ELECTRICAL DISCHARGES IN PLANETARY UPPER ATMOSPHERES: THERMAL AND CHEMICAL EFFECTS

Francisco C. Parra Rojas

Thesis Superviors: Dr. D. Francisco J. Gordillo Vázquez
Dr. D. Alejandro Luque Estepa

Instituto de Astrofísica de Andalucía, IAA-CIC

Physics and Space Sciences Program
Universidad de Granada

June 18, 2015

Table of contens

Table of contens

Table of contens

1. Introduction
2. Halos
3. Sprites

3.1 The state of the art

3.2 Chemical impact

3.3 Thermal impact

4. Electrical discharges on Saturn
5. Conclusions
6. Future work

Table of contens

Why Sprites and Halos?

Mesosphere is the “ignorosphere”

They are the most common TLEs

Why through simulations?

Too high air density to fly with spacecraft

Too low air density to fly with planes and ballons

Table of contens

1. Introduction

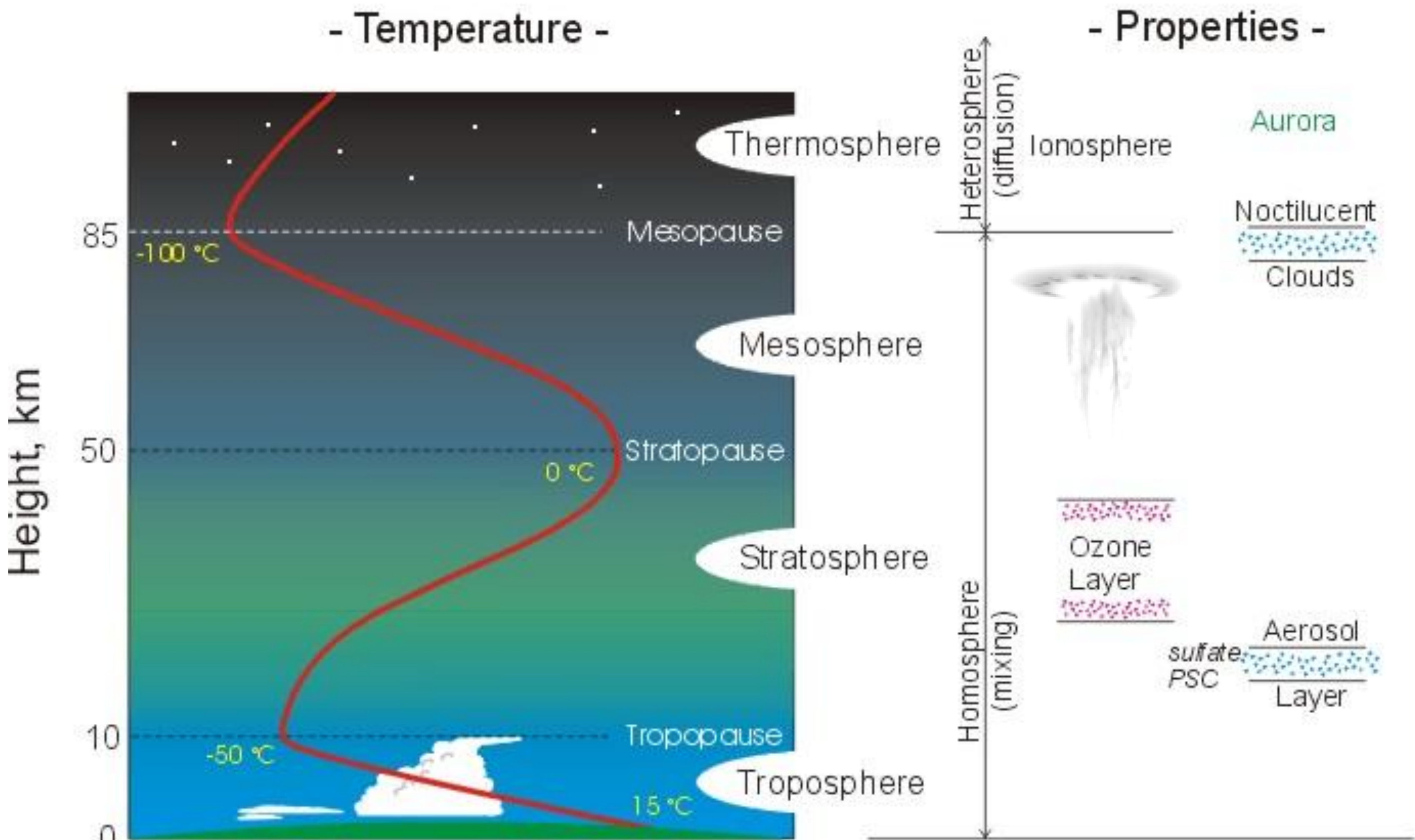
1.1 The atmosphere of the Earth

“The atmosphere is a gaseous layer that surrounds some planets and other celestial bodies”

Composition (below 100 km)

Constituent	Content
Nitrogen (N_2)	78.08 %
Oxygen (O_2)	20.95 %
Argon (Ar)	0.93 %
Water vapor (H_2O)	0-5 %
Carbon dioxide (CO_2)	380 ppm
Neon (Ne)	18 ppm
Helium (He)	5 ppm
Methane (CH_4)	1.75 ppm
Krypton (Kr)	1 ppm
Hydrogen (H_2)	0.5 ppm
Nitrous oxide (N_2O)	0.3 ppm
Ozone (O_3)	0–0.1 ppm

ATMOSPHERIC PROFILE



From Penn State University

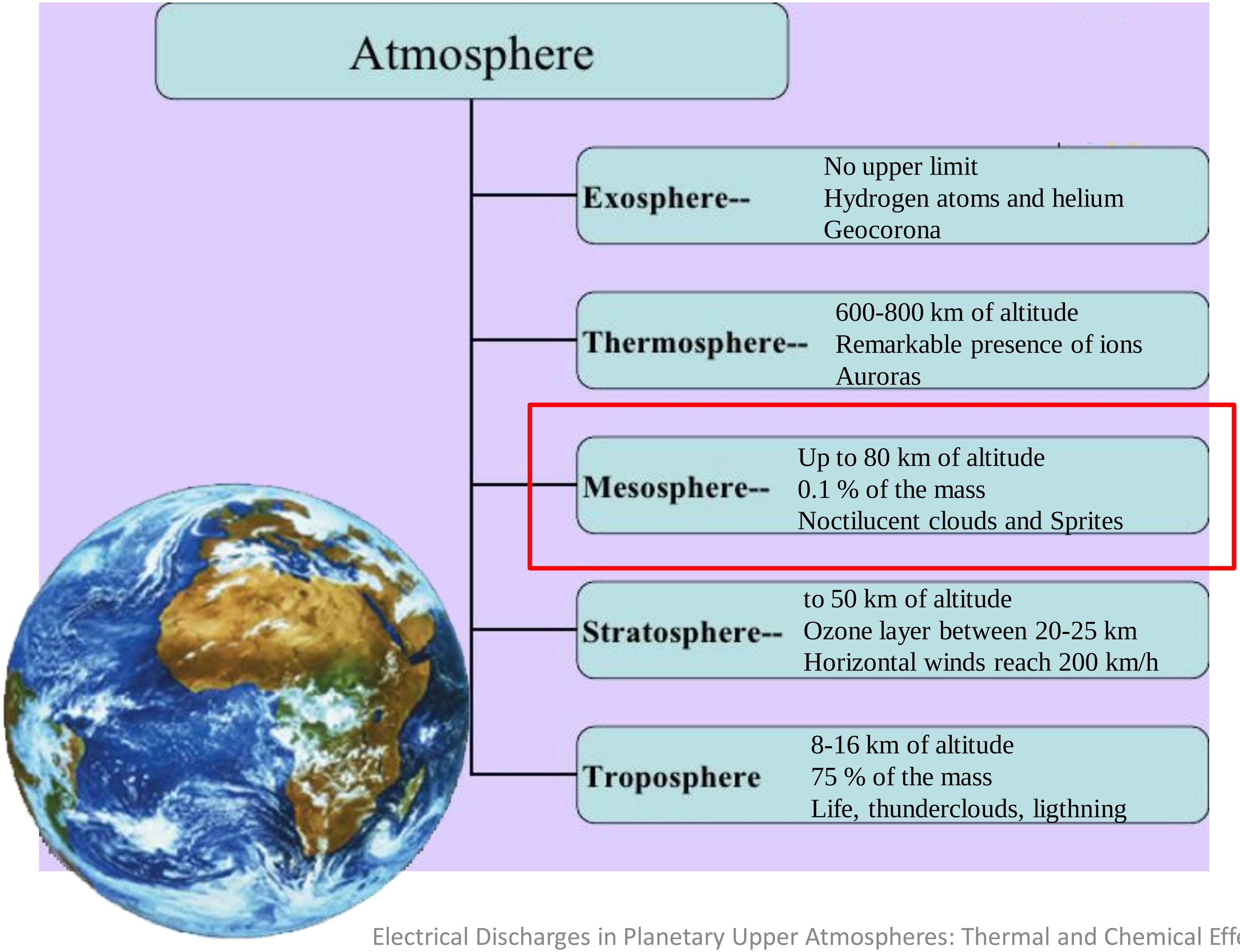

Atmosphere
Exosphere--
No upper limit
Hydrogen atoms and helium
Geocorona
Thermosphere--
600-800 km of altitude
Remarkable presence of ions
Auroras
Mesosphere--
Up to 80 km of altitude
0.1 % of the mass
Noctilucent clouds and Sprites
Stratosphere--
to 50 km of altitude
Ozone layer between 20-25 km
Horizontal winds reach 200 km/h
Troposphere
8-16 km of altitude
75 % of the mass
Life, thunderclouds, ligthning

Table of contens

1.2 Lightning discharges

-Cloud-to-Ground (CG) → Positive (10 %) / Negative (90 %)

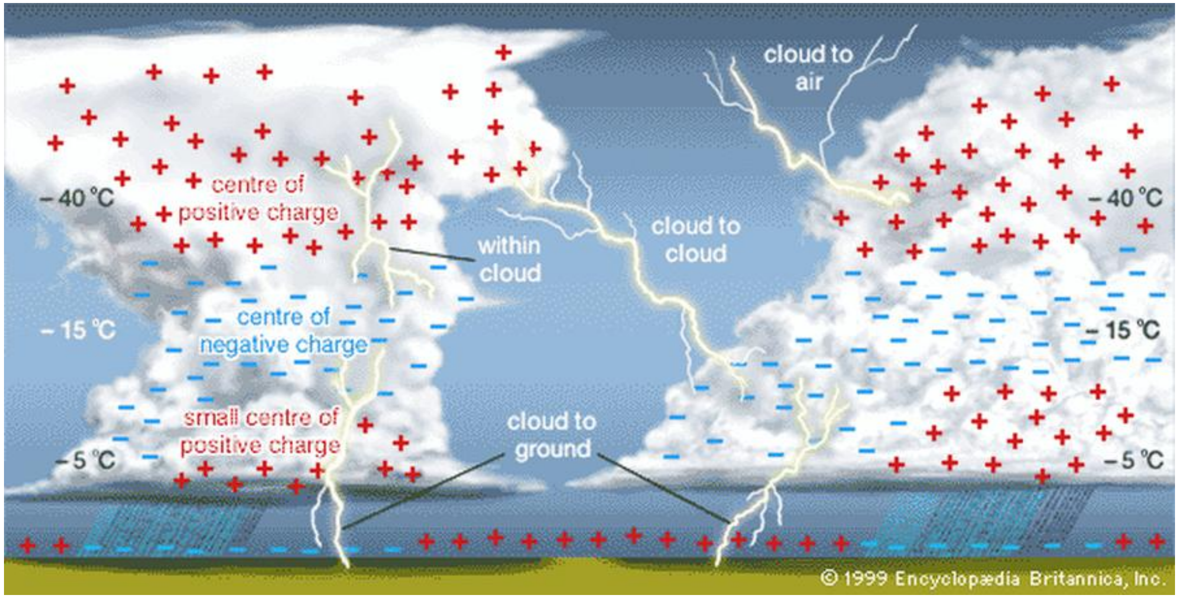
-Intra-Cloud (IC)

-Cloud-to-Cloud(CC)

-Ground-to-Cloud (GC)

-Ball Lightning

-Cloud-to-air

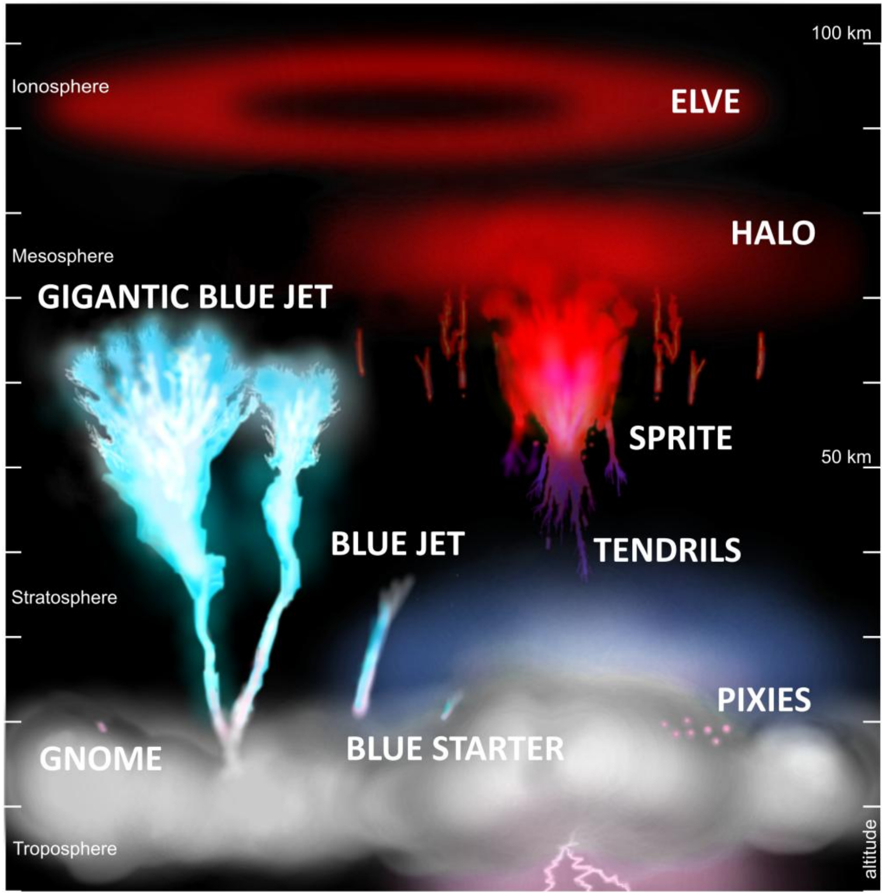


From Encyclopædia Britannica,Inc.

Table of contens

1. Introduction

1.3 Transient Luminous Events



Courtesy of María Passas

M. Passas *et al.*, IEEE Transactions on Plasma Science 2014

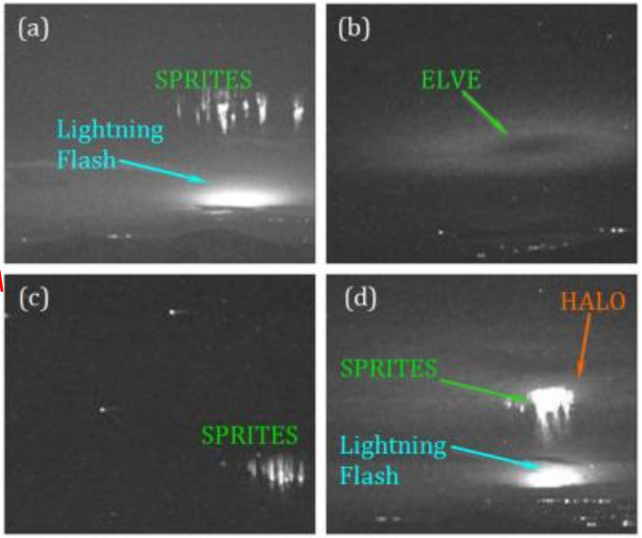
-Discovered serendipitously by

Franz *et al* in 1989

-Hipothesized by Wilson in 1925

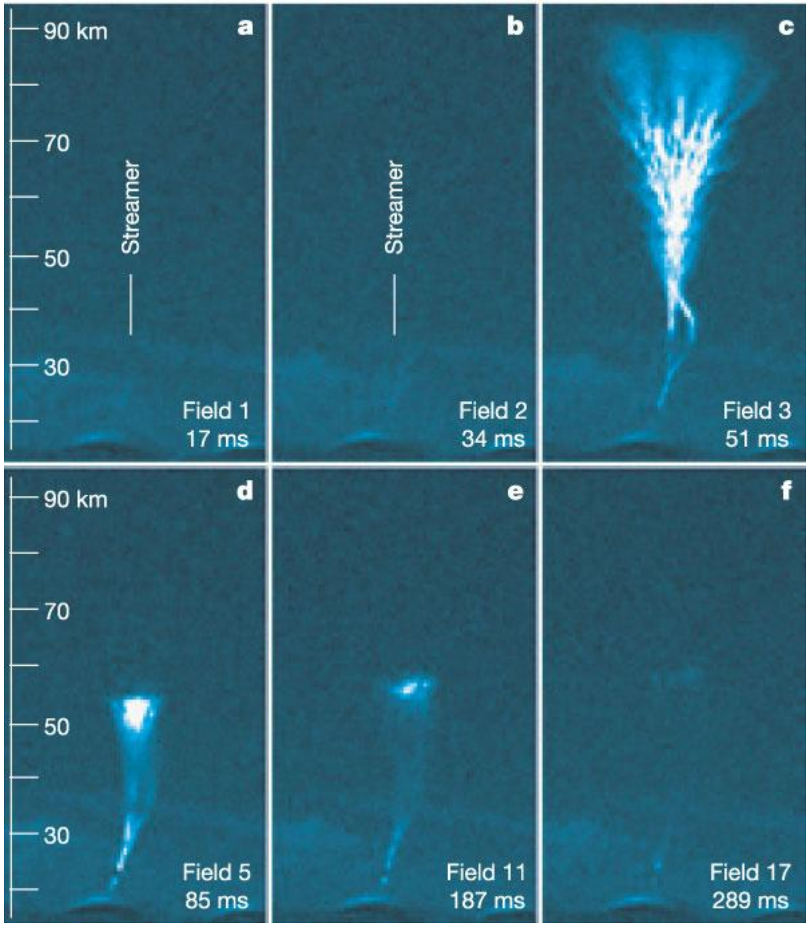
-Related with thunderstorms

-Between 15 – 100 km of altitude



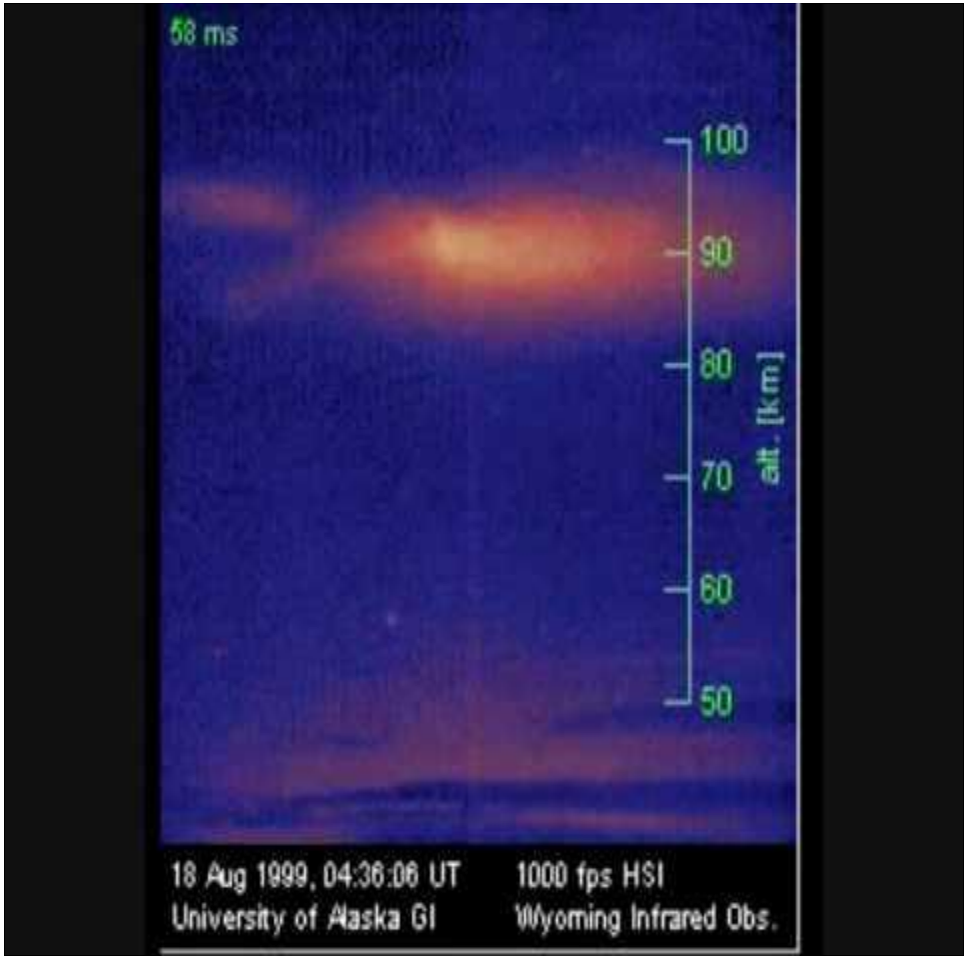
Blue Jets and Blue Starters

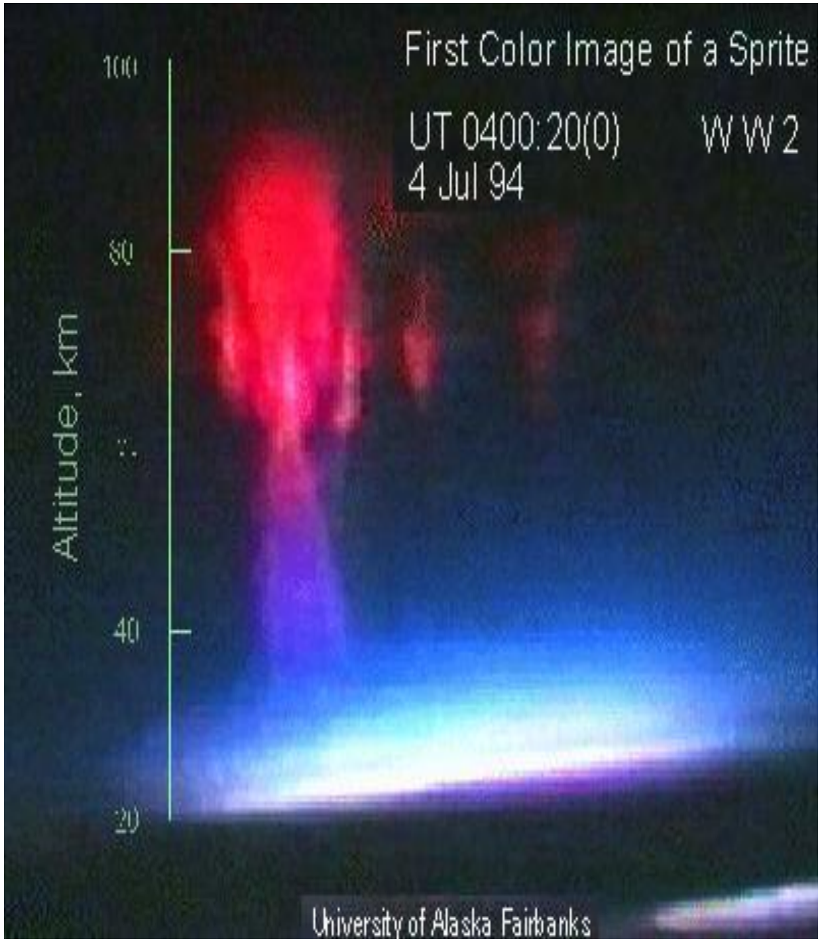
Gigantic Jets



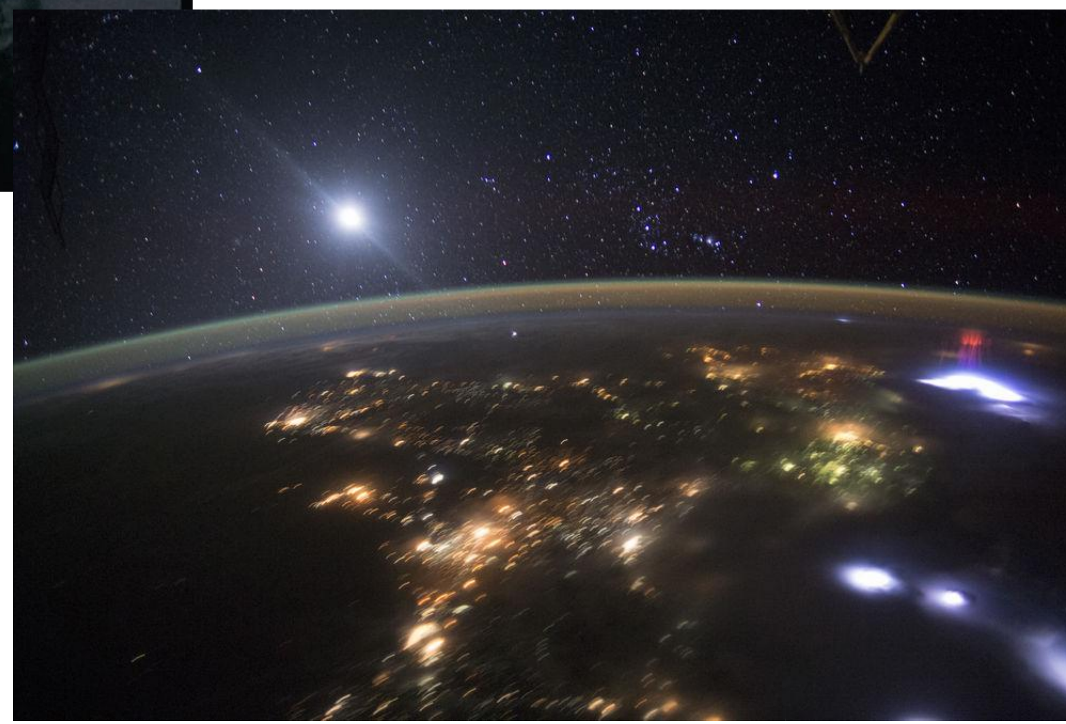
ELVES (**E**missions of **L**ight and **V**ery Low Frequency Perturbations from **E**lectromagnetic Pulse **S**ources)

Halos y Sprites

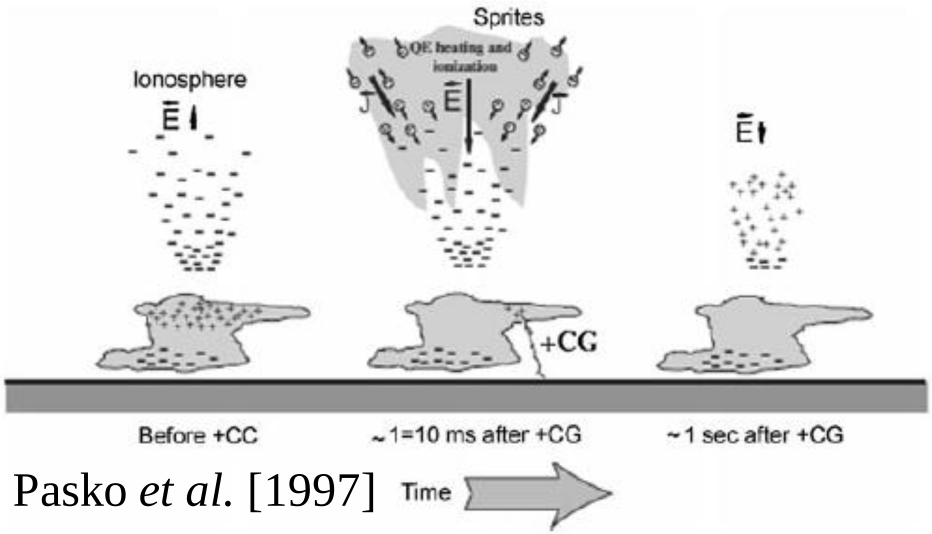




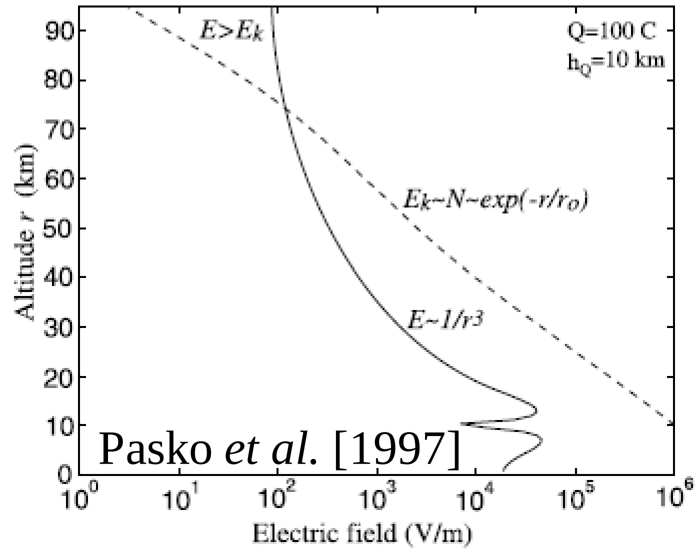

2015/09/01 19:13:47



Generation mechanism of Sprites and Halos



Pasko *et al.* [1997]



Pasko *et al.* [1997]

Breakdown E_k/N = 120 Td

($1\text{Td} = 10^{-17}$ V cm^{-2})

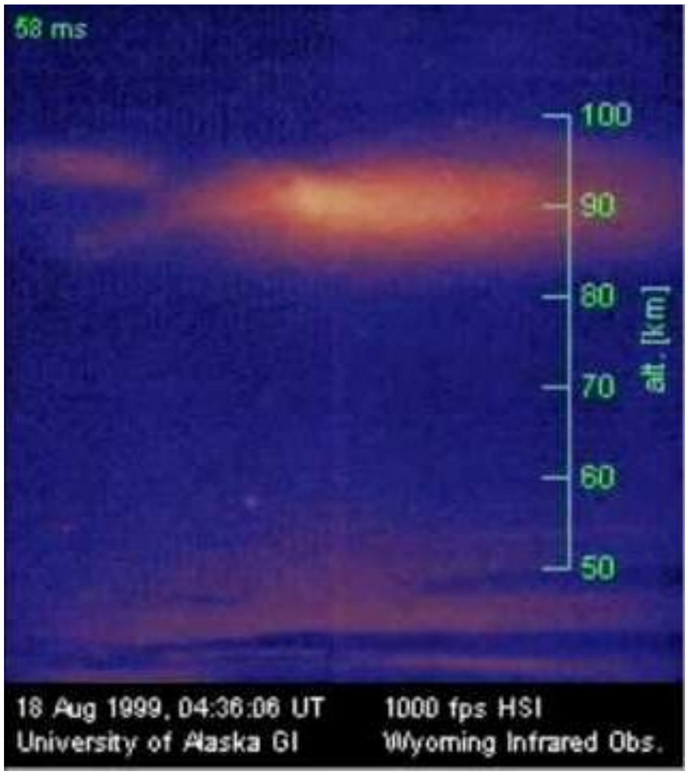
$\nu_a > \nu_i \rightarrow E < E_k$ Sub-breakdown ⟶ $e + A \rightarrow B^- + C$

$\nu_a < \nu_i \rightarrow E > E_k$ Over-voltage ⟶ $e + A \rightarrow A^+ + e + e$

Table of contens

2. Halos

2.1 State of the art



Sentman and Stenbaek-Nielsen
University of Alaska, 1999

-Flattened diffuse reddish flashes

-Between 75 km and 85 km

-Associated with ±CG lightning discharges

-Diameters up to 100 km

-Vertical width of up to 10 km

-QE field mechanims

Some previous simulations:

- +CG lightning discharges could trigger halos up to 70 km of altitude under sub-breakdown conditions (Liu [2012]).
- Successive lightning discharges could affect to the electron density in low ionosphere (Taranenko *et al.* [1993]). Measured by Shao *et al.* [2013].
- Strong increase of the $O(^1D)$ density due to halos (Hiraki *et al.* [2004]).

The theoretical side of our work has two main scientific goals:

(a) to quantify the influence of the mesospheric electric field generated by ±CG on the ambient electron density berteen 50 km and 85 km;

(b) to analyze the dependence on time and altitude of the other important species

Table of contens

2.2 Chemical impact

Ground Neutrals
N, N_2, O, O_2, O_3
NO, NO_2, NO_3, N_2O, N_2O_5
CO, CO_2, Ar

Excited Neutrals
$N_2(A^3\Sigma_u^+$, $B^3\Pi_g$, $C^3\Pi_u$, $a^1\Pi_g$,
$a'^1\Sigma_u^-$, $a''^1\Sigma_g^+$, $B'^3\Sigma_u^-$, $E^3\Sigma_g^+$,
$W^3\Delta_u$, $w^1\Delta_u)$, $O_2(a^1\Delta_g$, $b^1\Sigma_g^+$,
4.5eV), $O(^1D, ^1S)$, $NO(A^2\Sigma^+)$
$N(^2D, ^2P)$, $Ar(^3P)$, N_2(rot), O_2(rot)
$N_2(v=1,\ldots,8)$, $O_2(v=1,\ldots,4)$
$CO_2(v_1, v_2^l, v_3)$

Negative Ions
e^-, O^-, O_2^-, O_3^-
NO^-, NO_2^-, NO_3^-, N_2O^-
CO_3^-

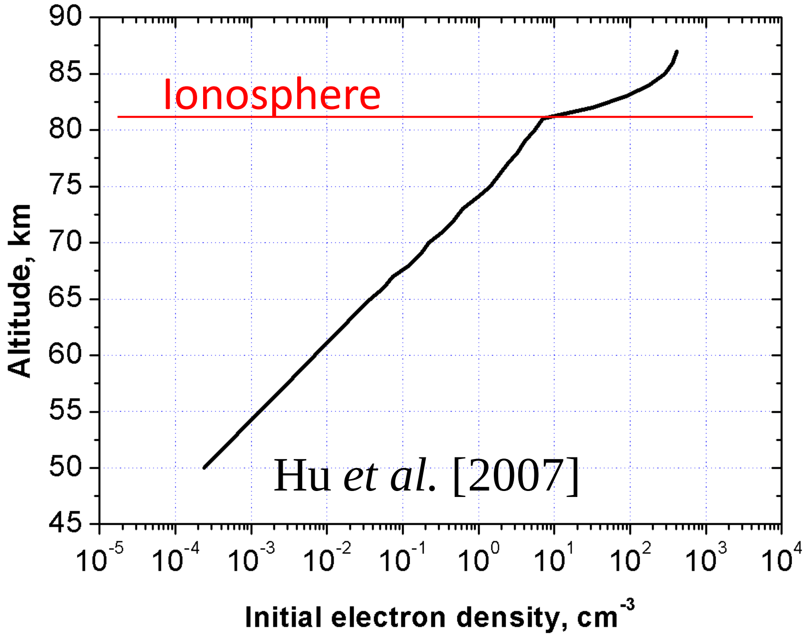
Positive Ions
N^+, N_2^+, $N_2^+(A^2\Pi_u$, $B^2\Sigma_u^+)$
N_3^+, N_4^+, O^+, O_2^+, O_4^+
NO^+, NO_2^+, N_2O^+, $N_2O_2^+$
Ar^+

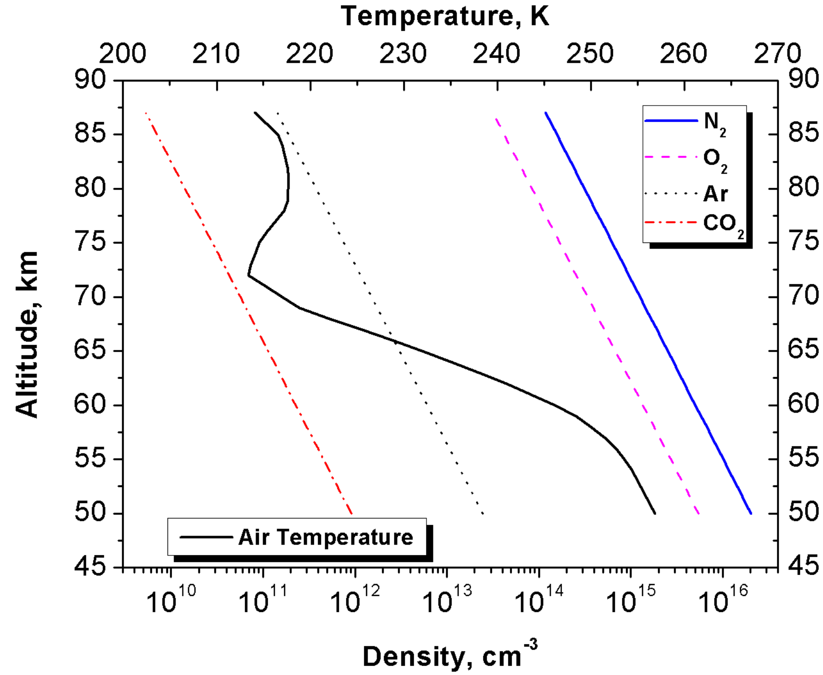
Based in Gordillo-Vázquez, 2008, 2010

…and more than 900 processes including V-T, V-V, electron impact, quenching,…

Parra-Rojas *et al.*, JGR-Space Physics, 2013a

Initial Conditions





<u>Hu *et al.* [2007] density profile</u>

-Midlatitude in Summer

-Nighttime conditions

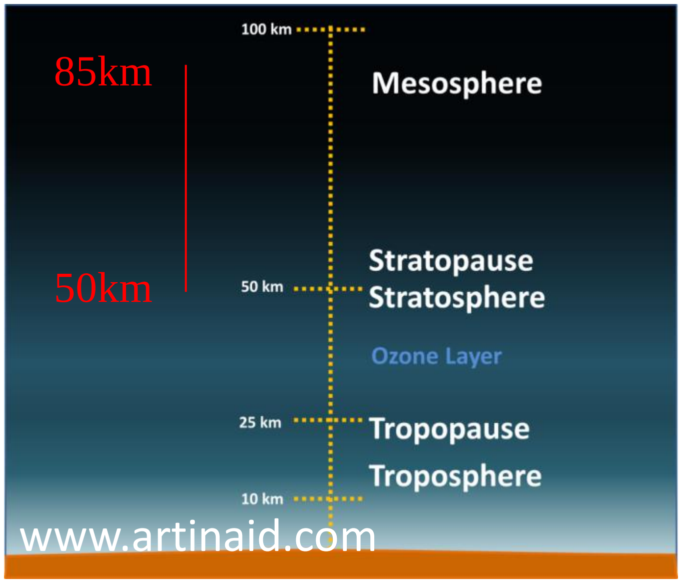
-Modeled (above 80 km)

-Interpolated from some datas (below 80 km)

- Initial electron density from Hu *et al.* [2007]
- Neutral densities extracted from WACCM
- Synthetic current moment profiles of ±CG
- Realistic current moment profile of +CG from Gamerota *et al.* [2012]

Electronic Relaxation

An array of 36 altitudes with
Δz = 1km of vertical resolution



Cosmic rays ionization rates have been adjusted

$$h\nu + N_2 \rightarrow N_2^+ + e^-$$

$$h\nu + O_2 \rightarrow O_2^+ + e^-$$

$$h\nu + N_2 \rightarrow N^+ + N + e^-$$

$$h\nu + O_2 \rightarrow O^+ + O + e^-$$

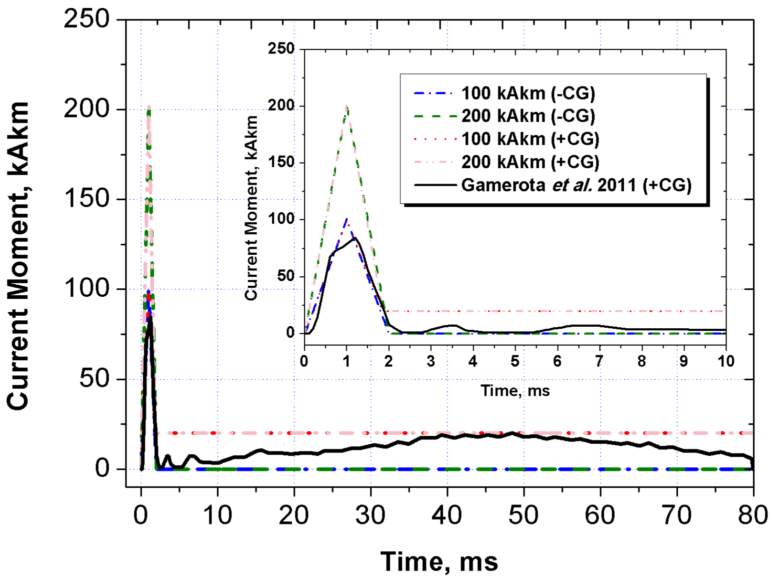
Ambient initial densities are obtained from Statistical Equilibrium Equations

-Perfectly planar geometry
- 1-D model at high altitudes

→ Planar halo
→ No streamers

t_{sim} = 10^6 s
E/N ~ 0 Td

Main Simulations



$$\mathbf{J_T}(t) = \varepsilon_0 \frac{\partial E_p}{\partial t} \propto hI$$

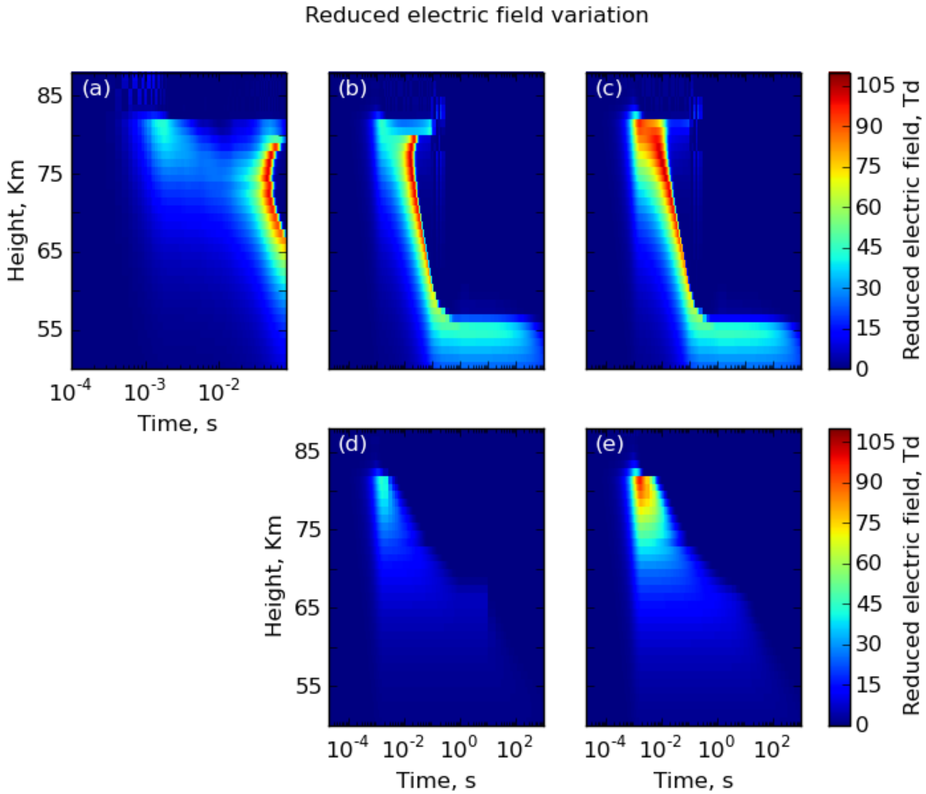
Luque and Gordillo-Vázquez, 2012

$$\frac{\partial n_i}{\partial t} = G_i - L_i$$

$$\frac{e\mathbf{E}(t)}{m_e} \nabla_{\mathbf{v}} f(\mathbf{v},t) = \left(\frac{\partial f}{\partial t}\right)_{collisions}$$

$$\varepsilon_0 \frac{d\mathbf{E}}{dt} = -\sigma\mathbf{E} + \mathbf{J_T}(t)$$

Results



Current Peak

100 kAkm → ~ 40 Td

200 kAkm → ~ 100 Td

} ±CG

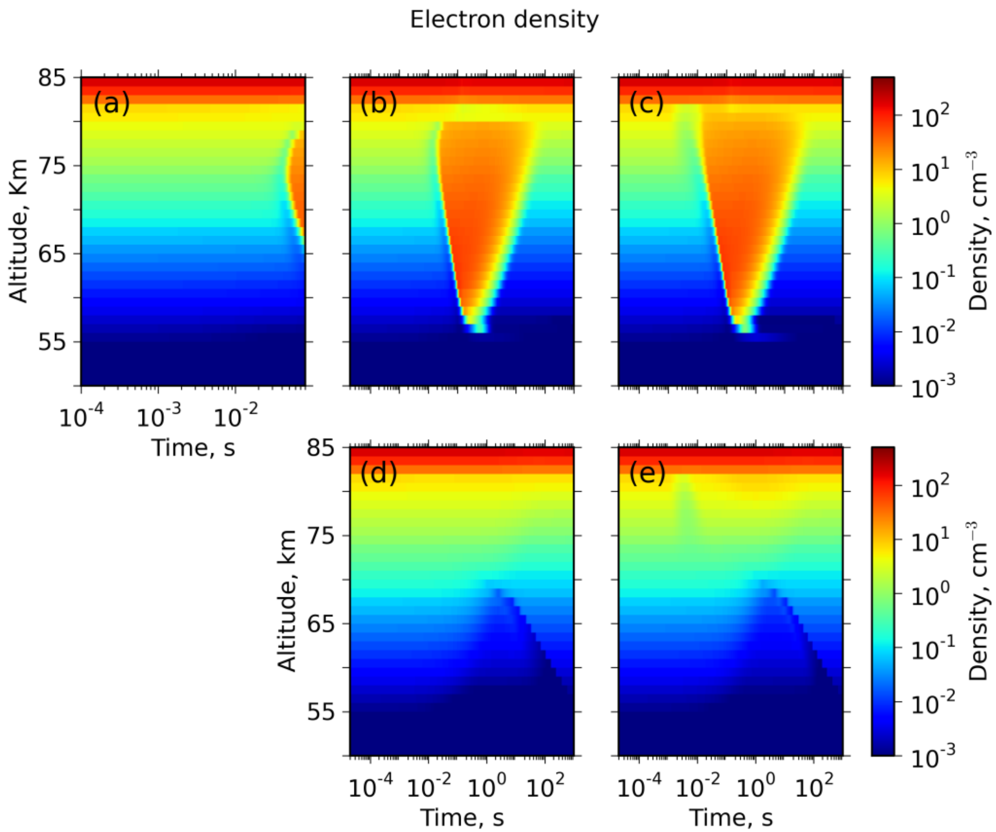
Continuous current

20 kAkm → ~ 100 Td → +CG

Sub-breakdown values !!

The reduced electric field is strongly coupled with N_e through the equation

$$\varepsilon_0 \frac{dE}{dt} = -eN_e \mu(E)E + J_T(t) \quad \Longrightarrow \quad \textbf{If } \mathbf{N_e} \uparrow\uparrow \; \Rightarrow \; \mathbf{E/N} \downarrow\downarrow$$



For +CG lightning discharges

Slight decrease in N_e before the maximum reduced electric field

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

Sharp increase in N_e at the time of maximum reduced electric field

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

Remain at "high" values due to the competition between

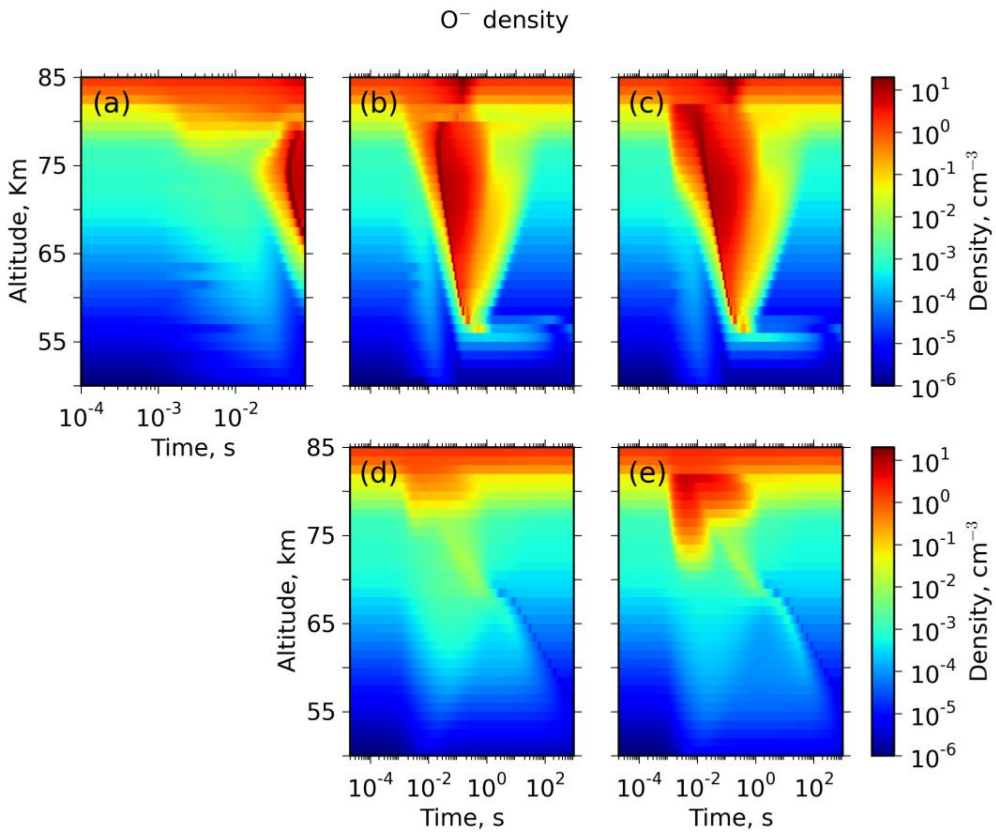
$O^- + CO \rightarrow CO_2 + e$

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

For -CG lightning discharges

Slight decrease in N_e after the maximum reduced electric field at low altitudes

$e + O_3 \rightarrow O^- + O_2$



Abrupt increase when E/N_{max} for ±CG lightning discharges

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

The O^- density descends to ambient values due to

$O^- + N_2 \rightarrow N_2O + e$ (100 ms)

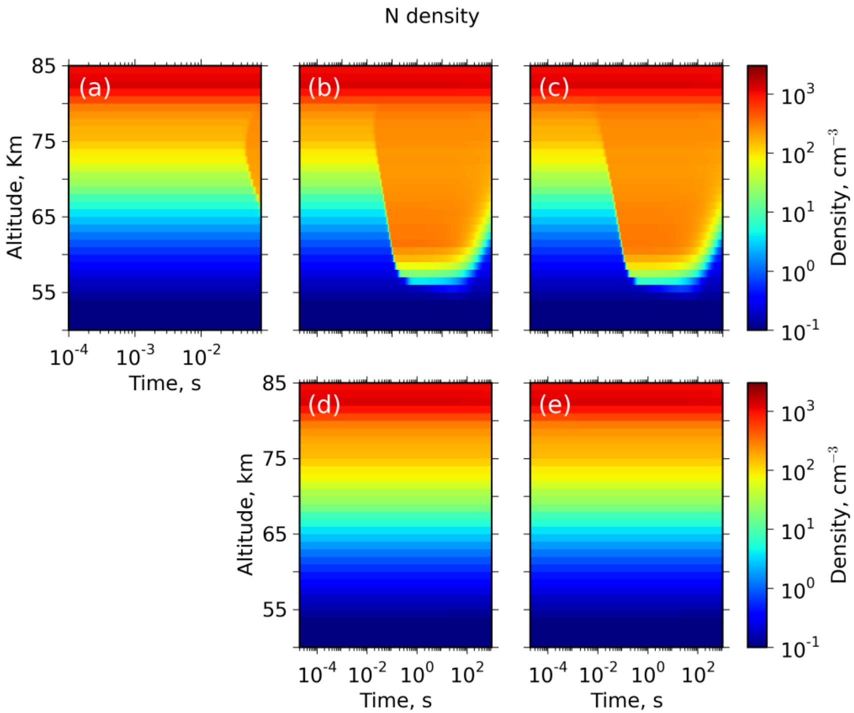
$O^- + CO \rightarrow CO_2 + e$

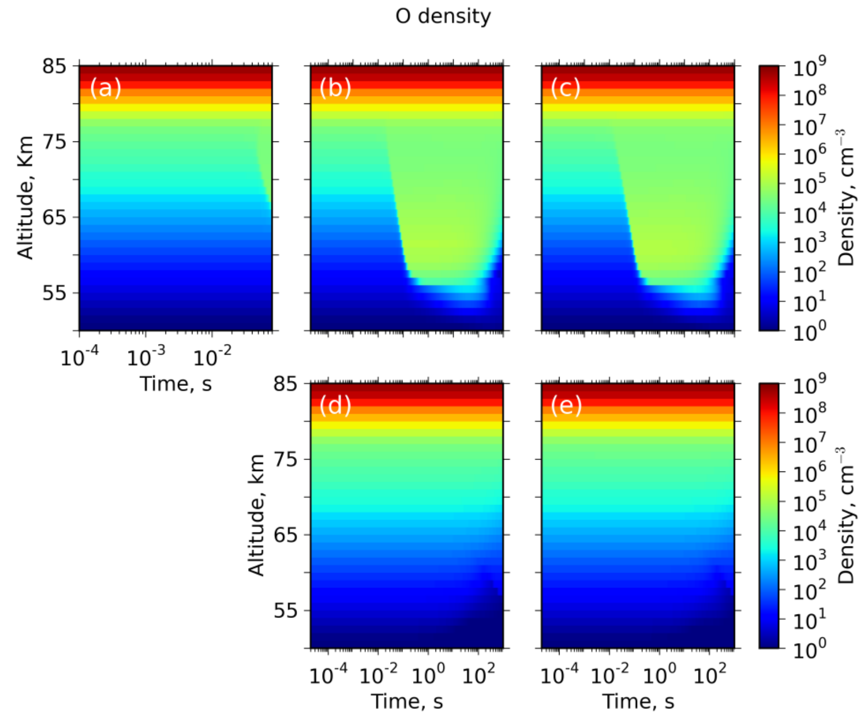
for +CG lightning discharges

for –CG lightning discharges

$O^- + O_3 \rightarrow O_2 + O_2 + e$

$O^- + O_3 \rightarrow O_3^- + O$





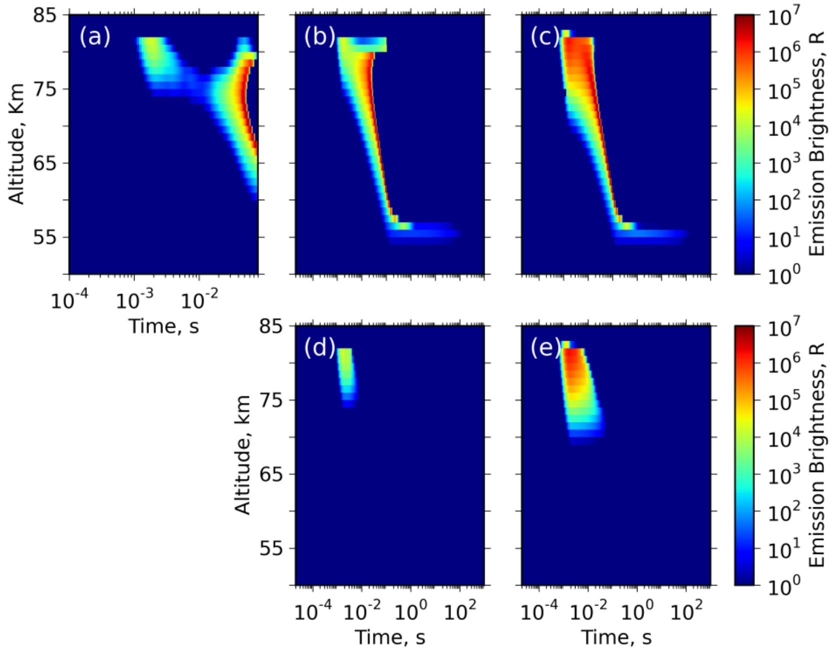
Their behavior significantly depends
on the intensity of the continuous current

$$e + O_2 \rightarrow O + O + e$$

$$e + N_2 \rightarrow N(^2D) + N + e$$

$$N_2(A^3\Sigma_u^+) + O_2 \rightarrow N_2 + O + O$$

Emission brightness of the first positive band system



Instantaneous emission brightness of the first positive band system of N_2

$N_2(B^3\Pi_g) \rightarrow N_2(A^3\Sigma_u^+) + h\nu$

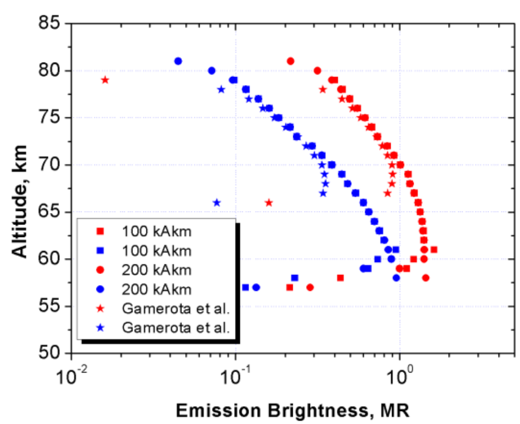
$$EB(R) = 10^{-6}\int_L V(L)dL$$

$$V(L) = A_k(s^{-1})N_k(cm^{-3})$$

L = 100 km

1R = 10^{10} photons m^{-2} s^{-1}

30 fps camera



1000 fps camera

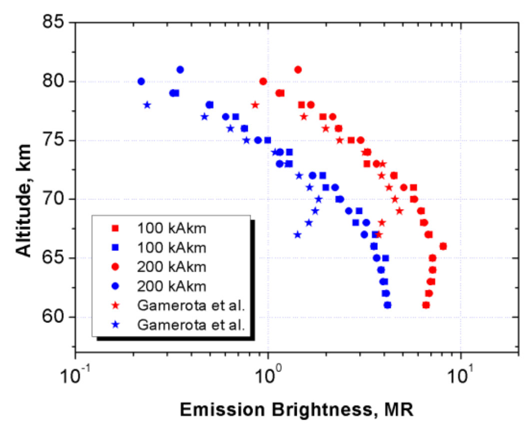
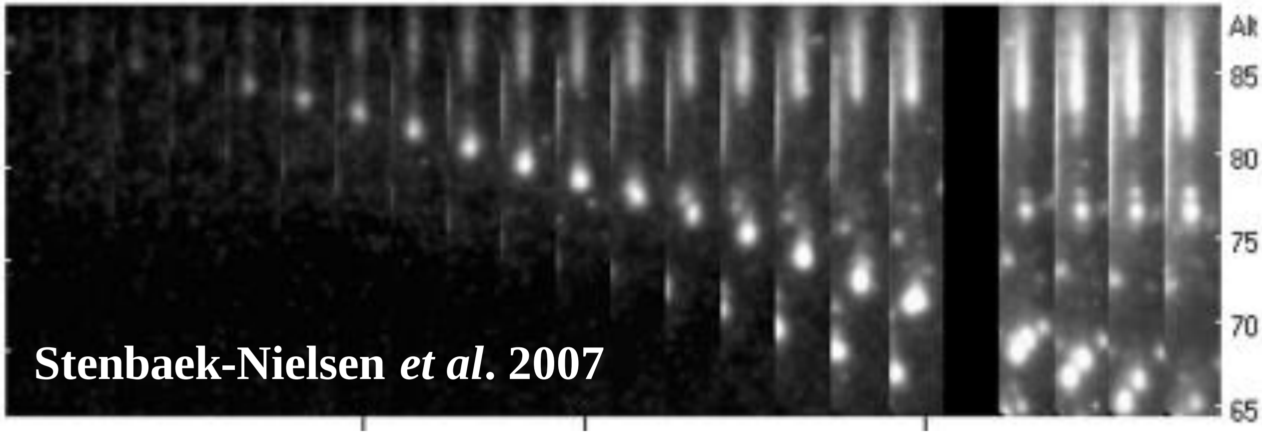


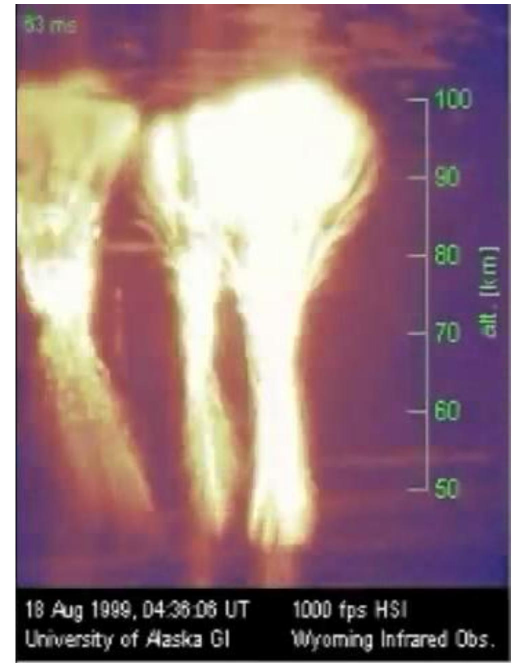
Table of contens

3. Sprites

3.1 State of the art



Stenbaek-Nielsen *et al*. 2007



Sentman and Stenbaek-Nielsen
University of Alaska, 1999

- -Filamentary structures (streamers)
- -Red ($1PN_2$) and blue ($2PN_2$) optical emissions
- -Between 40 km and 85 km
- -Associated with +CG lightning discharges
- -Diameters up to 30 km
- -QE field mechanims

Some previous simulations:

- Strong enhancement of NO_x density (among others) at different altitudes has been calculated (Sentman *et al.* [2008b], Gordillo-Vázquez [2008,2010], Enell *et al.* [2008]).

- The electron production due to AD of O^- by N_2 could be the mechanism responsible of the delayed sprites (Luque and Gordillo-Vázquez [2012]).

- Possible depletion of the ozone concentration (~ 15 %) under the action of diurnal sprites (Winkler and Nothold [2014]).

- A range of temperature variation between 0.2 – 2 % has been predicted in the lower mesosphere (Pasko *et al.* [1998]).

- The sprite IR emission could be detected from space (Picard *et al.* [1997], Milikh *et al.* [1998])

Some previous measurements:

- A possible sprite induced NO_2 enhancement of 10 % at 52 km over a thunderstorm was detected by MIPAS (Arnone *et al*. [2008]).

- Rodger *et al*. [2008] did not measure a significant global impact of TLEs in the concentration of NO_x between 20-70 km.

The theoretical side of our work has three main scientific goals:

(a) to analyze the dependence on time and altitude of the main species in mesosphere;

(b) to quantify the mesospheric heating produced by sprites and identify the mechanisms responsible of this;

(c) to study the possibility of detection of the sprite IR emission from the space.

Table of contens

3.2 Chemical impact

Ground Neutrals
N, N_2, O, O_2, O_3
NO, NO_2, NO_3, N_2O, N_2O_5
CO, CO_2, Ar

Excited Neutrals
$N_2(A^3\Sigma_u^+, B^3\Pi_g, C^3\Pi_u, a^1\Pi_g,$
$a'^1\Sigma_u^-, a''^1\Sigma_g^+, B'^3\Sigma_u^-, E^3\Sigma_g^+,$
$W^3\Delta_u, w^1\Delta_u)$, $O_2(a^1\Delta_g, b^1\Sigma_g^+,$
4.5eV), $O(^1D, ^1S)$, $NO(A^2\Sigma^+)$
$N(^2D, ^2P)$, $Ar(^3P)$, N_2(rot), O_2(rot)
$N_2(v=1,\ldots,8)$, $O_2(v=1,\ldots,4)$
$CO_2(v_1, v_2^l, v_3)$

Negative Ions
e^-, O^-, O_2^-, O_3^-
NO^-, NO_2^-, NO_3^-, N_2O^-
CO_3^-

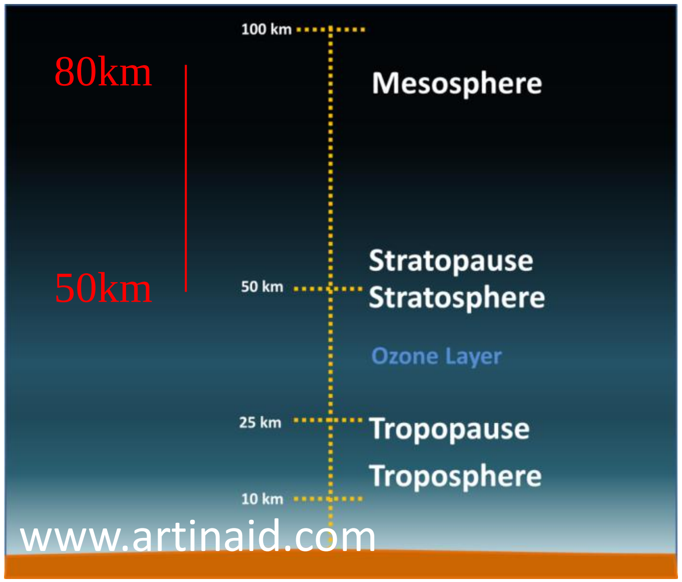
Positive Ions
N^+, N_2^+, $N_2^+(A^2\Pi_u, B^2\Sigma_u^+)$
N_3^+, N_4^+, O^+, O_2^+, O_4^+
NO^+, NO_2^+, N_2O^+, $N_2O_2^+$
Ar^+

…and more than 900 processes including V-T, V-V, electron impact, quenching,…

Parra-Rojas et al., JGR-Space Physics, 2015, Accepted

Electronic and Thermal Relaxation

An array of 31 altitudes with
Δz = 1km of vertical resolution



Be careful!!
At low altitude we have **tendrils**

Cosmic rays ionization rates have been adjusted

$$h\nu + N_2 \rightarrow N_2^+ + e^-$$

$$h\nu + O_2 \rightarrow O_2^+ + e^-$$

$$h\nu + N_2 \rightarrow N^+ + N + e^-$$

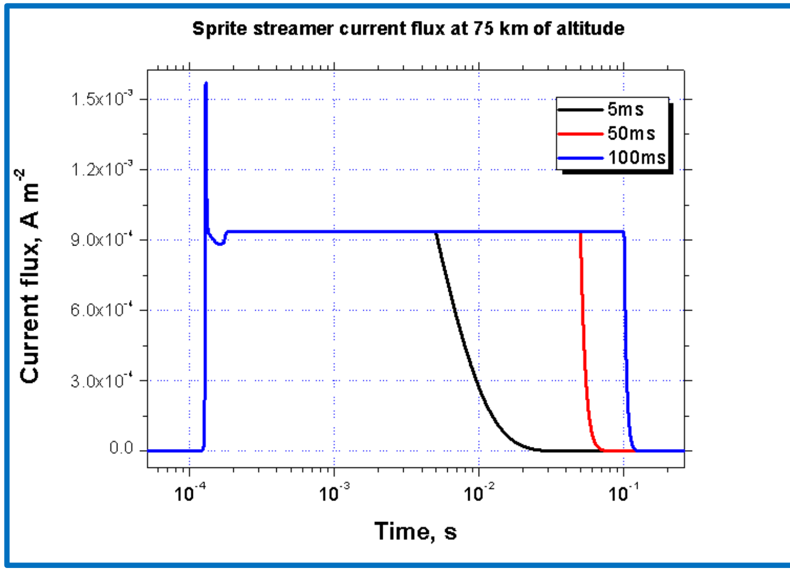
$$h\nu + O_2 \rightarrow O^+ + O + e^-$$

Ambient initial densities are obtained from Statistical Equilibrium Equations

Thermal equilibrium in nighttime conditions

$t_{sim} = 10^6$ s
$E/N \sim 0$ Td

Main Simulations



Luque *et al.*, JPhD, 2008
Luque and Ebert, GRL, 2010

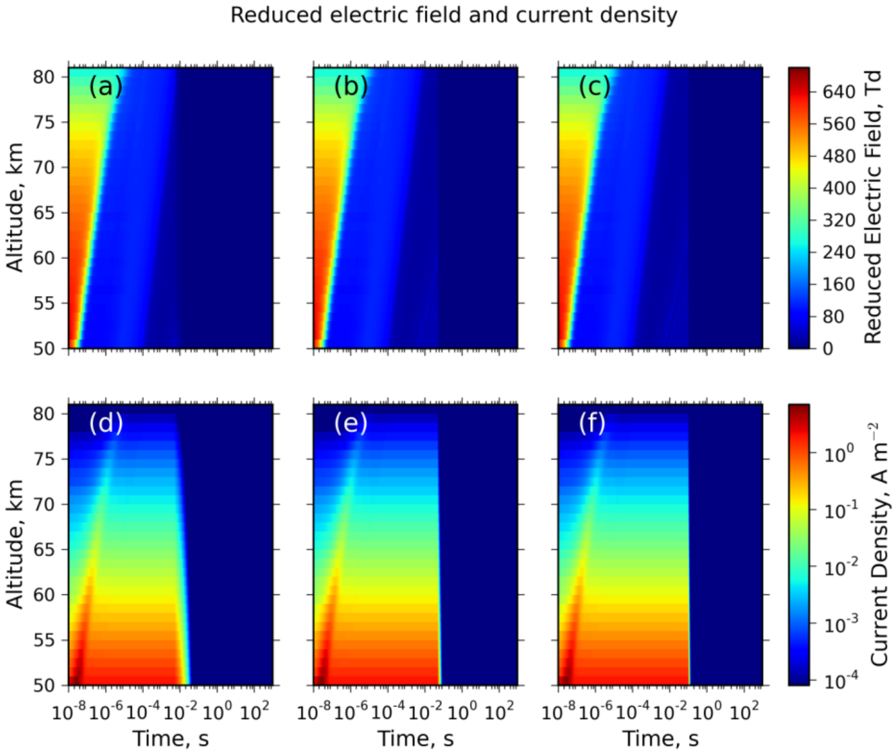
$$\frac{\partial n_i}{\partial t} = G_i - L_i$$

$$E = \frac{J}{\sigma}$$

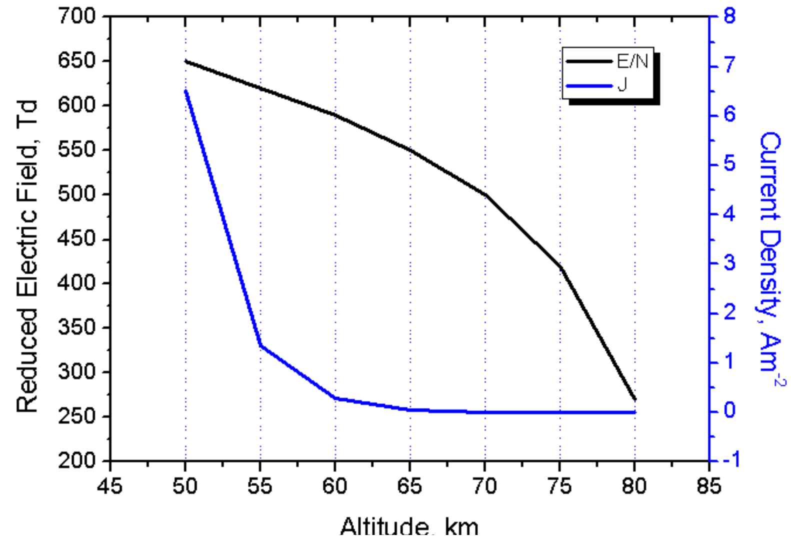
$$P_{gas} = P_{ext} + P_{abs} - P_{elec} - P_{chem} - P_{rad}$$

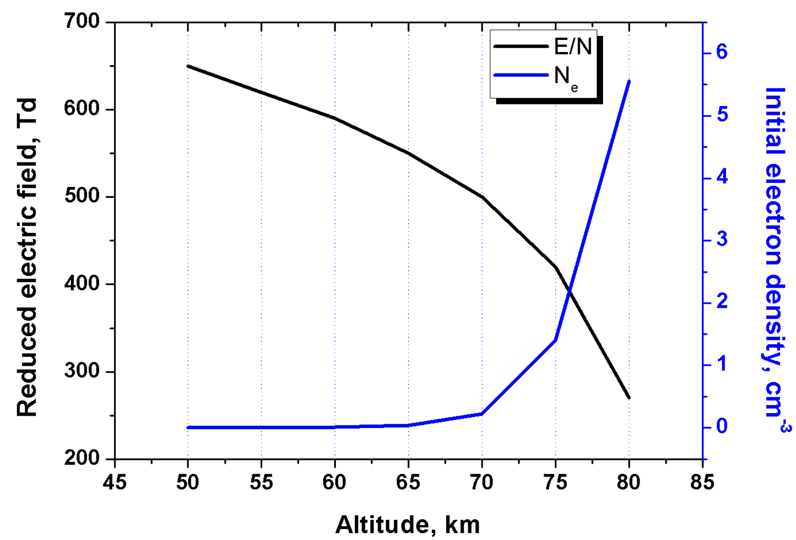
$$\frac{e\mathbf{E}(t)}{m_e} \nabla_{\mathbf{v}} f(\mathbf{v}, t) = \left(\frac{\partial f}{\partial t} \right)_{collisions}$$

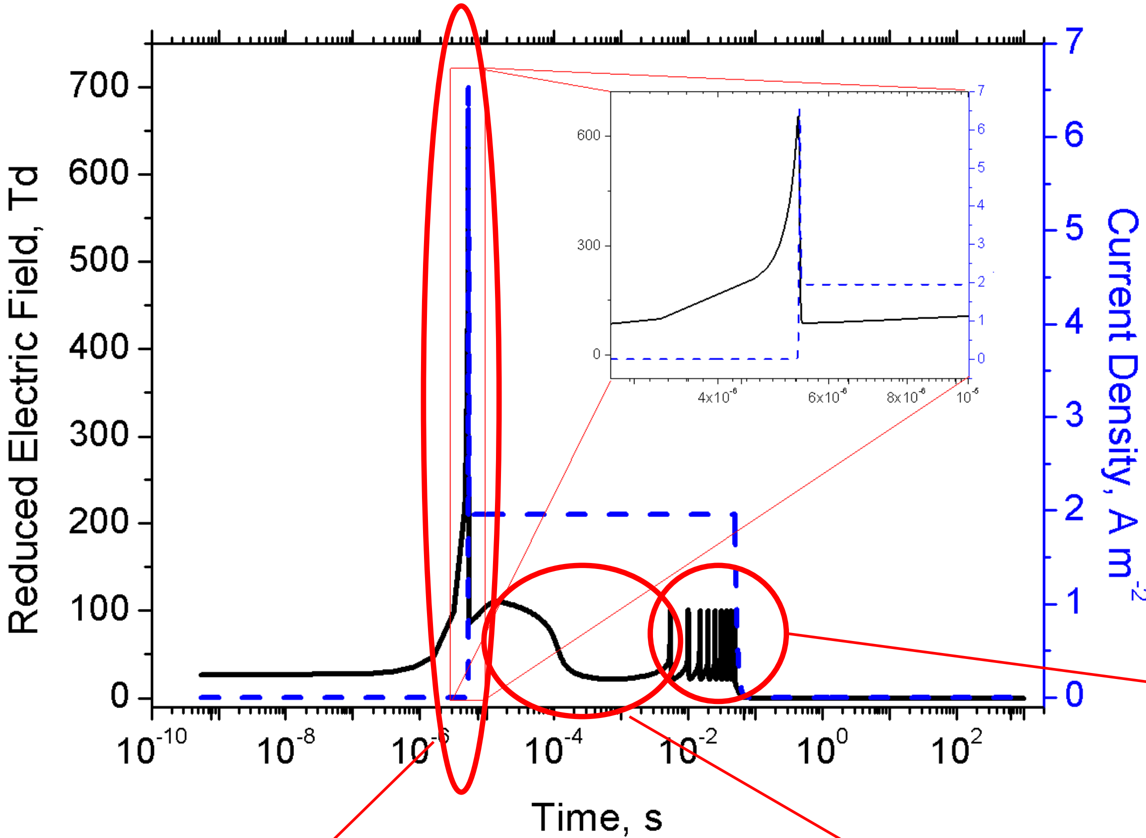
Results



$$E = \frac{J}{\sigma} = \frac{J}{e n_e \mu_e}$$







Oscillations (Crawlers?)

v = 10^5 m/s

$10^4 – 10^5$ m/s [Moudry 2003]

Streamer head

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

$e + N_2 \rightarrow N_2^+ + e + e$

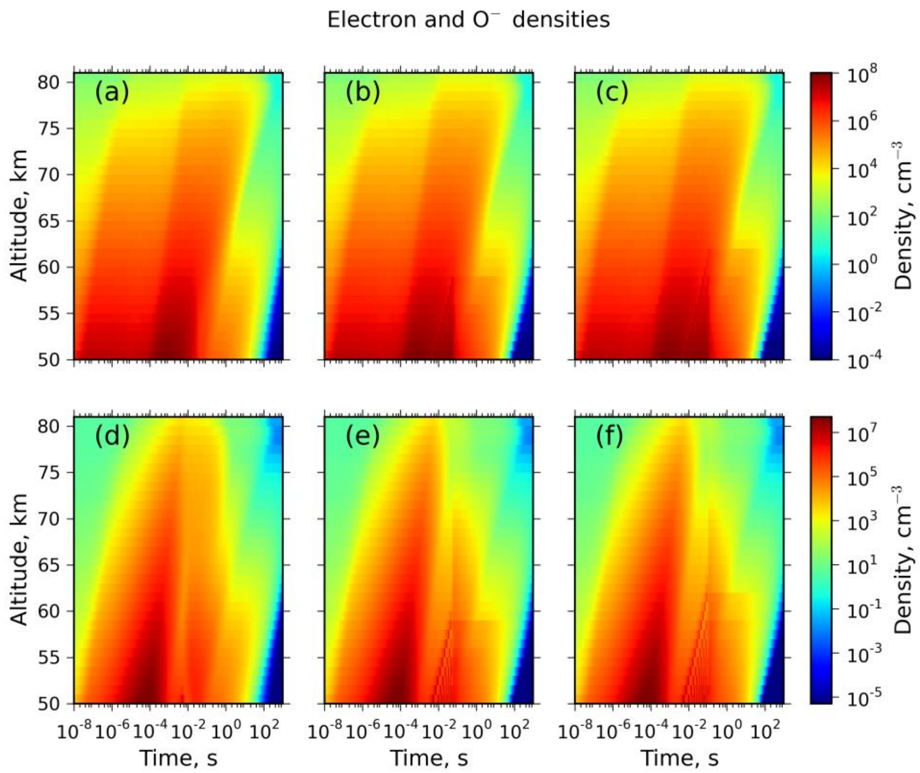
$e + O_2 \rightarrow O_2^+ + e + e$

Afterglow

$e + O_2 \rightarrow O^- + O$ (E < 60 Td)

$O^- + N_2 \rightarrow N_2O + e$ (60 Td < E < 120 Td)

Luque and Gordillo-Vázquez, 2012



Strong increase of electron density

$e + N_2 \rightarrow N_2^+ + e + e$
$e + O_2 \rightarrow O_2^+ + e + e$

Secondary enhancement

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

Remains high due to the fight between

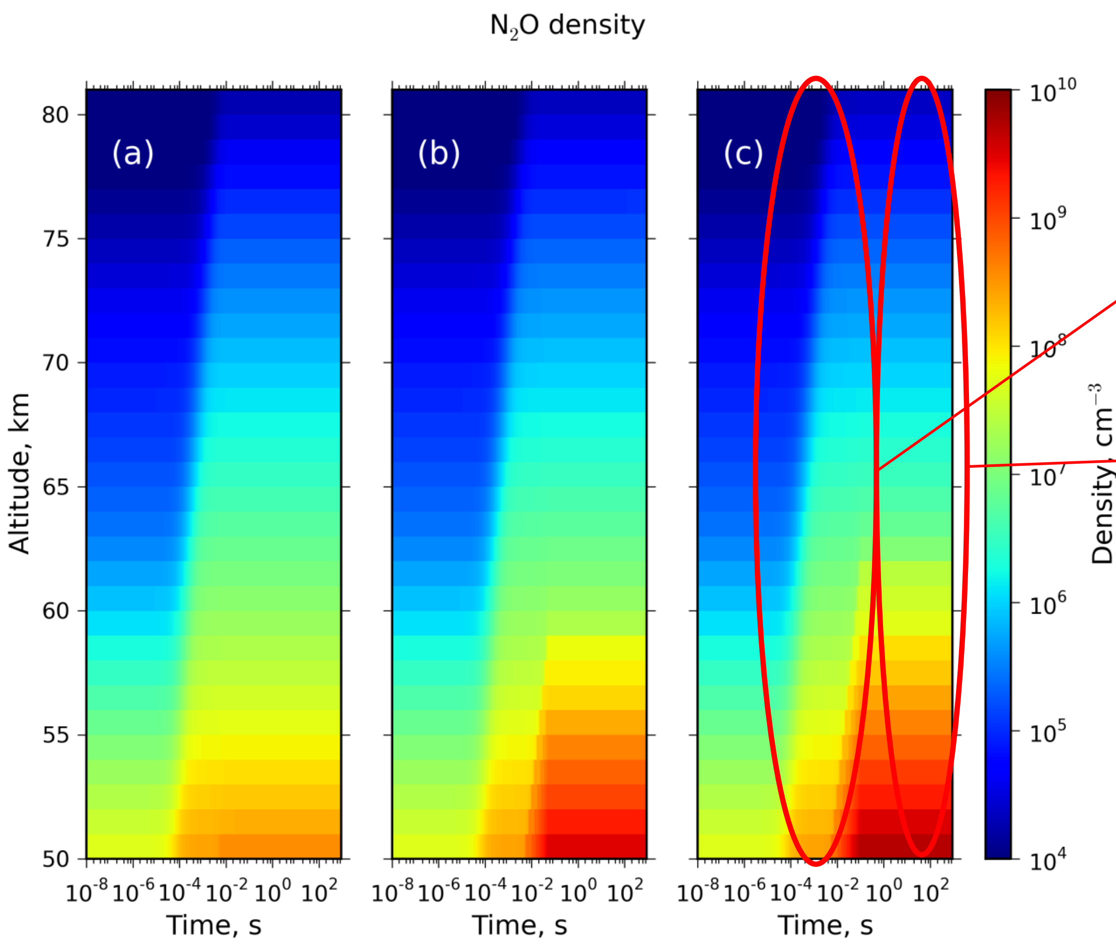
$O^- + N_2 \rightarrow N_2O + e$
$e + O_4^+ \rightarrow O_2 + O + O$
$e + O_4^+ \rightarrow O_2 + O_2$

Increase up to 13 orders of magnitude

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

and fall down by AD

$O^- + N_2 \rightarrow N_2O + e$
$O^- + CO \rightarrow CO_2 + e$
$O^- + O_2 \rightarrow O_3 + e$

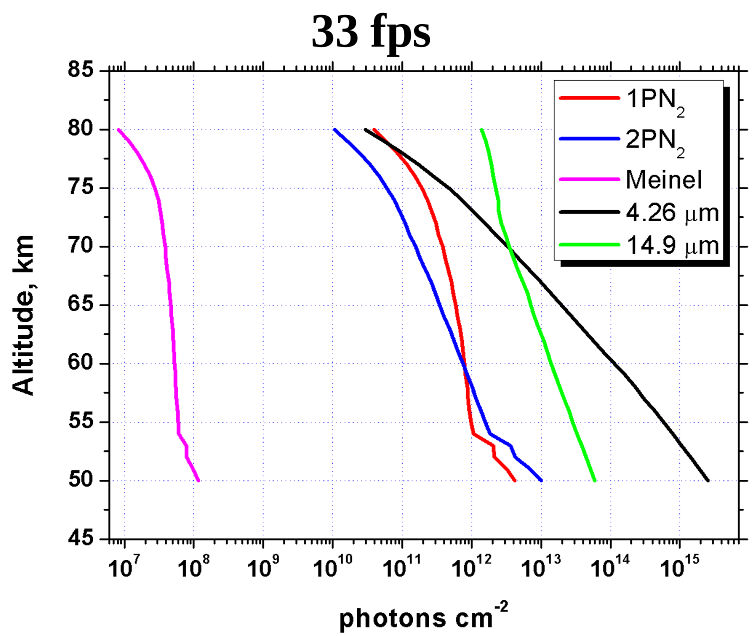


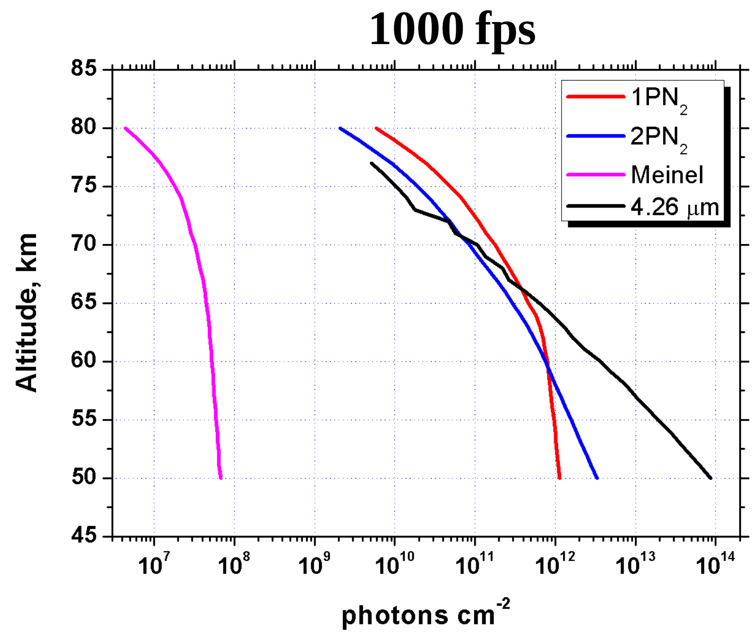
$O^- + N_2 \rightarrow N_2O + e$

$N + NO_2 \rightarrow N_2O + O$

$e + N_2O \rightarrow N_2 + O + e$

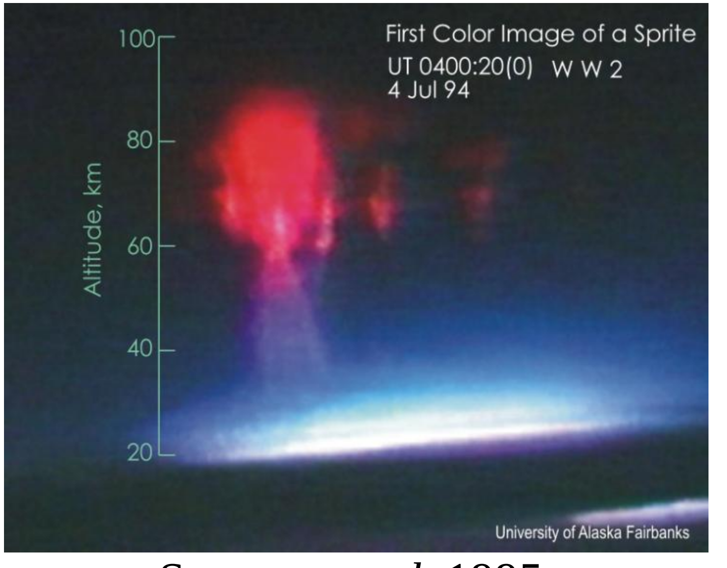
$O^- + N_2O \rightarrow NO^- + NO$





4.26 μm $$\frac{[CO_2(00^01)]_{after}}{[CO_2(00^01)]_{before}} > 100$$

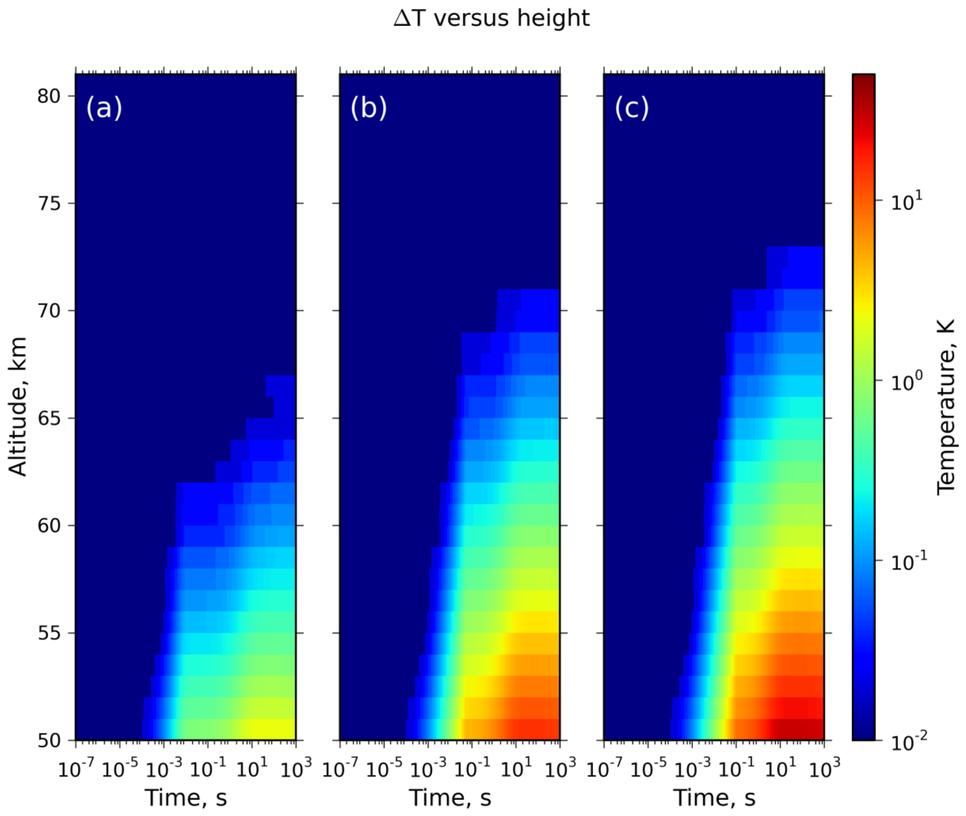
14.9 μm $$\frac{[CO_2(01^10)]_{after}}{[CO_2(01^10)]_{before}} > 10$$



Sentman *et al.* 1995

Table of contens

3.3 Thermal impact

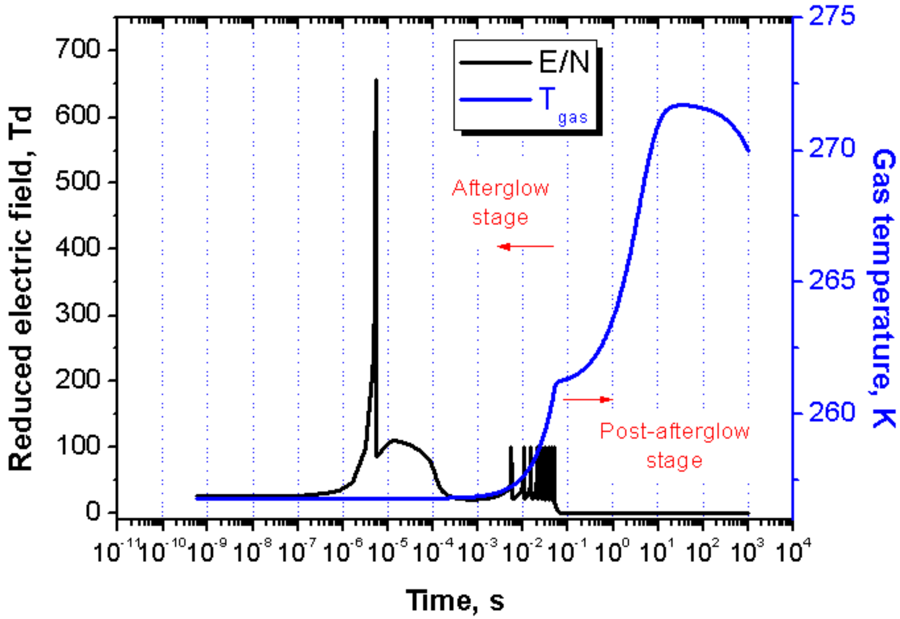


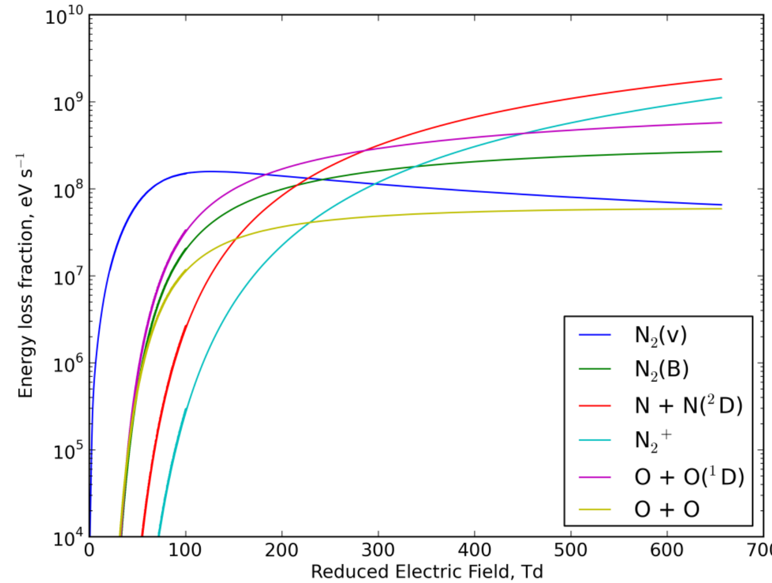
ΔT/T(100 ms) ~ 11 %

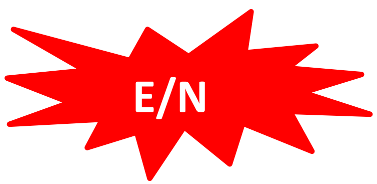
ΔT/T(50 ms) ~ 6 %

ΔT/T(5 ms) ~ 0.9 %

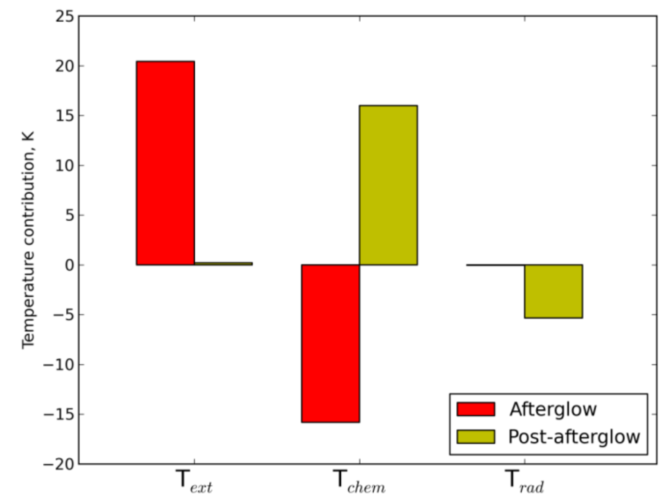
ΔT/T ~ 0.2-2 %
(Pasko *et al*. GRL 1998)







$e + N_2 \rightarrow N_2(v) + e$



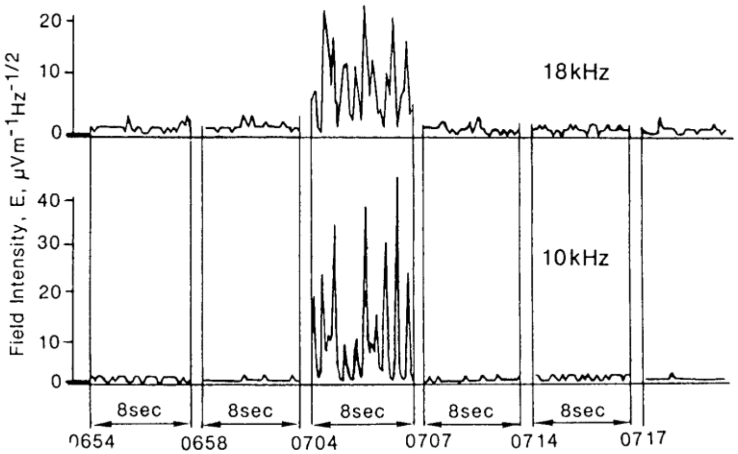
$N_2(v) + CO_2 \rightarrow N_2 + CO_2(v_1\ v_2^l\ v_3)$ ➡ $CO_2(v_1\ v_2^l\ v_3) \rightarrow CO_2 + h\nu$

Table of contens

4. Electrical discharges on Saturn

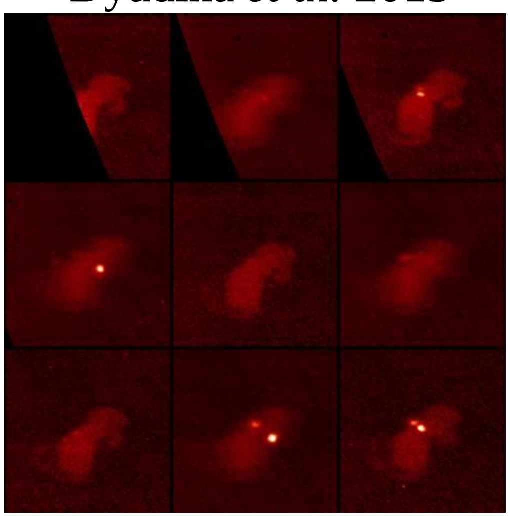
4.1 Lightning flashes in other planets

Ksanfomaliti, 1980



Smith *et al.* 1979

Dyudina *et al.* 2013



De Pater *et al.* 2015

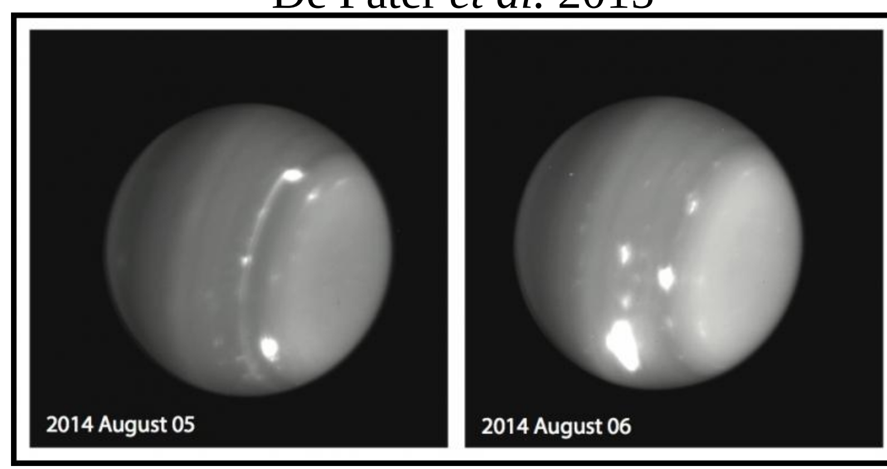
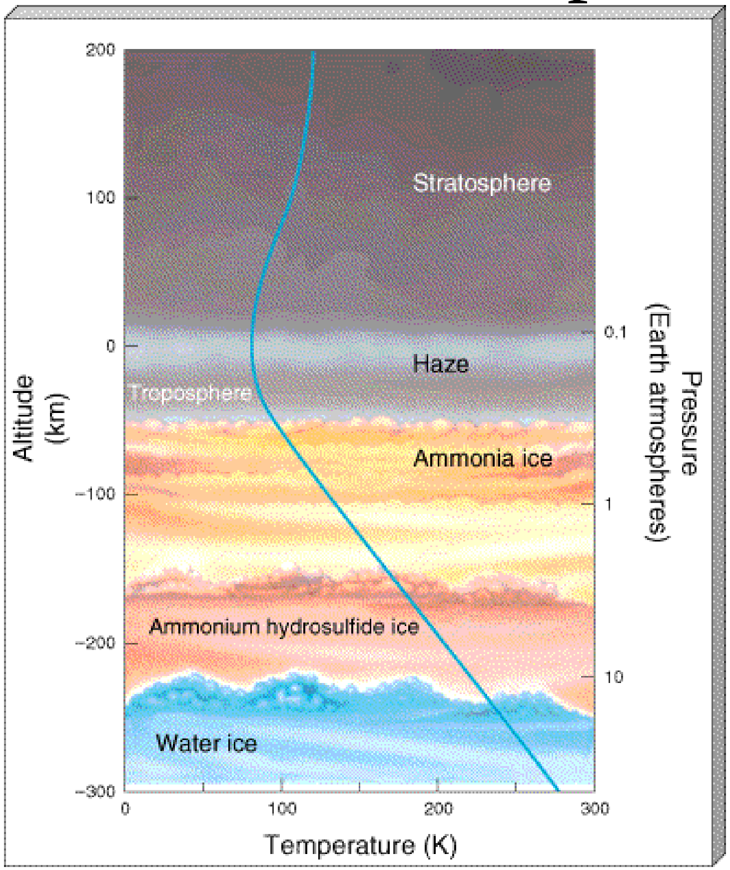


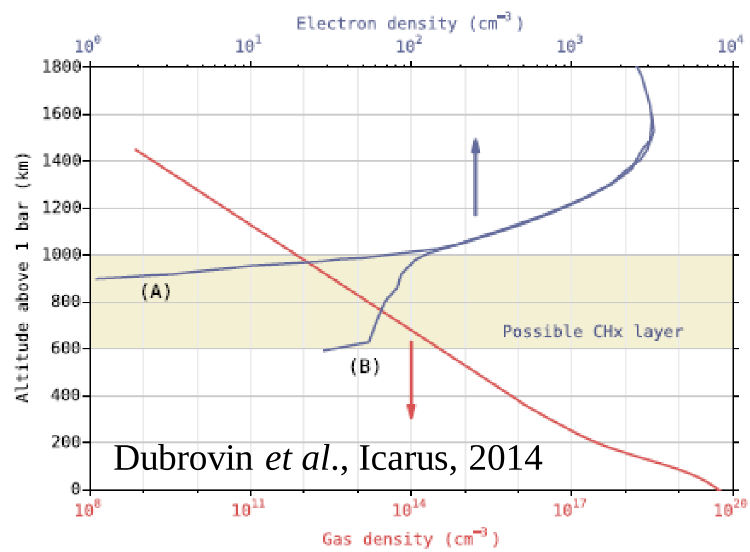
Table of contens

4.2 Chemical impact



www.lifeng.lamost.org

- H_2:He (90:10) (Conrath and Gautier [2000], Gautier *et al.* [2006])
- IC lightning discharges
- Lightning flashes, between 130-160 km below 1-bar and 100 km above 1-bar
- M(t) ~ $10^5 – 10^6$ C km
- 1 ms of duration
- Saturn's ionosphere:



Dubrovin *et al.*, Icarus, 2014

Profile (A) from Moore *et al.* [2004]
Profile (B) from Galand *et al.* [2009]

4.2 Model

Ground Neutrals
H, H_2,
He

Excited Neutrals
$H_2(B^1\Sigma_u^+, d^3\Pi_u, c^3\Pi_u, C^1\Pi_u,$
$a^3\Sigma_g^+)$, $H(^2S, ^2P, 3, 4, 5)$,
$H_2(v=1,\ldots,9)$,
$He(^3S)$, $He_2(a^3\Sigma_u^+)$

Negative Ions
e^-, H^-

Positive Ions
H^+, H_2^+, H_3^+,
He^+, He_2^+,

…and more than 170 processes including V-T, V-V, electron impact, quenching,…

Dubrovin *et al.*, Icarus, 2014

Farrell *et al.* 2007

$$I(t) = I_0\left(\exp(-t/\tau_1) - \exp(-t/\tau_2)\right)$$

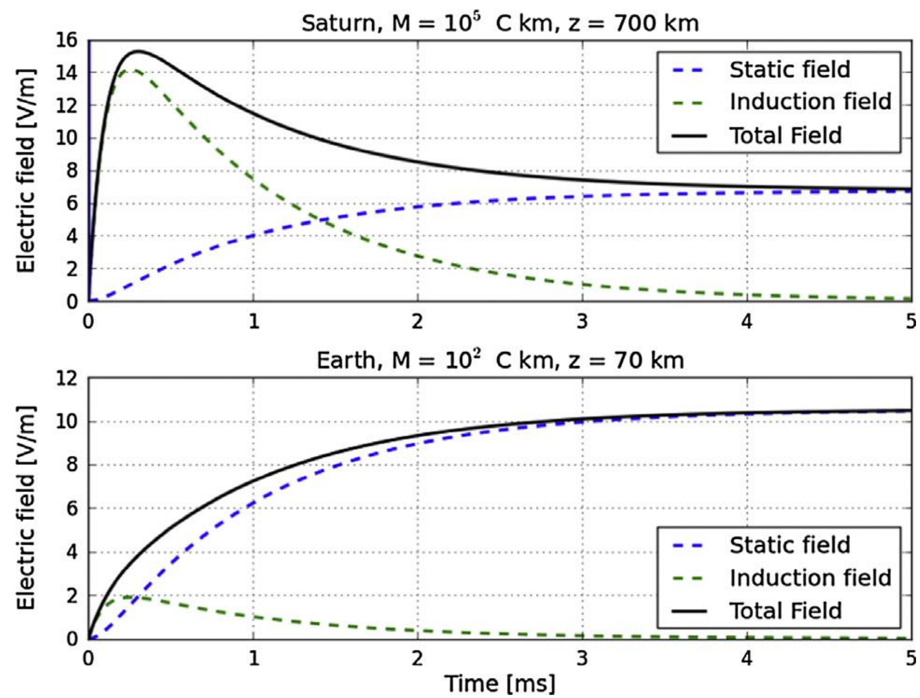
$\tau_1 = 1$ ms
$\tau_2 = 0.1$ ms

$$M(t) = \frac{a}{2}\int_0^t I(t')dt'$$

$$E_p(z,t) \propto \left[\frac{M(z,t)}{(z-z_p)^3} + \frac{1}{c(z-z_p)^2}\frac{d}{dt}M(z,t)\right]$$

Static field

Induction field



$$E_{rad} \approx \frac{M\sin 2\alpha}{4\pi\varepsilon_0 c^2\tau^2(z-z_p)}$$ ⟹ 1-D model ($\alpha = 0$) ⟹ $E_{rad} \approx 0$

Farrell *et al.* 2007

$$I(t) = I_0\left(\exp(-t/\tau_1) - \exp(-t/\tau_2)\right)$$

τ_1 = 1 ms

τ_2 = 0.1 ms

$$M(t) = \frac{a}{2}\int_0^t I(t')dt'$$

$$E_p(z,t) \propto \left[\frac{M(z,t)}{(z-z_p)^3} + \frac{1}{c(z-z_p)^2}\frac{d}{dt}M(z,t)\right]$$

$$\mathbf{J}_\mathbf{T}(t) = \varepsilon_0 \frac{\partial E_p}{\partial t}$$

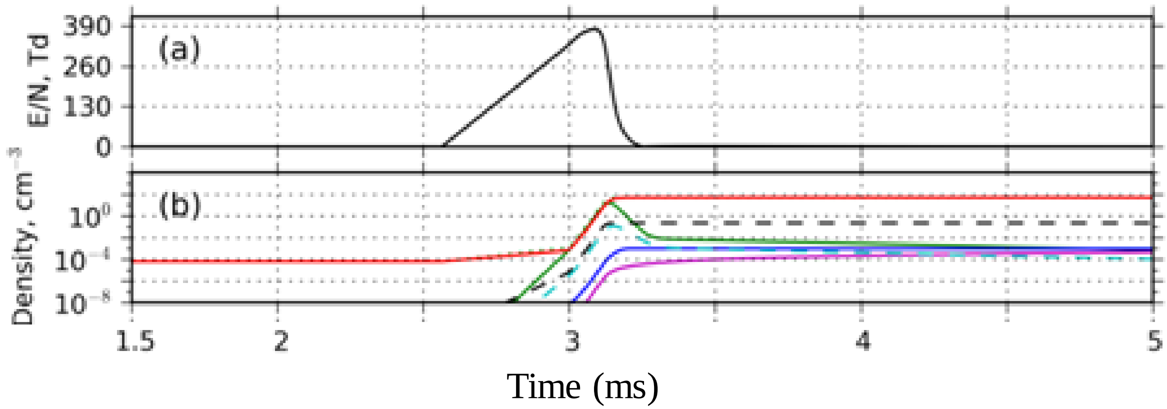
$$\frac{\partial n_i}{\partial t} = G_i - L_i$$

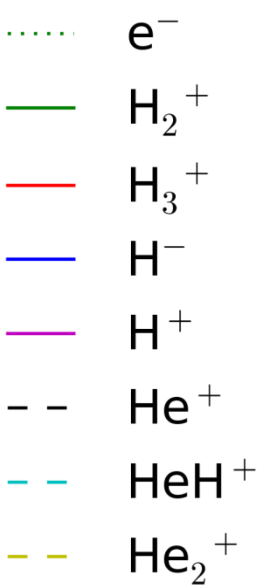
$$\frac{e\mathbf{E}(t)}{m_e}\nabla_\mathbf{v} f(\mathbf{v},t) = \left(\frac{\partial f}{\partial t}\right)_{collisions}$$

$$\varepsilon_0 \frac{d\mathbf{E}}{dt} = -\sigma\mathbf{E} + \mathbf{J}_\mathbf{T}(t)$$

4.3 Results

Profile A), 10^5 C km, 750 km





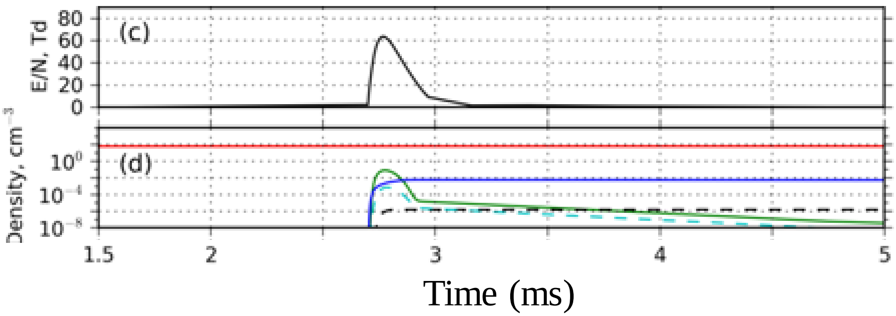
$$e + H_2 \rightarrow H_2^+ + e + e$$

Quick conversion → $H_2^+ + H_2 \rightarrow H_3^+ + H$

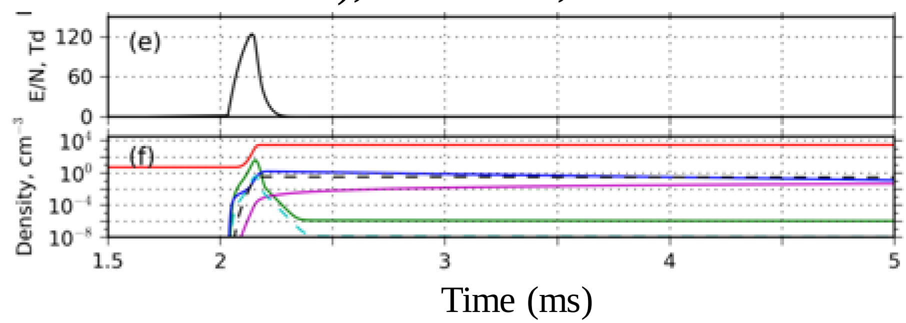
Persist in time

$$He(^3S) + H_2 \rightarrow H_2^+ + He + e$$
$$He(^3S) + H_2 \rightarrow H + HeH^+ + e$$
$$e + H_3^+ \rightarrow H + H + H$$
$$e + H_3^+ \rightarrow H_2 + H$$

Profile B), 10^5 C km, 700 km



Profile B), 10^6 C km, 500 km



$e + H_2 \rightarrow H_2^+ + e + e$

Quick conversion → **$H_2^+ + H_2 \rightarrow H_3^+ + H$**

Persist in time

$H^- + He \rightarrow He + H + e$

$e + H_3^+ \rightarrow H + H + H$

$e + H_3^+ \rightarrow H_2 + H$

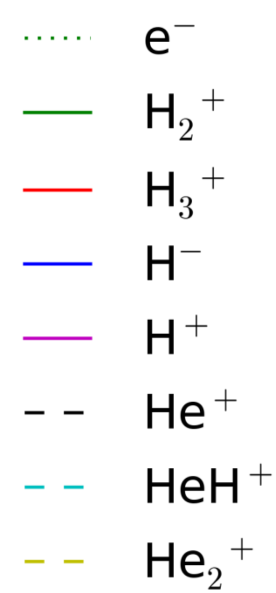


Table of contens

1. Introduction
2. Halos
3. Sprites
4. Electrical discharges on Saturn
5. Conclusions
6. Future work

5. Conclusions

1. The reduced electric field in Earth's mesosphere associated to lightning discharges reaches values close to breakdown limit for all the +CG studied and the –CG lightning discharges with hI_{max} higher than 200 kAkm.

2. The high electron production generated by the continuous current of +CG lightning discharges (20 kAkm) affects more significantly to the mesospheric chemistry.

3. The instantaneous emission brightness of the first and second positive band system of N_2 exceeds 1 MR for +CG lightning discharges and for –CG lightning discharges with high hI_{max}.

4. The model for halos does not predict a significant variation in ground state neutral species such as CO_2 , NO_x and N_2O. However we have found a strong increase in the atomic oxygen and nitrogen densities due to the electron-impact dissociation of O_2 and N_2 respectively during +CG lightning discharges.

5. We can see an increase of more than 7 orders of magnitude in the electron concentration after the passage of a sprite streamer. This increase is produced in the streamer head by ionization and remains high in time due to AD of O^- by N_2.

6. The sprite streamers have a great impact in the chemistry of NO_x and N_2O. We obtain an increase of 2 orders of magnitude in N_2O density and more than 7 orders of magnitude in NO concentration. These, can affect the local ozone density.

7. The gas heating of the surrounding atmosphere produced by a sprite streamer depends mainly of the duration of the current afterglow and is more intense at low altitudes. Most of the energy of the electric field goes to excitation of $N_2(v)$.

8. The IR emission in 4.26 μm could be more than 100 times higher than the background emission. This emission could be detected from space with suitable instrumentation.

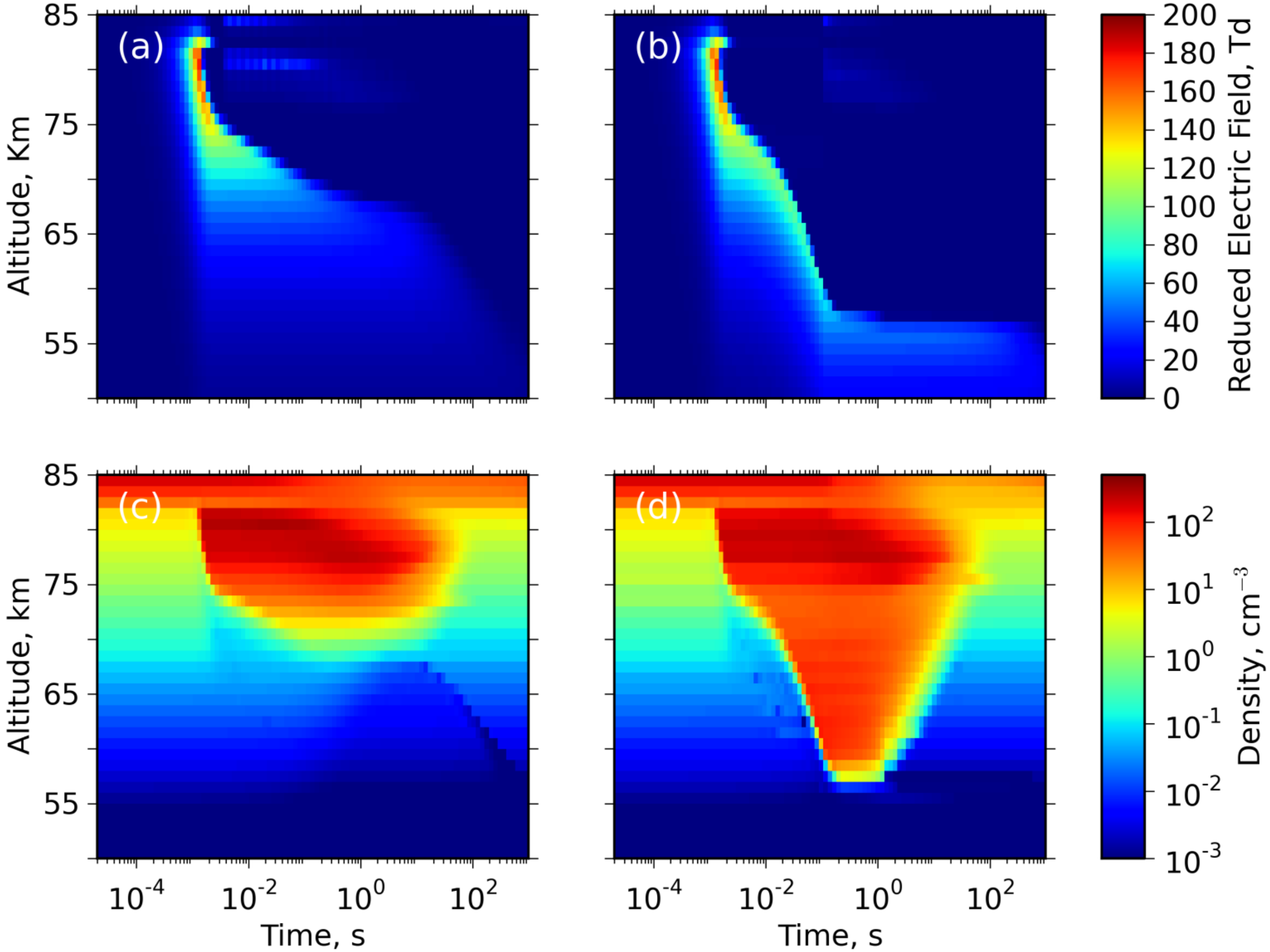
9. We found that H_3^+ ions are rapidly produced from the parent H_2^+ ions on Saturn's atmosphere through the fast reaction $H_2^+ + H_2 \rightarrow H_3^+ + H$, so that H_3^+ becomes the dominant ion in all the scenarios considered.

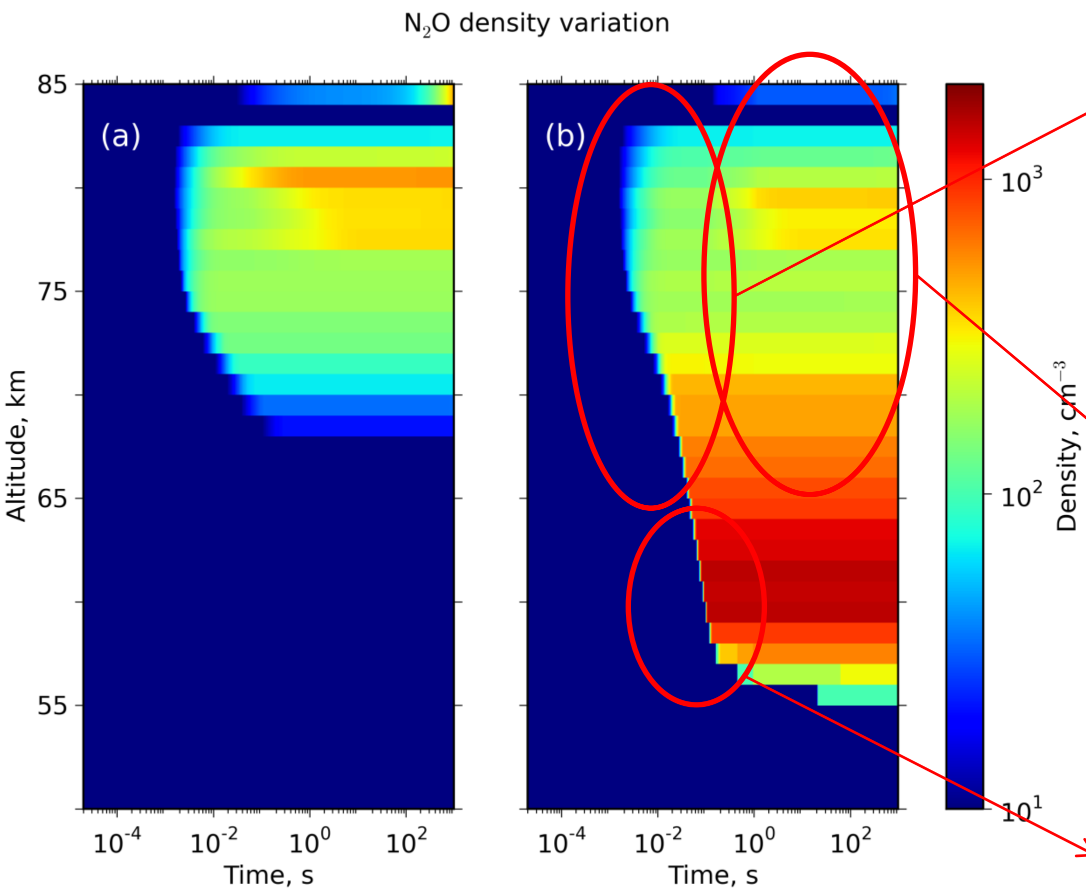
Table of contens

6. Future work

1. To implement the wet air chemistry, with focus in the chemistry of the OH(v).
2. To study how the Blue Jets can affect to the gas heating of the surrounding atmosphere.
3. To extend the model to other planetary atmospheres with electrical activity (Venus, Jupiter, Titan, Uranus, Neptune,...).
4. And beyond of the Solar System as exoplanets or brown dwarfs.
5. To quantify the capabilities of the model for the recreation of complex organic molecules in a primitive atmosphere.

Reduced electric field and electron density



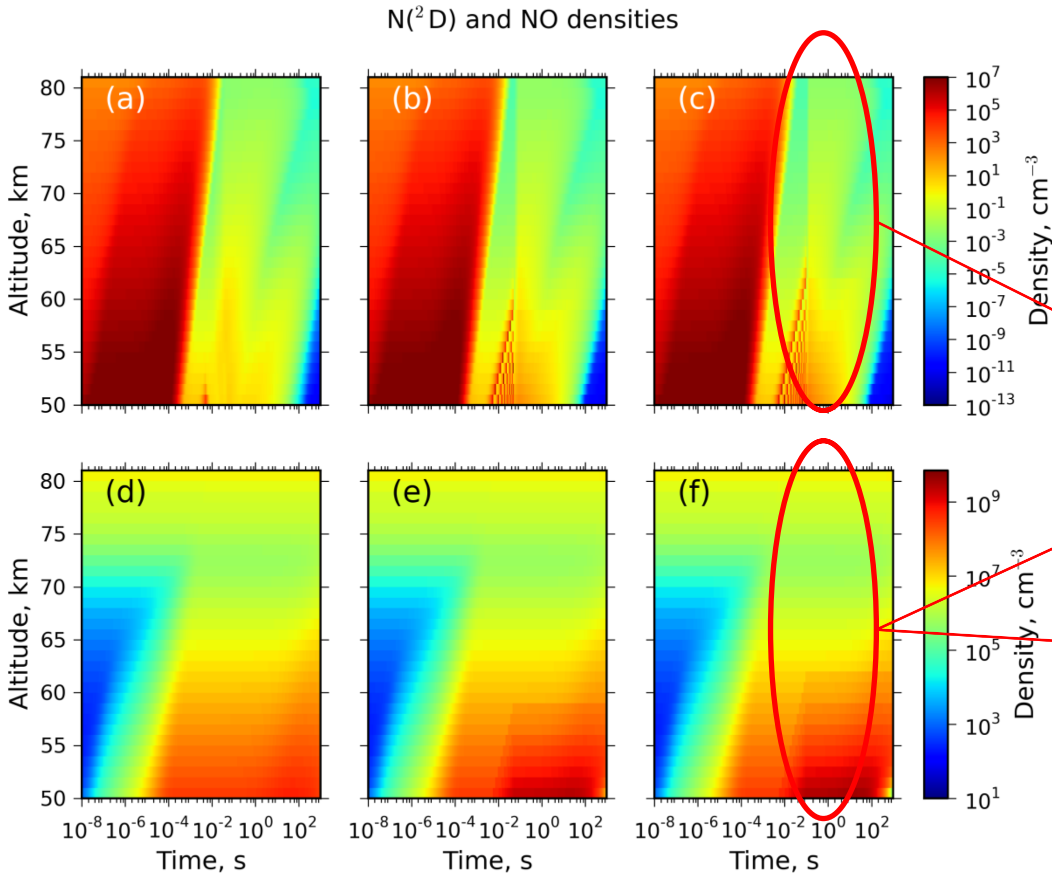


$N_2(A^2) + O_2 \rightarrow N_2O + O$

$N_2(A^2) + O_2 \rightarrow N_2O + O$
$O^- + N_2 \rightarrow N_2O + e$

$O^- + N_2O \rightarrow NO^- + NO$
$e + N_2O \rightarrow N_2 + O + e$

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

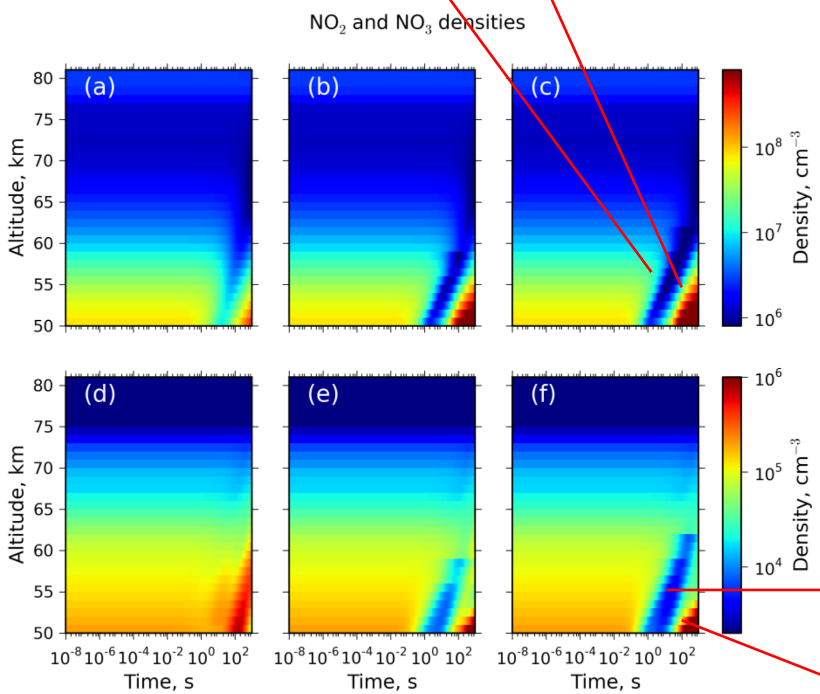


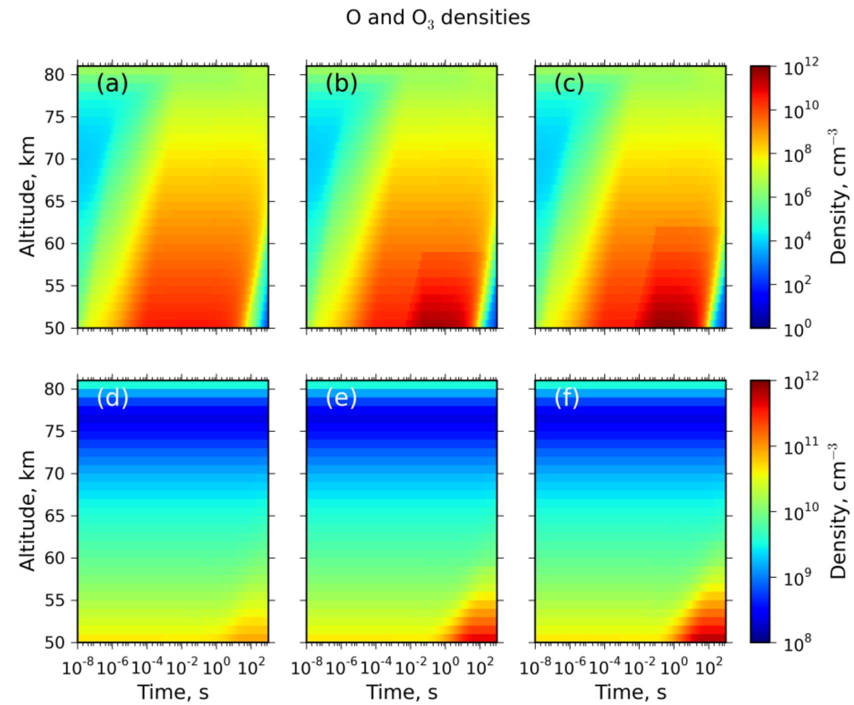
$N(^2D) + O_2 \rightarrow NO + O(^1D)$

$N(^2D) + O_2 \rightarrow NO + O$

$$O_3 + NO \rightarrow NO_2 + O_2$$

$$O + NO_2 \rightarrow O_2 + NO$$





$$O + NO_3 \rightarrow NO_2 + O_2$$

$$O_3 + NO_2 \rightarrow NO_3 + O_2$$