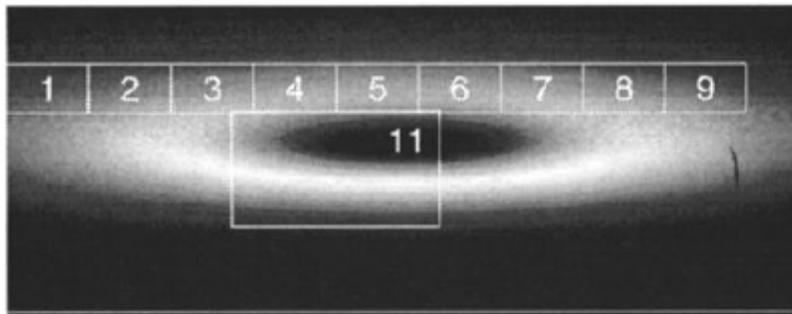
Expected view:  $t = 778 \mu\text{s}$



Actual view:  $t = 1500 \mu\text{s}$



- **Inan et al [1991]** predicted optical emissions through lightning-induced heating of ambient D-region electrons
- **Boeck et al [1992]** discovered the first optical emissions
- **Taranenko et al [1993a,b]** went on to quantitatively calculate emission intensities and effects on ionosphere
- **Fukunishi et al [1996]** was the first to observe elves from the ground with photometers
- **Inan et al [1997]** and **Barrington-Leigh et al [1999]** confirmed the predicted shape of elves





# Stanford University photometer arrays for elves studies (high frame rate, sensitive)

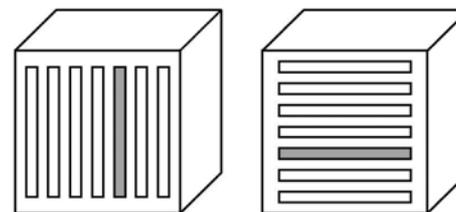
## Fly's eye

[Barrington-Leigh, 2000]

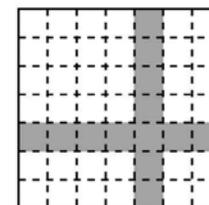


## PIPER

[Marshall et al, 2008; Newsome et al. 2009]



(a) Multi-anode photometers



(b) Discretized field of view

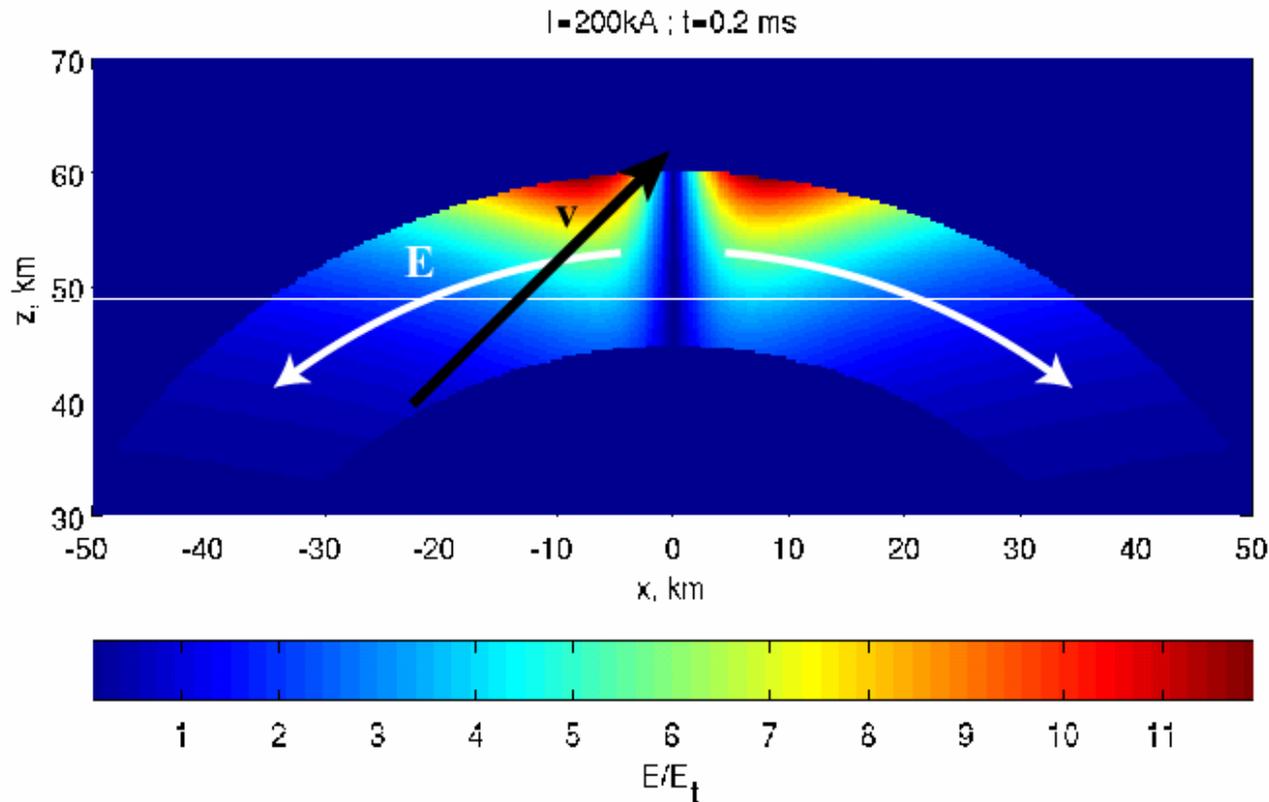


# EMP theory of TGF (Terrestrial Gamma Flashes)



# EMP theory of TGF production [Inan and Lehtinen, 2005]

- EMP field is  $\sim 1/R$ , which is higher than QES dipole field  $1/R^3$  at high altitudes
- Unlike QES, can accelerate electrons at the equator
- However, also requires extreme values of return stroke speed ( $v > 0.99c$ ) and current ( $I > 400$  kA)





# Summary of TGF theories

**All mechanisms involve relativistic runaway electron (RRE) avalanche (лавина релятивистских убегающих электронов, пробой на убегающих электронах).**

## Seeding of the avalanche:

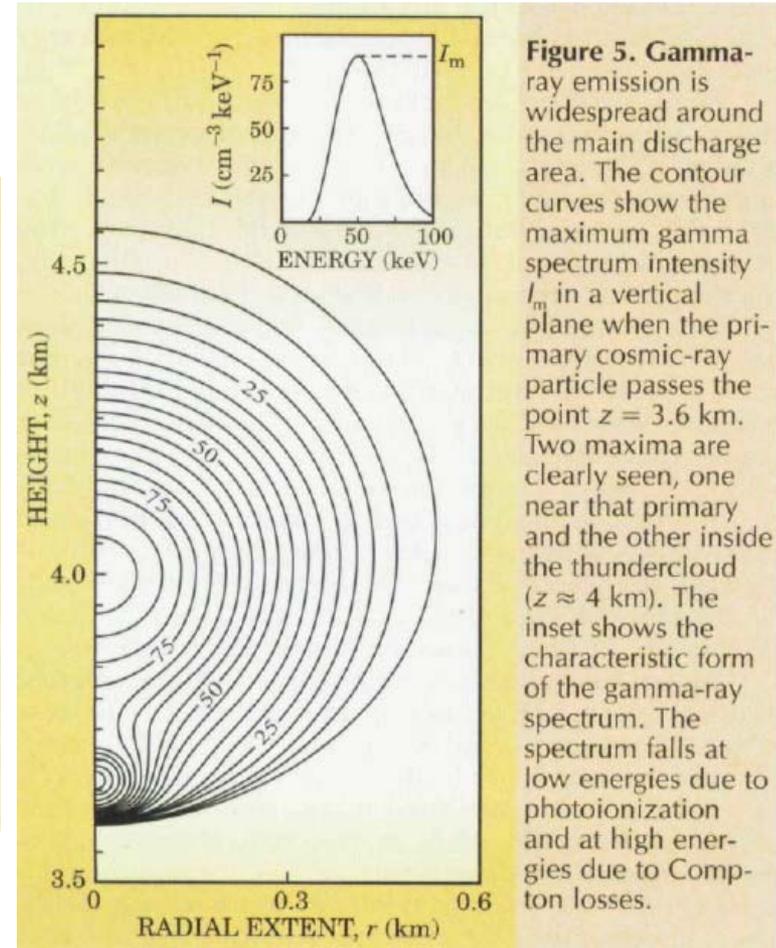
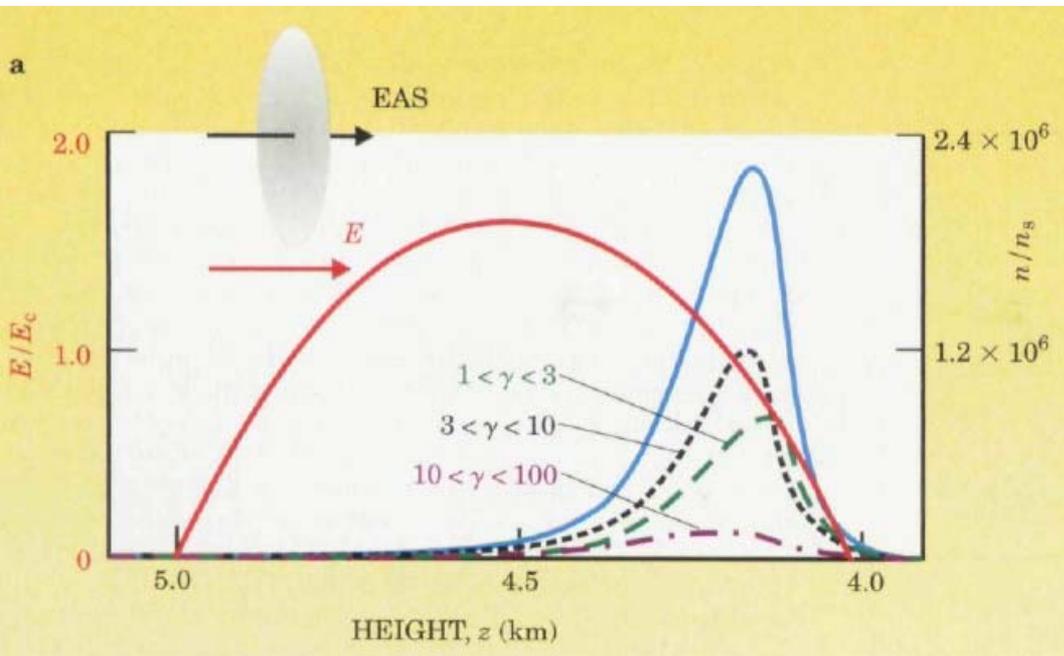
- High-energy tail of electron distribution in streamers and leaders [Carlson et al, 2010]
- Ambient flux of cosmic rays [Bell et al., 1995]
- Extensive air showers (EAS) by ultra-high energy cosmic rays (UHECR) [Gurevich and Zybin, 2001]

## Avalanche mechanisms:

- Field of a lightning leader [Carlson et al, 2010]
- QES post-discharge field above thunderstorms [Lehtinen et al, 1999; Babich et al, 2004]
- EMP field in mesosphere [Milikh and Valdivia, 1999; Inan and Lehtinen, 2005]
- QES (pre-discharge) field inside a thundercloud [Gurevich et al., 1994]

# RREA inside a thundercloud

## [Gurevich and Zybin, 2004]



**Figure 5.** Gamma-ray emission is widespread around the main discharge area. The contour curves show the maximum gamma spectrum intensity  $I_m$  in a vertical plane when the primary cosmic-ray particle passes the point  $z = 3.6$  km. Two maxima are clearly seen, one near that primary and the other inside the thundercloud ( $z \approx 4$  km). The inset shows the characteristic form of the gamma-ray spectrum. The spectrum falls at low energies due to photoionization and at high energies due to Compton losses.



# Requirements from different TGF production models:

- **Leader field inside a cloud:**
  - $E > E_t = 2 \text{ kV/cm (8 Td)}$
  - RREA (Relativistic Runaway Electron Avalanche) seed from the leader
- **Post-discharge QES above thunderstorms:**
  - Large ( $>100 \text{ C}$ ) positive CG discharge
  - Ambient conductivity profile that provides high screening charges
- **EMP mechanism:**
  - $I > 400 \text{ kA}$
  - $v > 0.99c$
- **Pre-discharge QES inside a cloud:**
  - $E > E_t = 2 \text{ kV/cm (8 Td)}$
  - UHECR (ultra-high energy cosmic ray) seed

# Summary: QES and EMP mechanisms

## Mechanisms

