Elve Background and Modeling

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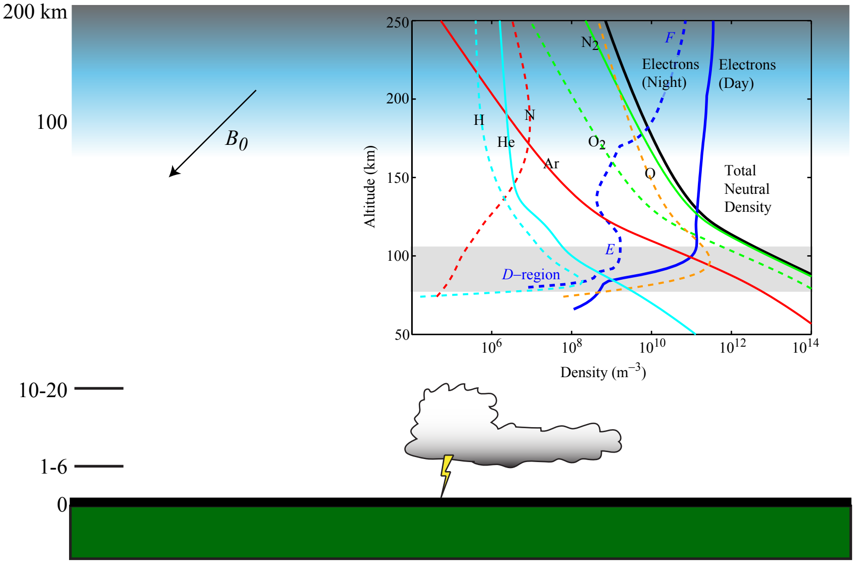
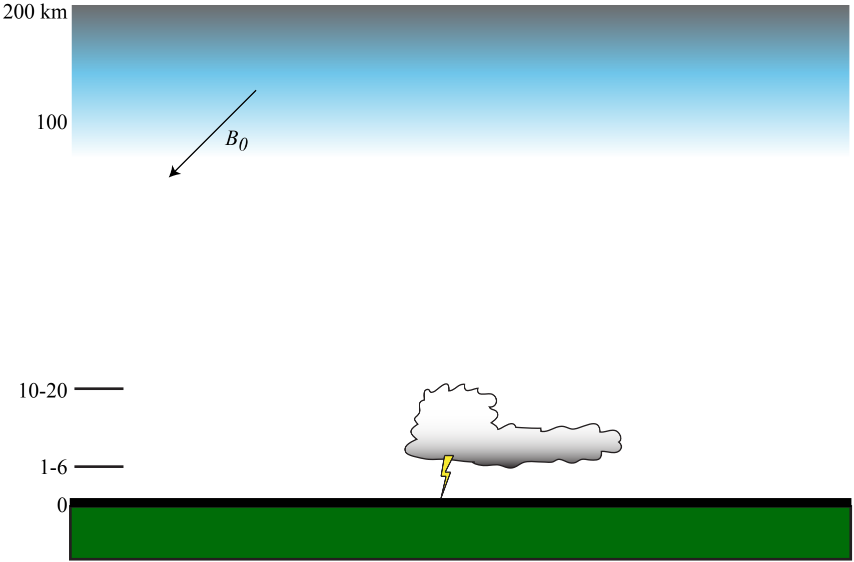
September 28, 2013

Lightning and the Ionosphere



Lightning and the Ionosphere



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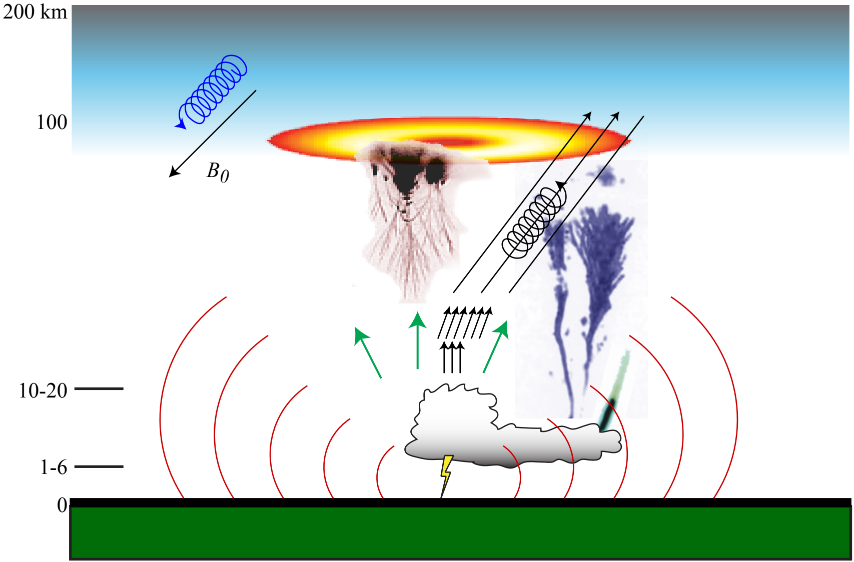

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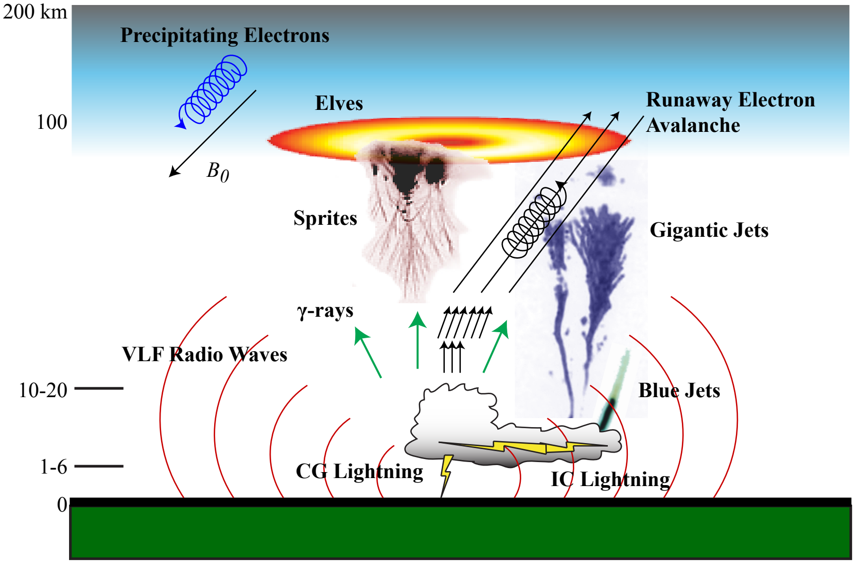
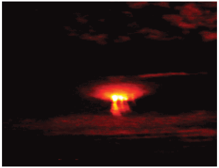
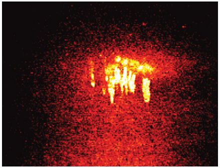
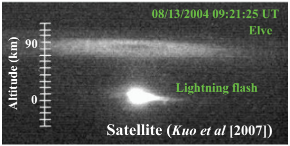
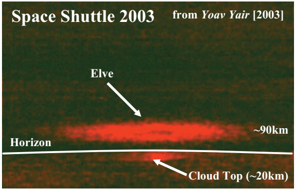


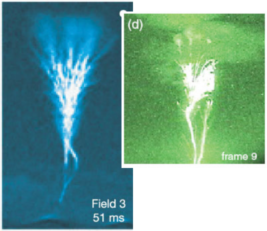
Transient Luminous Events (TLEs)











Sprites

- Produced by QE field when E > Ek
- GR brightness
- streamers; < 1 us

Elves

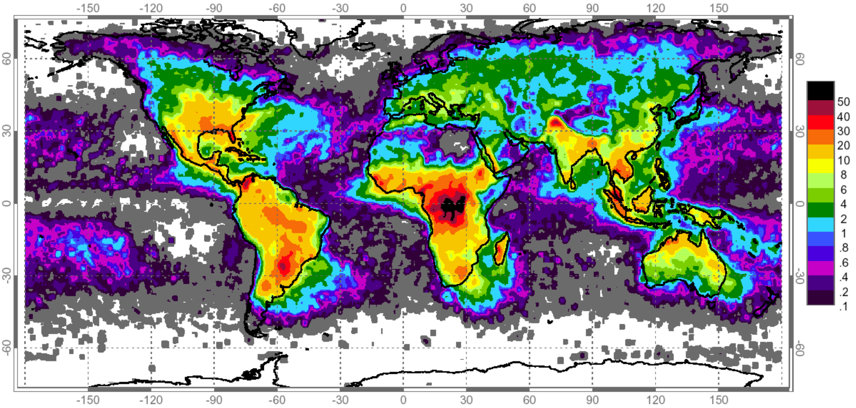
- Produced by EMP field when E > Eth (optical)
- MR brightness
- glow; ~100 us

Jets / Gigantic Jets

- Form of upward lightning
- brightness? (GR)
- leader--streamer; ~100 ms

Lightning Density Worldwide

Units of flashes / year / km^2

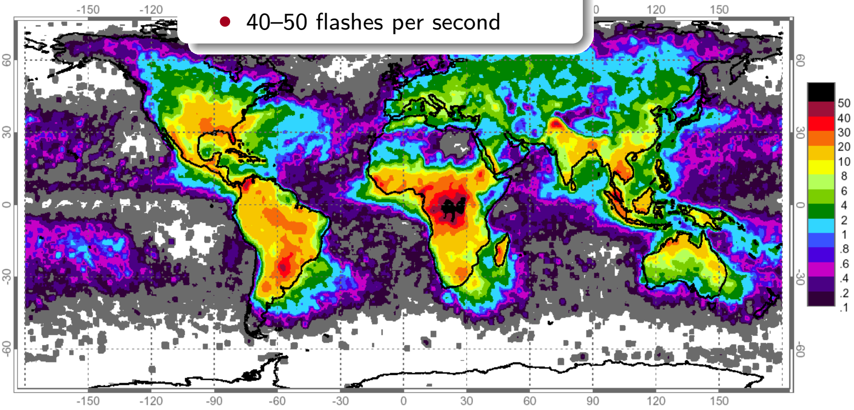


Data from the Optical Transient Detector (OTD) on the MicroLab-1 satellite

From *Christian et al* [2003]

Lightning Density Worldwide

- ∼2000 active thunderstorms
- 40–50 flashes per second



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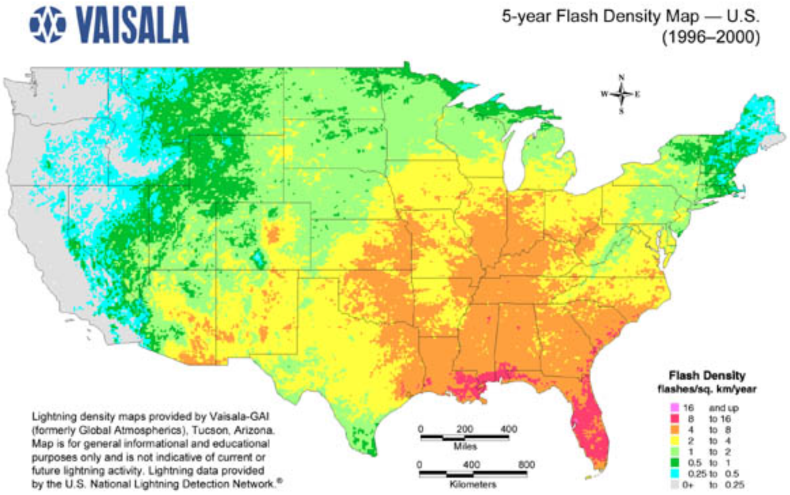
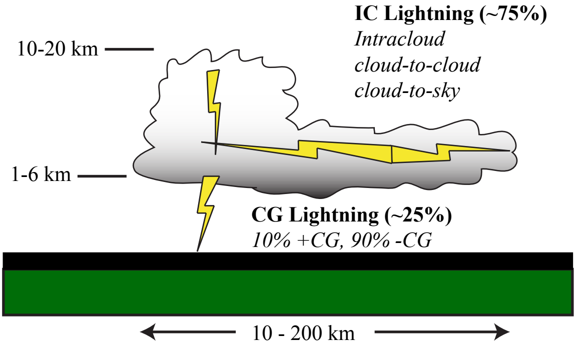
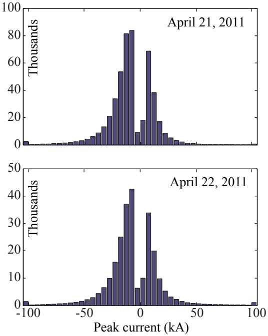
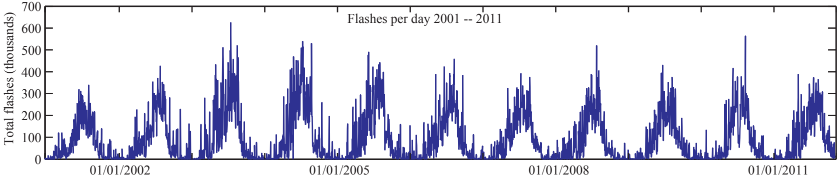
Lightning Density in the U.S.



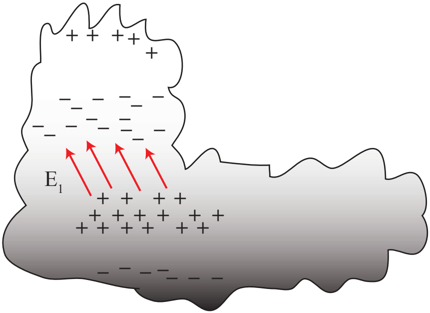
Some Lightning Statistics

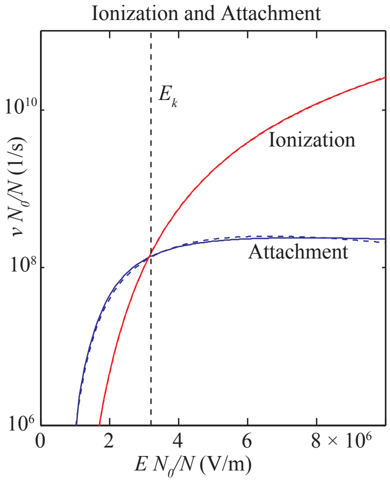




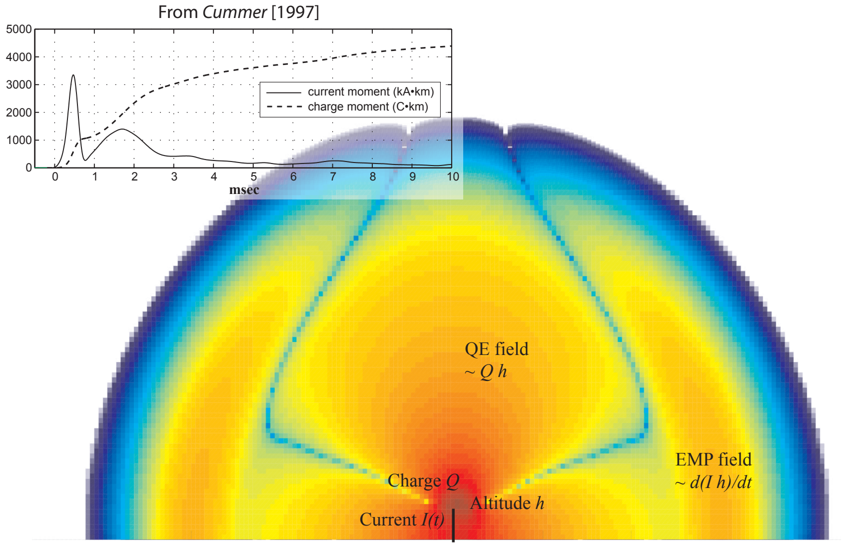


How Lightning Initiates: Breakdown



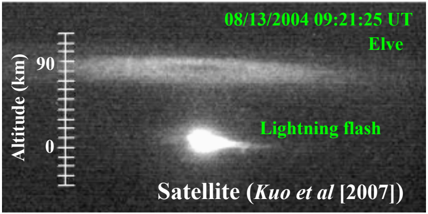


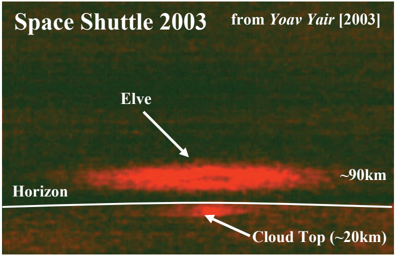
Lightning Fields: QE and EMP

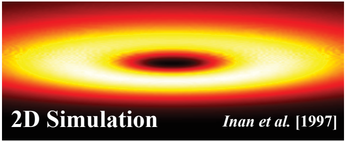


Elves

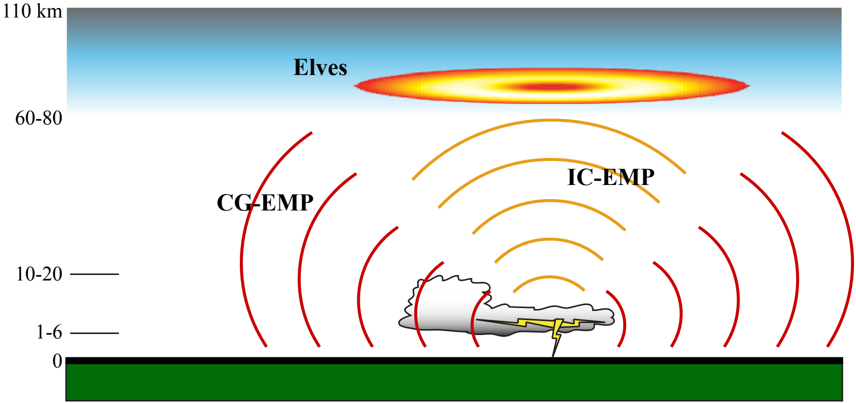
- Endure $\ll$1 ms
- Intense red emissions (>1 MR)
- Radial extent up to 200km
- Satellite and ground observations show 6 times as many elves as sprites







Elves and the EMP Mechanism



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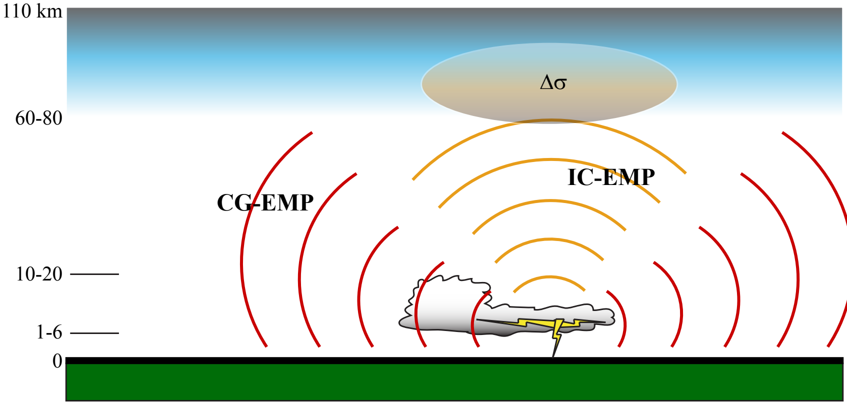
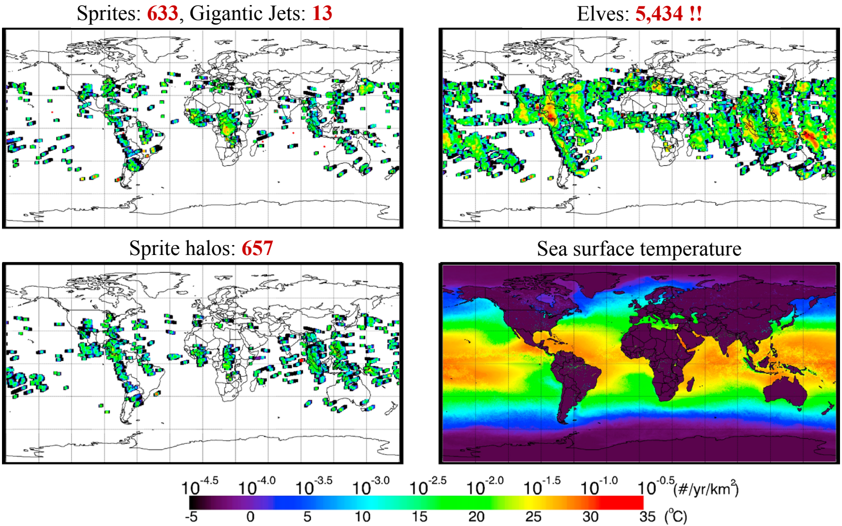


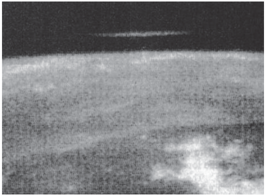
Global Distribution of Elves



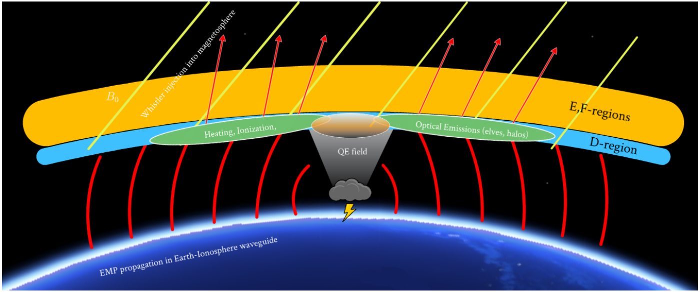
From *Chern et al* [2008]

A Brief History of Elve Research

- *Inan, 1991* first theorized that lightning EMPs could heat the D-region and produce optical emissions.
- *Boeck et al. 1992* provided first the unambiguous recording of an elve
- *Taranenko 1991, 1993* developed a model to predict optical emissions from the EMP-ionosphere interaction.
- *Fukunishi et al. 1996* convincingly showed that elves are distinct from sprites
- *Inan et al. 1997* provided experimental evidence of the rapid lateral expansion of elves.



Time Domain Modeling of Lightning-Ionosphere Interactions



Goals:

1. Model the complete lightning-ionosphere interaction
2. Assess local/global effect of lightning fields on lower ionosphere
3. Model optical emissions (Elves)

Field Equations

$$\epsilon_0 \frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{H} - \mathbf{J}_{\text{tot}}$$

$$\mu_0 \frac{\partial \mathbf{H}}{\partial t} = -\nabla \times \mathbf{E}$$

$$\frac{\partial \mathbf{J}_n}{\partial t} + \nu_n \mathbf{J}_n = \vec{\omega}_{c,n} \times \mathbf{J}_n + \omega_{p,n}^2 \epsilon_0 \mathbf{E}$$

$$\mathbf{J}_{\text{tot}} = \sum_n \mathbf{J}_n$$

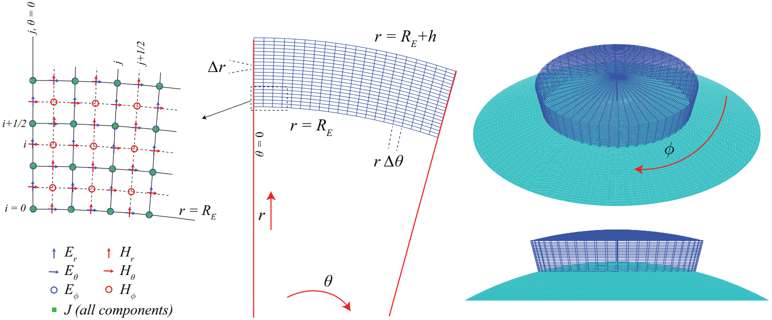
Where

$$\omega_{p,n}^2 = \frac{n_n q^2}{m_n \epsilon_0}$$ is the plasma frequency of species n

$$\vec{\omega}_{c,n} = \frac{q_n \mathbf{B}_0}{m_n}$$ is the gyrofrequency of species n

- Updated using finite-difference time-domain (FDTD) scheme
- One **J** equation for each species

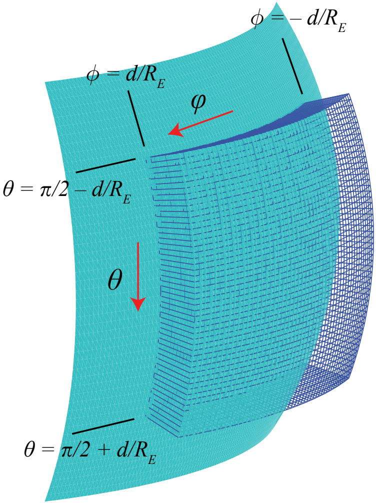
2D Grid



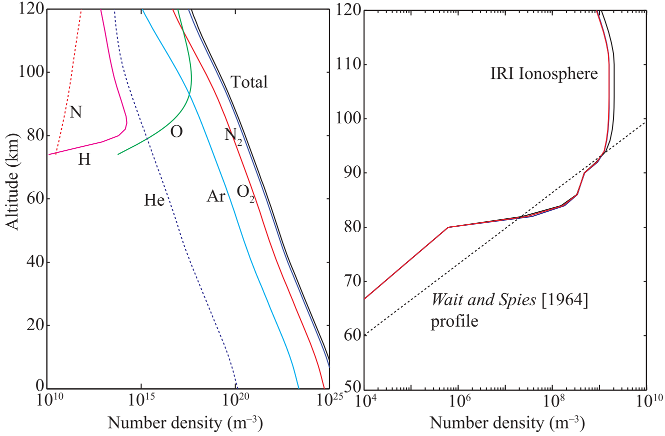
- Spherical coordinates take care of Earth's curvature.
- **J** components are located at integer grid points *[Lee and Kalluri, 1999]*

3D Grid

Shifting grid to "equator" provides roughly equal-size grid cells.



Atmosphere and Ionosphere



- Neutral densities are taken from MSIS-E-90 model and electron densities from the IRI 2007 model.

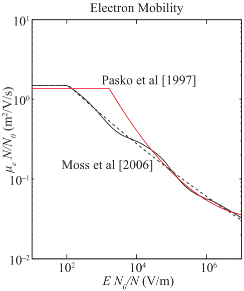
Electron Collisions

$$\frac{\partial \mathbf{J}_n}{\partial t} + \nu_n \mathbf{J}_n = \bar{\omega}_{c,n} \times \mathbf{J}_n + \omega_{p,n}^2 \epsilon_0 \mathbf{E}$$

Electron collisions are related to mobility

$$\nu_e = \frac{q_e}{\mu_e m_e}$$

Mobility depends on atmospheric constituents and electric field



Nonlinear Effects

- Intense fields produce ionization, attachment, and detachment
- Rate coefficients are obtained from BOLSIG+ Boltzmann Equation solver code
- Used to update electron density self-consistently:

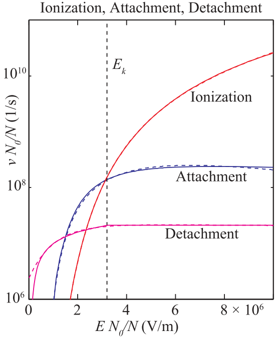
$$\frac{\partial N_e}{\partial t} = (\nu_i - \nu_a)N_e + \nu_d N_{O^-}$$
$$\frac{\partial N_{O^-}}{\partial t} = \nu_a N_e - \nu_d N_{O^-}$$

- Solved using backward Euler scheme

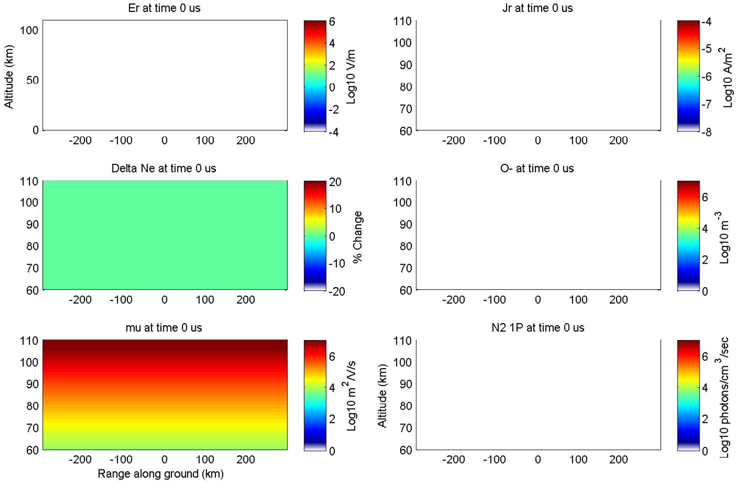
Nonlinear Effects (cont.)

The dominant associative detachment process is

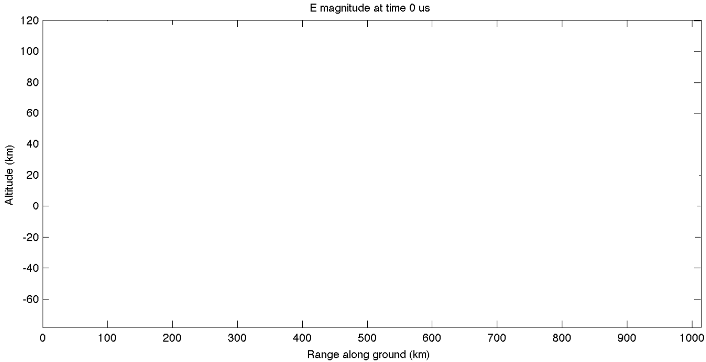
$$O_2 + e^- \rightarrow O + O^-$$
$$O^- + N_2 \rightarrow N_2O + e^-$$



Example Simulation

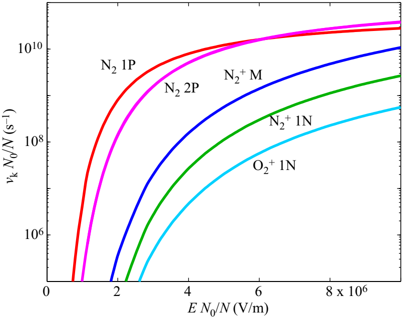


Another Example

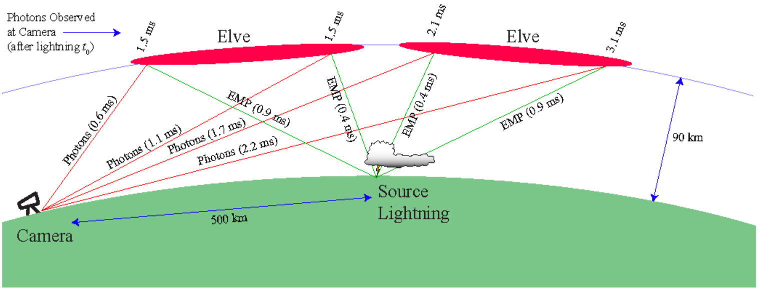


Optical Emissions

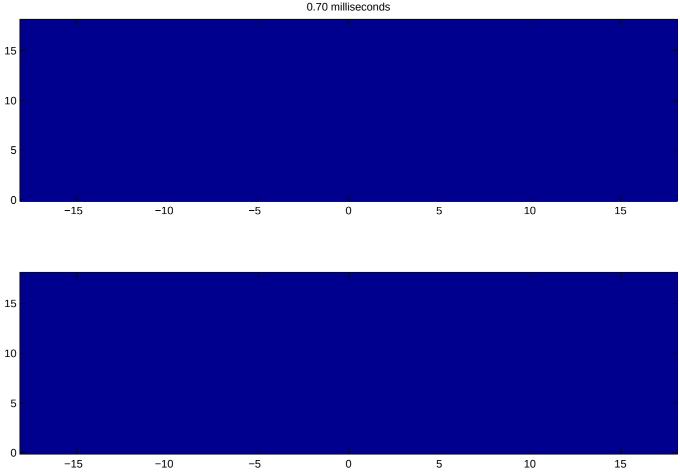
- Optical emissions are similarly obtained by solving a set of rate equations
- Rates depend on electric field and neutral density (altitude). Also obtained from BOLSIG+.
- Calculate photons produced at each grid point at each time step
- Integrate through line-of-sight to camera at arbitrary location



Viewing Geometry



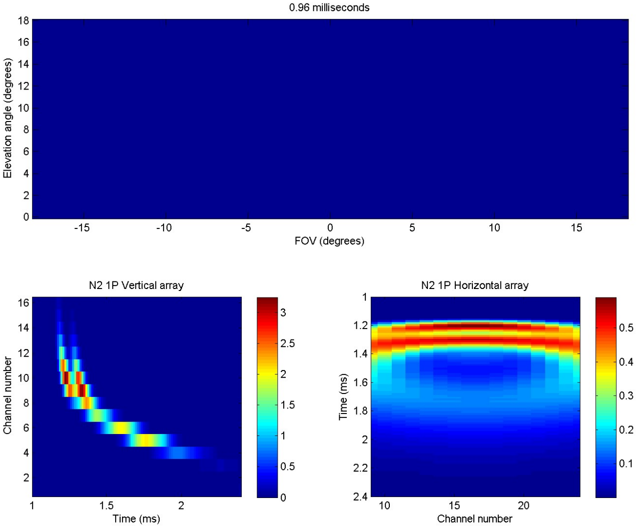
Camera View of Elves!



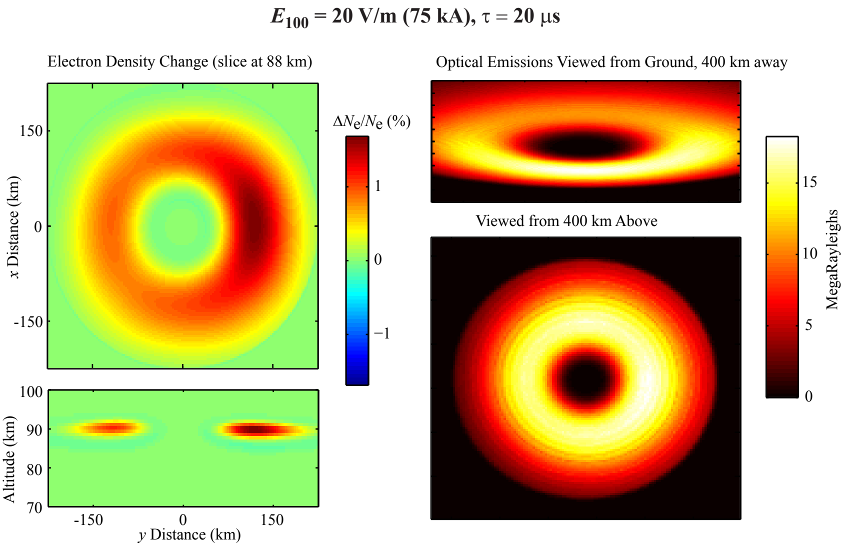
Some Select Simulations

1. Elve Doublets
2. Asymmetry of Elves
3. Elves caused by IC Lightning
4. Modeling of the Lightning Return Stroke

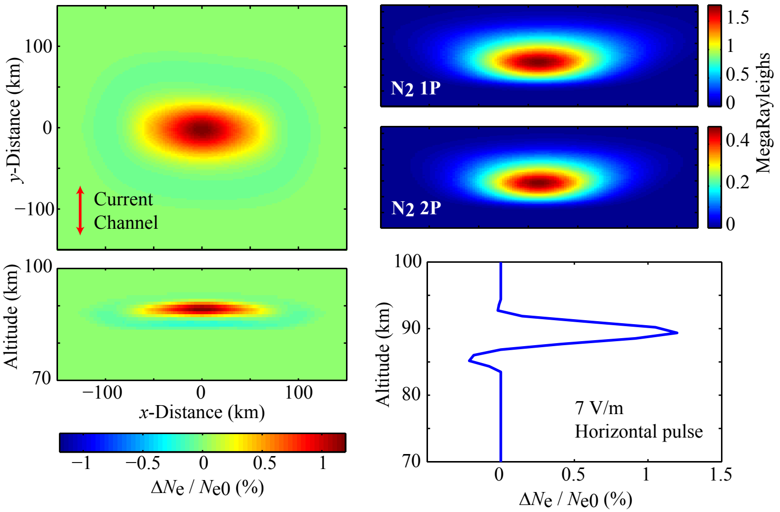
Simulation of Elve Doublets



Asymmetry of Elves due to B Field



Elves Caused by IC Lightning



Modeling the Lightning Source

- The lightning source is input to the model as a time dependent current density, **J**, along the $\theta = 0$ axis
- How this current pulse is modeled is not simple!
  - Old method was to have current rise and fall uniformly along the channel
  - Equivalent to current pulse traveling at $v = \infty$

Improved Lightning Model

- New method: more accurate spatial and temporal description of traveling current
- Two families of current models
    - Transmission line (TL) models
    - Traveling Current Source (TCS) models

[Rakov and Uman, 2003]

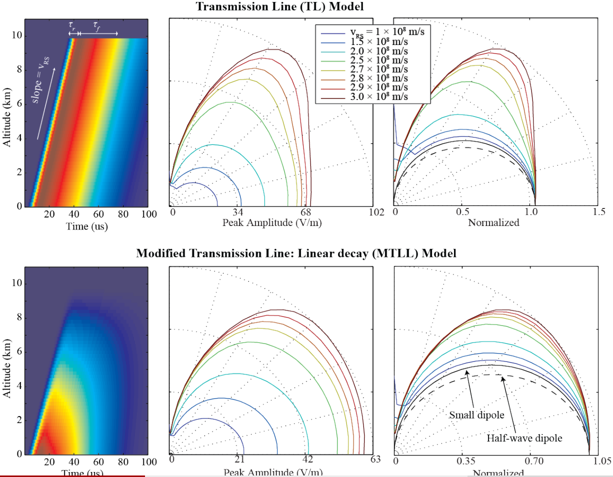
Traveling Current Source (TCS)

Modified Transmission Line Linear Decay (MTLL) Source

Modified Transmission Line Exponential Decay (MTLE) Source

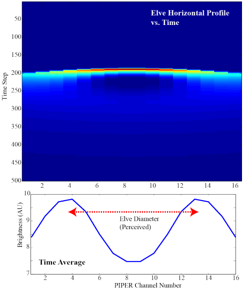
Effects of Return Stroke Model

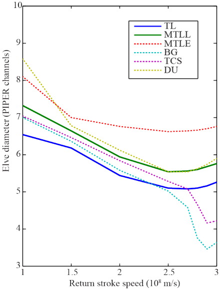
- Radiation pattern is similar to half-wave dipole (depending on channel length, current shape)
- Different current waveforms will produce different radiation patterns



Effects on Elves

- Do different radiation patterns lead to different elve shapes?
- Can we use the geometry of observed elves to learn about the lightning return stroke?





- Needs to be experimentally verified...

Summary

Model Features:

- FDTD solutions of Maxwell's equations in spherical coordinates
- Automatically accounts for Earth curvature
- solution of Langevin equation for cold plasma
- CPML at boundaries
- realistic representation of ionosphere, magnetic field, ground
- Incorporate any spatial / temporal source definition (lightning, transmitter, other)
- Calculation of heating, ionization, etc in any atmosphere (does not include relaxation!)
- Simulates thousands of km in distance, hundreds of km in altitude