Introduction to the Ionosphere

Anthea J. Coster

MIT Haystack Observatory

References

- Kelley, M. C. 1989; 2009. *The Earth's ionosphere: Plasma physics and electrodynamics.* International Geophysics Series, vol 43. San Diego: Academic Press. (Hardcover - 2009/05/19)
- Rishbeth, Henry, Garriott, Owen K., Introduction to Ionsopheric Physics, New York, NY, Academic Press, 1969. International geophysics series, v. 14
- Jursa, Adolph S., Handbook of Geophysics and the Space Environment, 4th edition, 1985, Air Force Geophysics Laboratory, Hanscom AFB, MA
- Brekke, A. Physics of the Upper Atmosphere, John Wiley & Son, 1997
- Hunsucker, R.D. and J. K. Hargreaves, The High-Latitude Ionosphere and its Effects on Radio Propagation, Cambridge University Press, 2003.

Sun – Earth System Overview

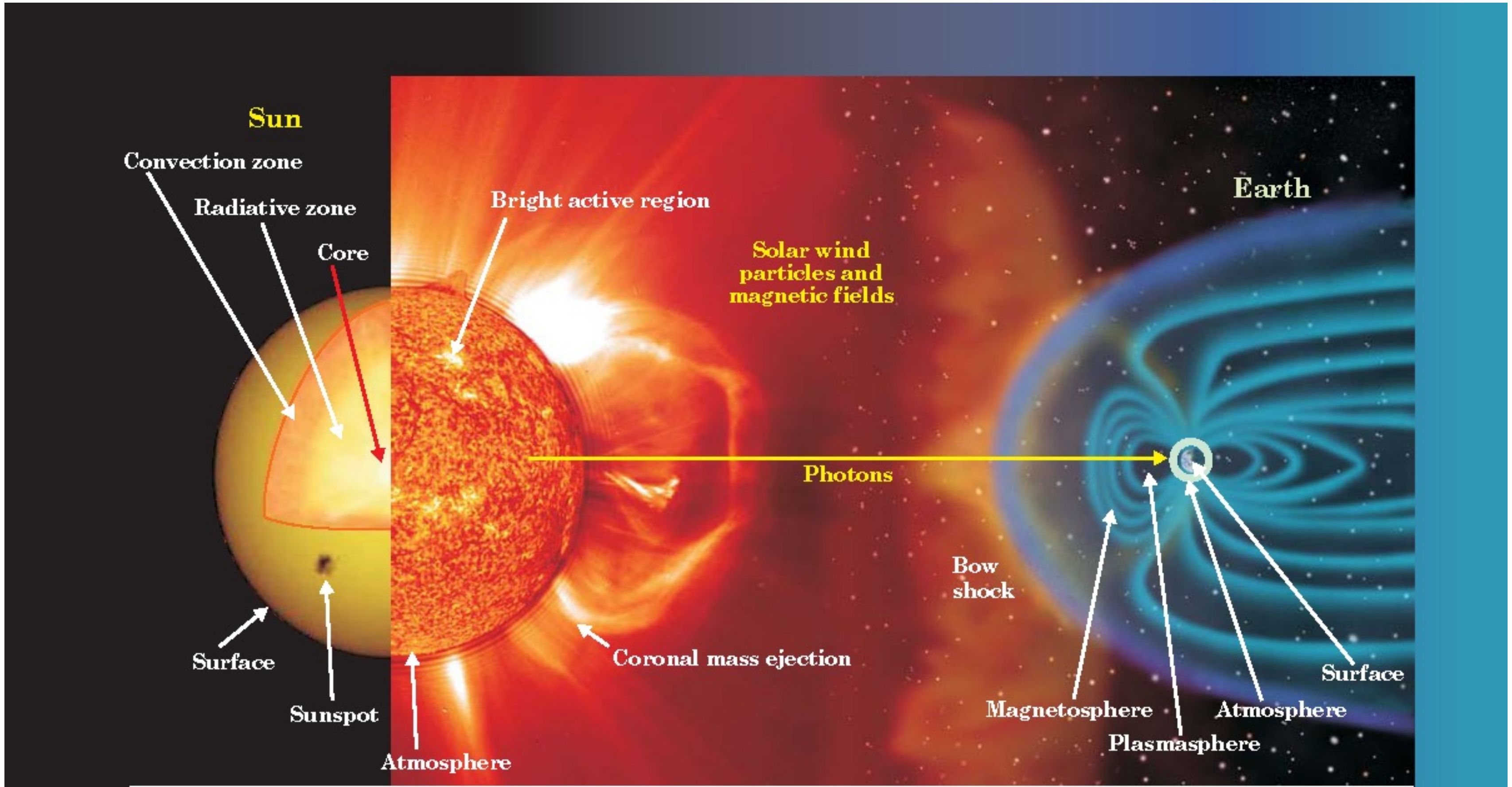


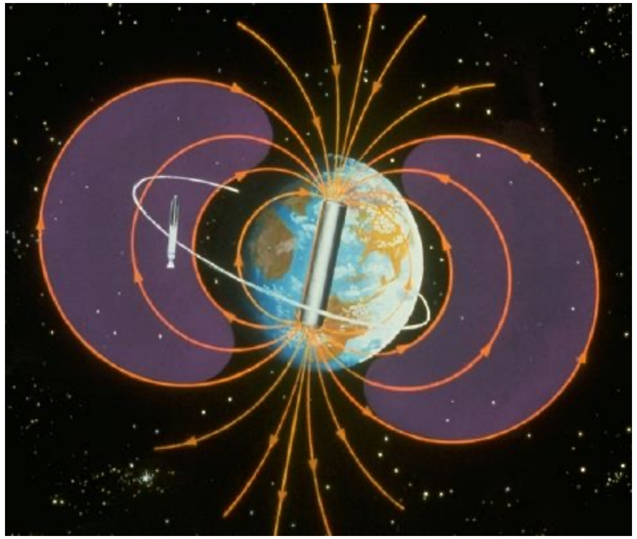
Figure 1. The Sun–Earth system. Energy in various forms is constantly flowing from the Sun to Earth. Dynamo action in the convection zone drives variations in this energy flow by producing sunspots and bright active regions. Photons from the Sun's surface and atmosphere reach Earth's surface and atmosphere, but particles and fields that together form the solar wind are intercepted by the magnetosphere (blue). Eruptive events such as coronal mass ejections, shown emerging from the Sun's atmosphere into the solar wind, perturb the magnetosphere and allow energetic particles to penetrate Earth's atmosphere in the polar regions, where the magnetic field lines are anchored. (Figure not to scale.)

Earth's Upper Atmosphere (and most of the Solar System): Is a Natural Plasma

- Plasma is the fourth state of matter

- The universe is filled with plasma

- Extreme ultraviolet output from the Sun creates a plasma in Earth's upper atmosphere through ionization



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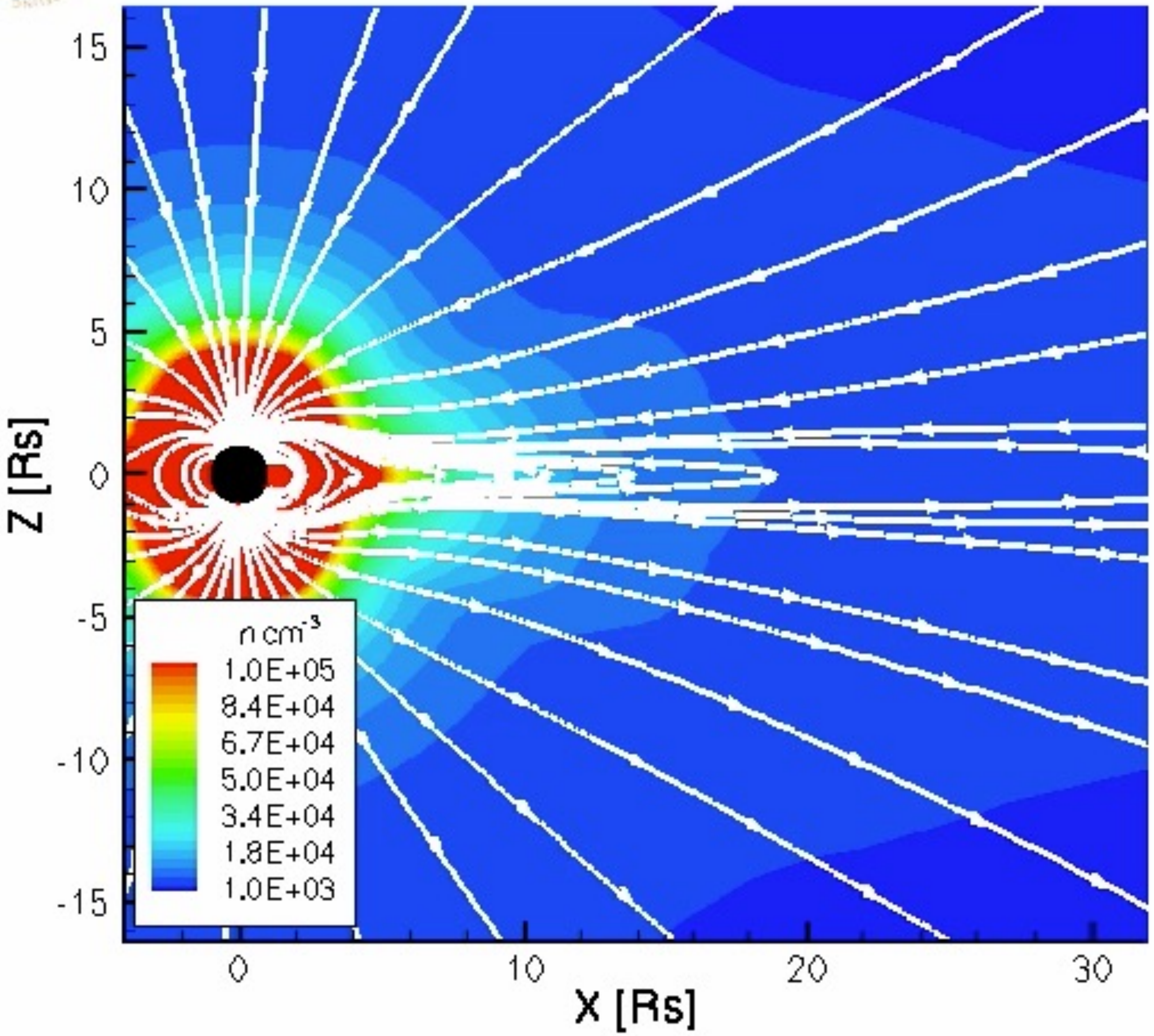
University of Michigan
Manchester et. al.
2003



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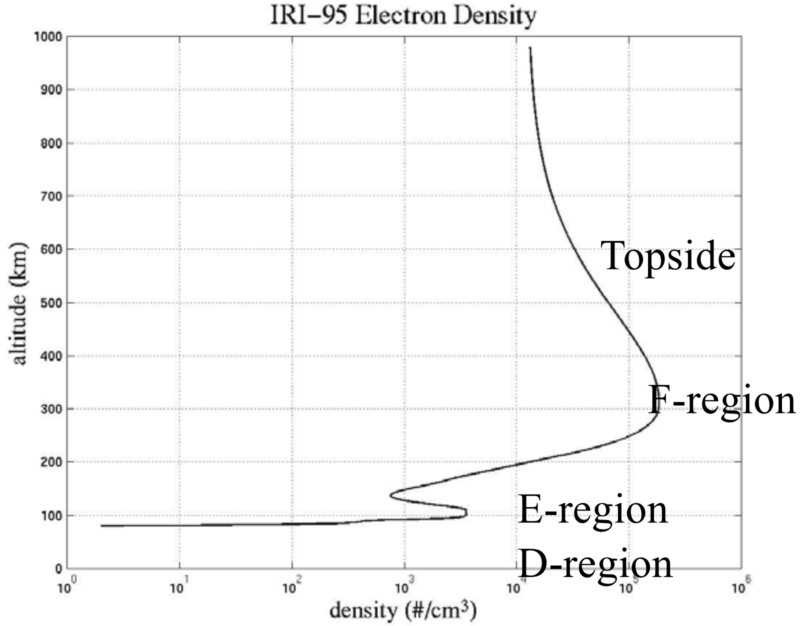
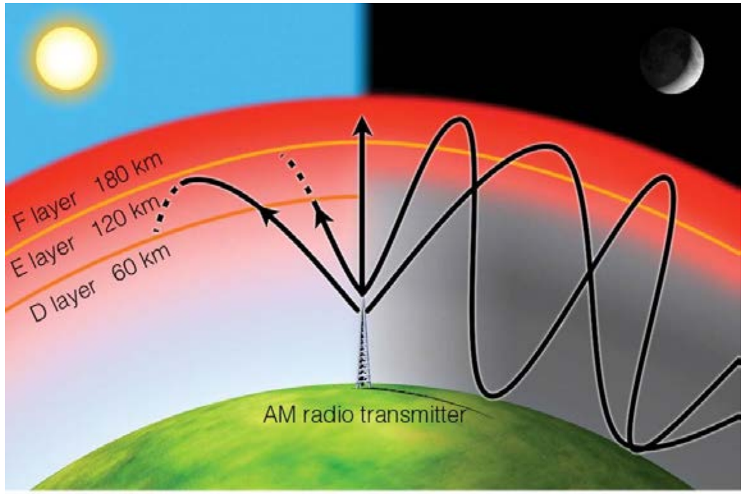
1. Ionosphere – What is it? Where is it? Why do we care? (Provide answers in chat!)

Structure of the Ionosphere





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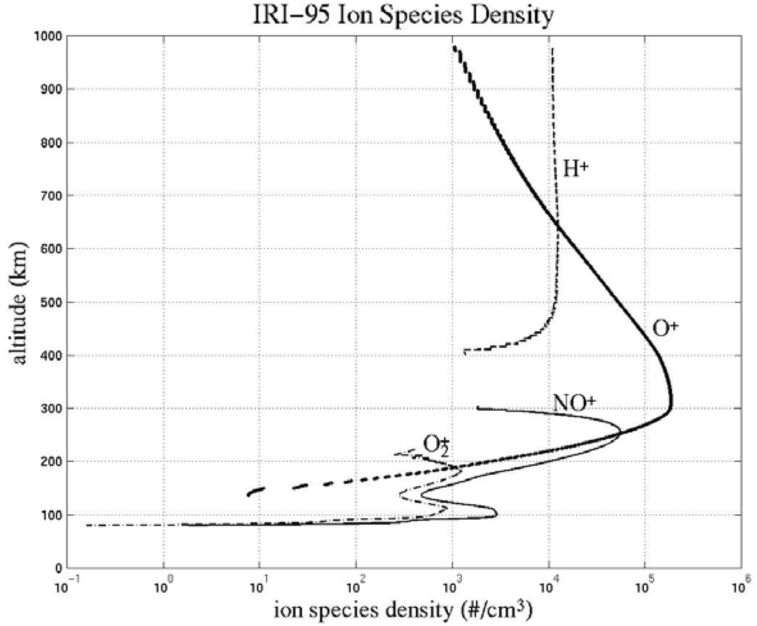
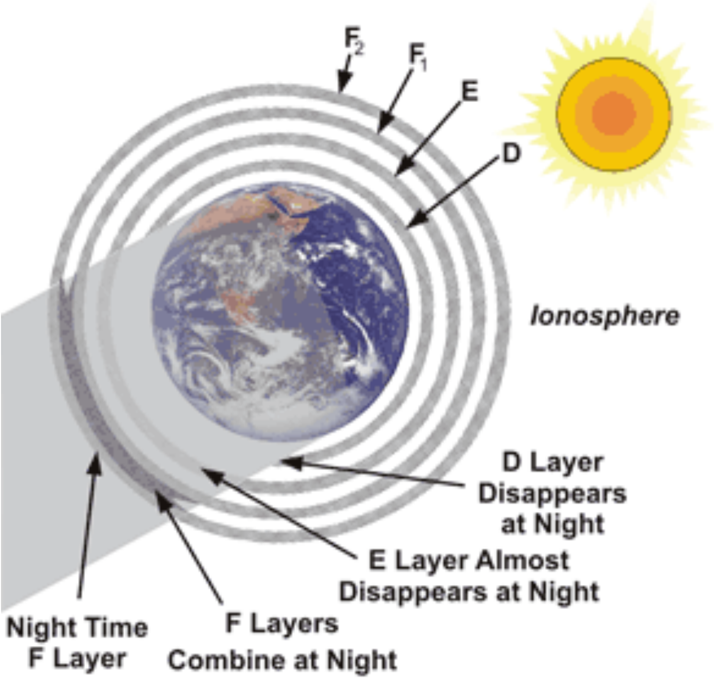




The Discovery of the Ionosphere

1902 AD - Oliver Heaviside

Predicts layer of ionized gas between 90 and 150 km

1924 AD – Edward Appleton

Measurement of ionospheric reflecting layer height

BBC Bournemouth Transmitter to Cambridge

Frequency change method

1925 AD – Gregory Breit and Merle Antony Tuve

Height of the Ionosphere with Seasonal and Diurnal variations

Pulse sounding technique

1926 AD - Robert Watson-Watt introduces the name “Ionosphere

G. Breit

M.A. Tuve

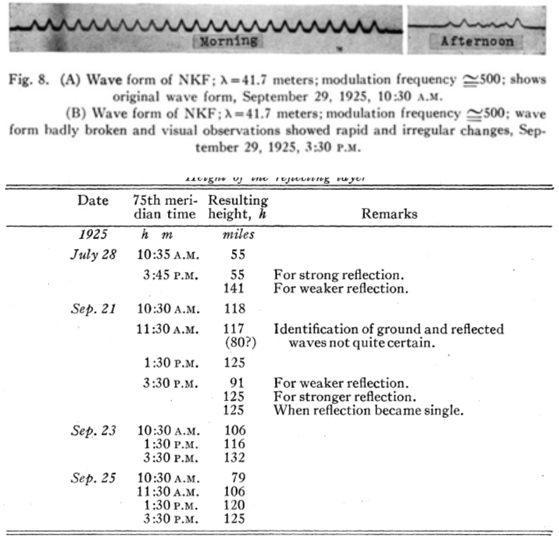
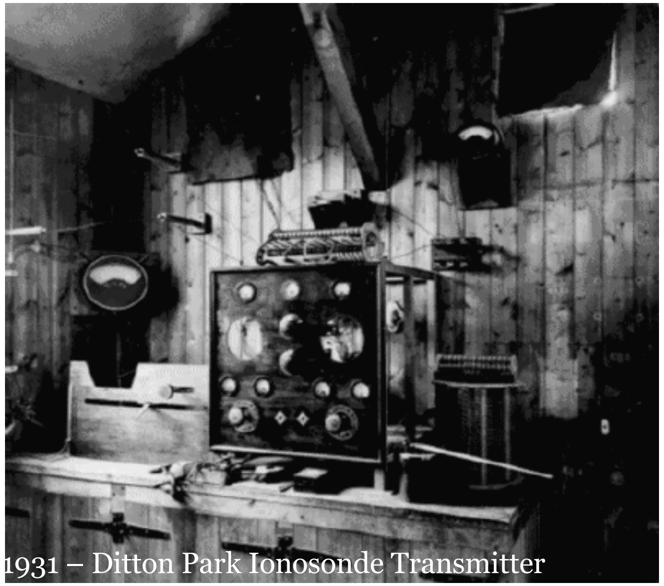


Fig. 8. (A) Wave form of NKF; λ=41.7 meters; modulation frequency ≅500; shows original wave form, September 29, 1925, 10:30 A.M.

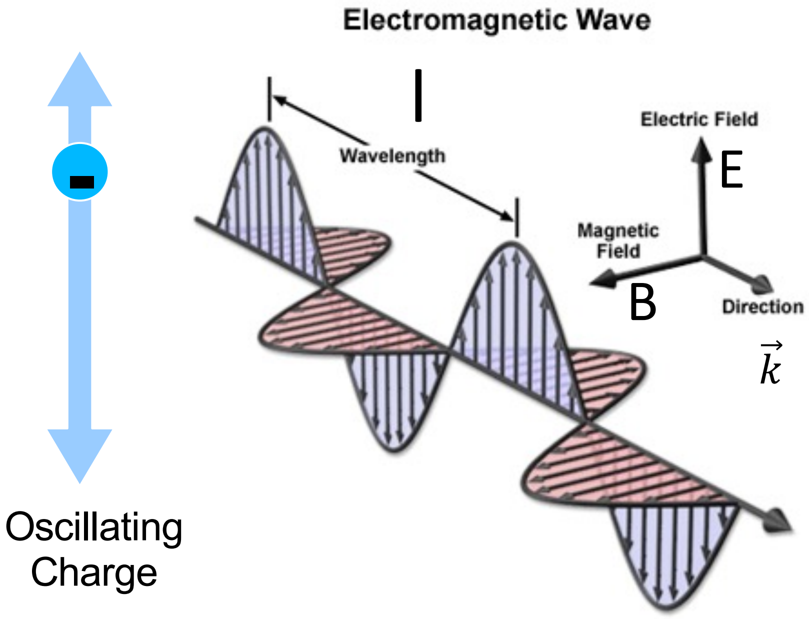
(B) Wave form of NKF; λ=41.7 meters; modulation frequency ≅500; wave form badly broken and visual observations showed rapid and irregular changes, September 29, 1925, 3:30 P.M.

Date	75th meridian time	Resulting height, *h*	Remarks
1925	*h m*	*miles*	
July 28	10:35 A.M.	55	
	3:45 P.M.	55	For strong reflection.
		141	For weaker reflection.
Sep. 21	10:30 A.M.	118	
	11:30 A.M.	117 (80?)	Identification of ground and reflected waves not quite certain.
	1:30 P.M.	125	
	3:30 P.M.	91	For weaker reflection.
		125	For stronger reflection.
		125	When reflection became single.
Sep. 23	10:30 A.M.	106	
	1:30 P.M.	116	
	3:30 P.M.	132	
Sep. 25	10:30 A.M.	79	
	11:30 A.M.	106	
	1:30 P.M.	120	
	3:30 P.M.	125	

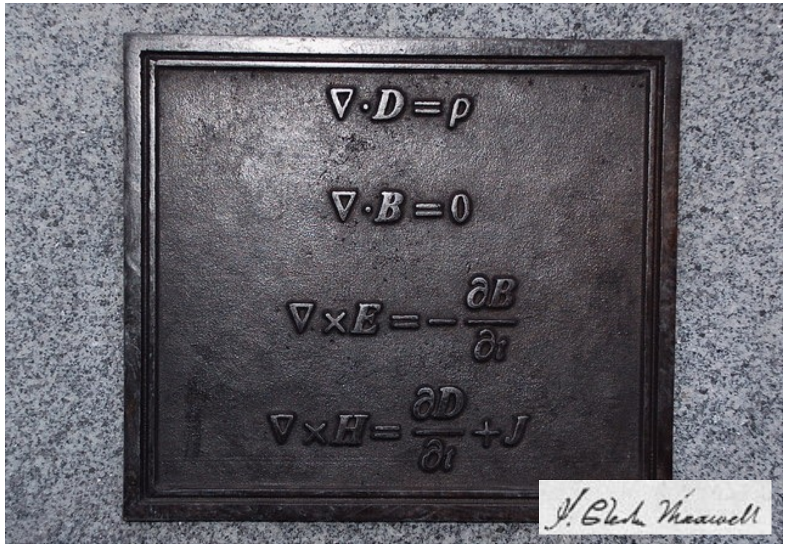


1931 – Ditton Park Ionosonde Transmitter

Radio Waves and Propagation



Maxwell's Equations



$$\nabla \cdot D = \rho$$

$$\nabla \cdot B = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times H = \frac{\partial D}{\partial t} + J$$

J. Clerk Maxwell

Waves are described by :

Wavelength, Amplitude, Polarization
Phase and Direction of Propagation
Propagate at the speed of light (in the medium)
Can be superimposed linearly (mostly true)

Radio Propagation in the Ionospherere

Index of Refraction (no **B** field)

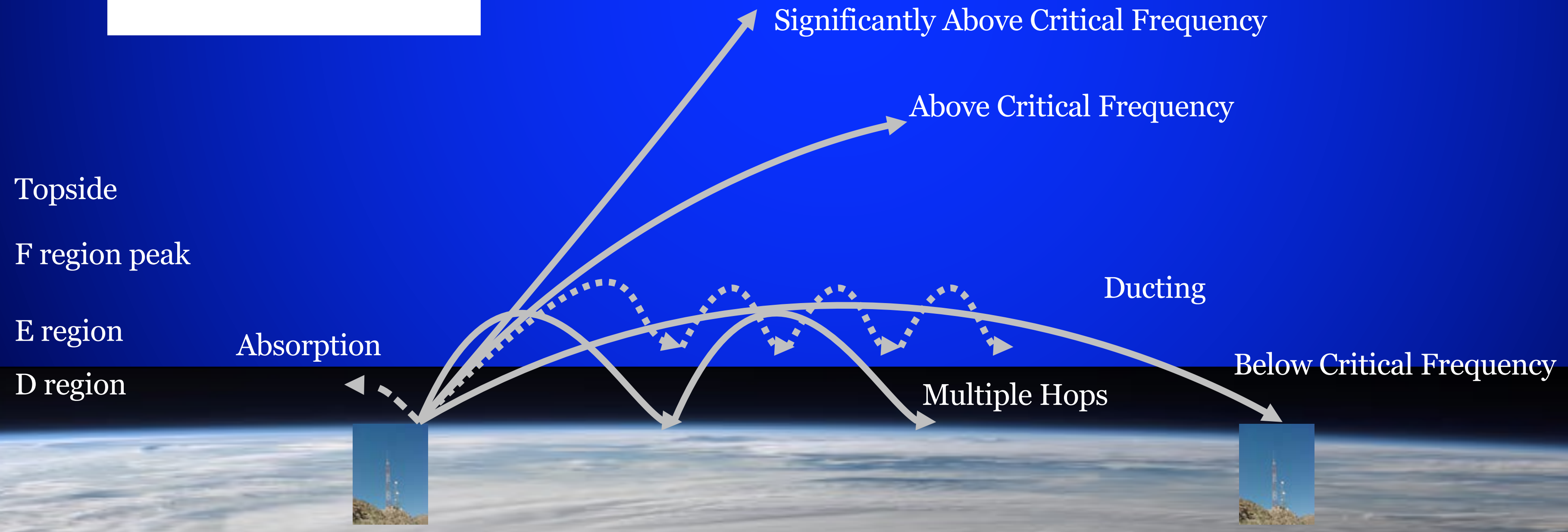
$$n^2 = \frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2}$$

Plasma Frequency

$$\omega_p^2 = \frac{n_0 e^2}{m\epsilon_0}$$

Phase Velocity

$$V_{ph} = \frac{\omega}{k}$$



Significantly Above Critical Frequency

Above Critical Frequency

Topside

F region peak

E region

D region

Absorption

Ducting

Below Critical Frequency

Multiple Hops

[Hurricane Felix, NASA]

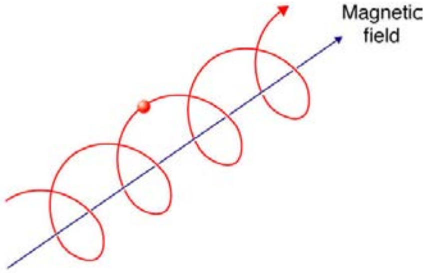
Magnetic Field Effects on Propagation

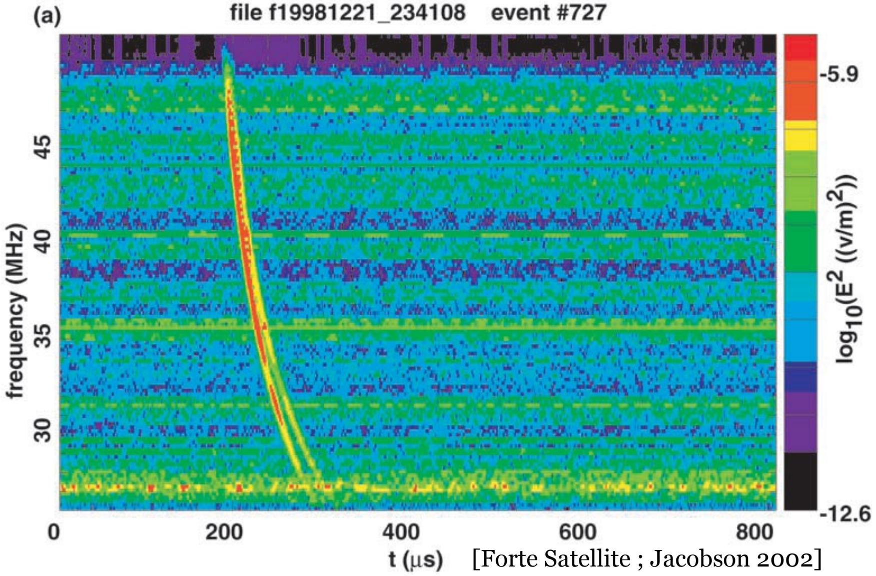
$k \perp B$

$$m\frac{dv}{dt} = q(E + v \times B)$$

Charged particles gyrate around B-field and drift perpendicular due to applied forces.

$$\omega_c = \frac{qB}{m}$$



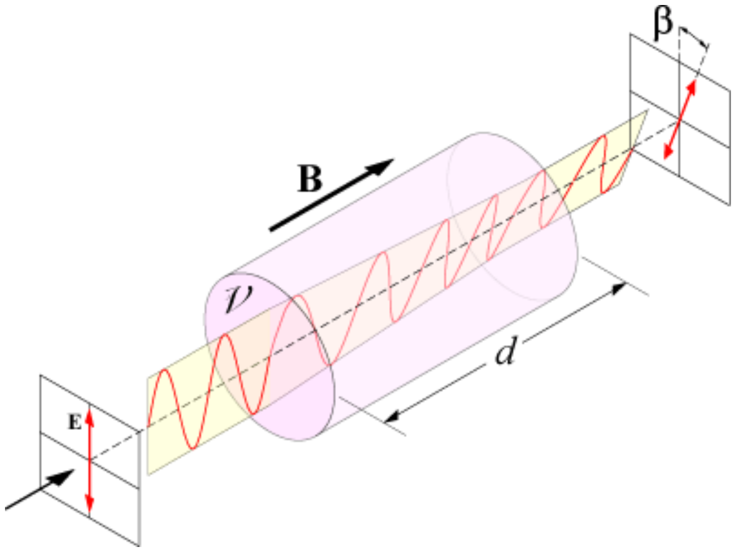


[Forte Satellite ; Jacobson 2002]

$k \parallel B$

$$\beta = RM\lambda^2$$

$$RM = \frac{e^3}{8\pi^2\epsilon_0 m^2 c^3}\int_0^d n_e\, B \cdot dS$$



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Index of Refraction $n = \frac{c}{v_{\mathrm{p}}}.$ in the Ionosphere

$$n^2 = 1 - \frac{X(1-X)}{(1-X) - \frac{1}{2}Y_T^2 \pm \left(\frac{1}{4}Y_T^4 + (1-X)^2 Y_L^2\right)^{1/2}}$$

where

n is the index of refraction

$$X = \frac{\omega_N^2}{\omega^2} \qquad Y = \frac{\omega_H}{\omega} \qquad \omega_N = \left(\frac{Ne^2}{\varepsilon_0 m_e}\right)^{1/2} \qquad \omega_H = \frac{e|B|}{m_e}$$

ω = the angular frequency of the radar wave,

$\mathrm{Y_L} = \mathrm{Y}\cos\theta$, $\mathrm{Y_T} = \mathrm{Y}\sin\theta$,

θ = angle between the wave vector $\bar{\mathrm{k}}$ and $\bar{\mathrm{B}}$,

$\bar{\mathrm{k}}$ = wave vector of propagating radiation,

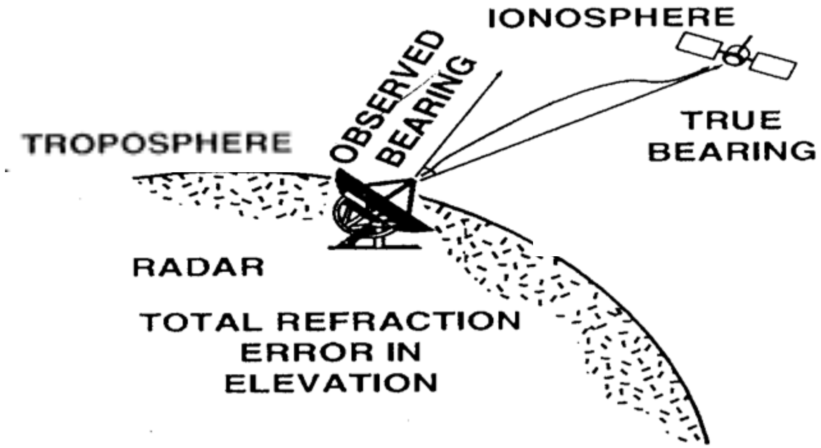
$\bar{\mathrm{B}}$ = geomagnetic field, N = electron density

e = electronic charge, $\mathrm{m_e}$ = electron mass,

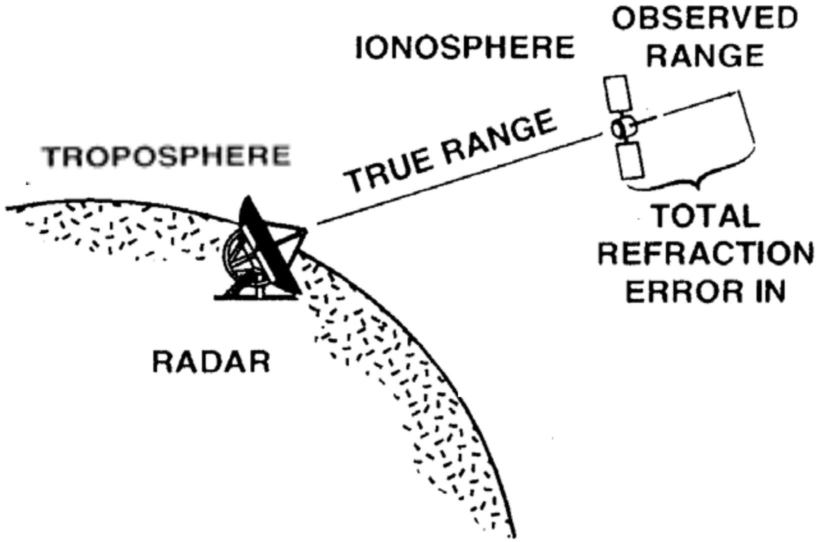
and ε_0 = permittivity constant.

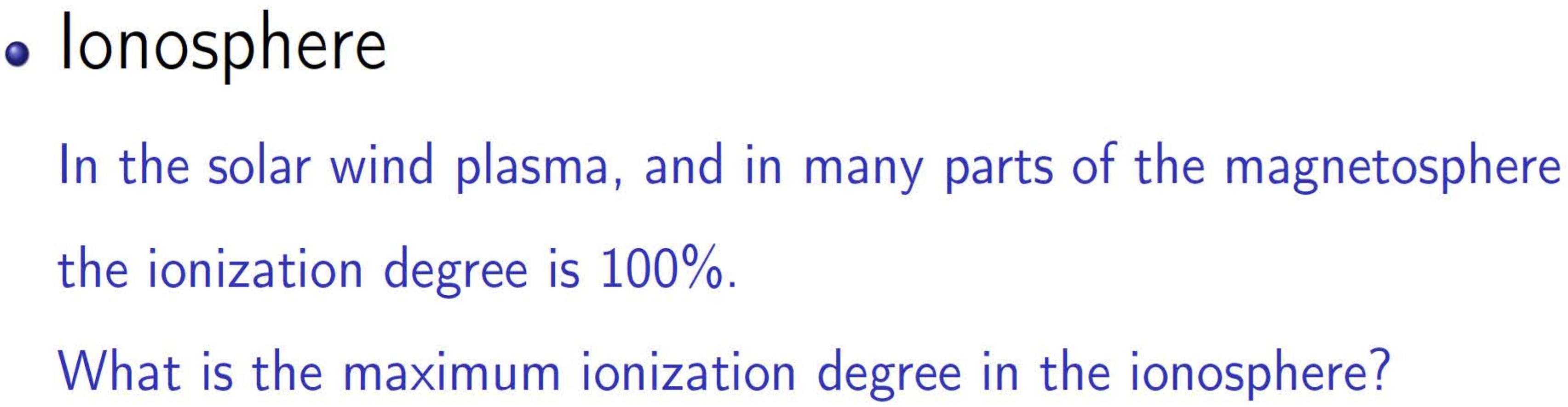
Illustration of Atmospheric Effects

Elevation Refraction



Range Delay





- Ionosphere

  In the solar wind plasma, and in many parts of the magnetosphere

  the ionization degree is 100%.

  What is the maximum ionization degree in the ionosphere?

- Ionosphere

  At maximum 1‰ of the neutral atmosphere is ionized.

2. What is the ionosphere made of?

What are Scale Heights?

Why are there Different regions (D/E/F - importance of different processes in different regions).?

How does it form? What are the primary mechanisms of Production and Loss ?

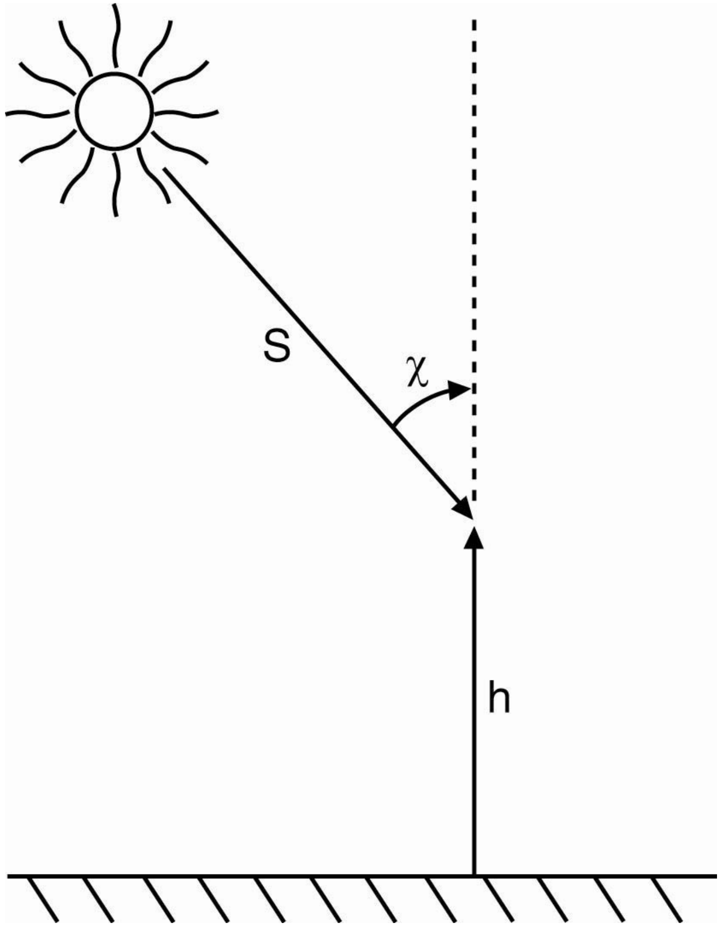
Distinct Regions in the Ionosphere Form because:

The Solar spectrum deposits its energy at various heights depending on the absorption characteristics of the atmosphere.

The physics of recombination depends on the atmospheric density which changes with height.

The composition of the atmosphere changes with height

Photoionization



Scale Height

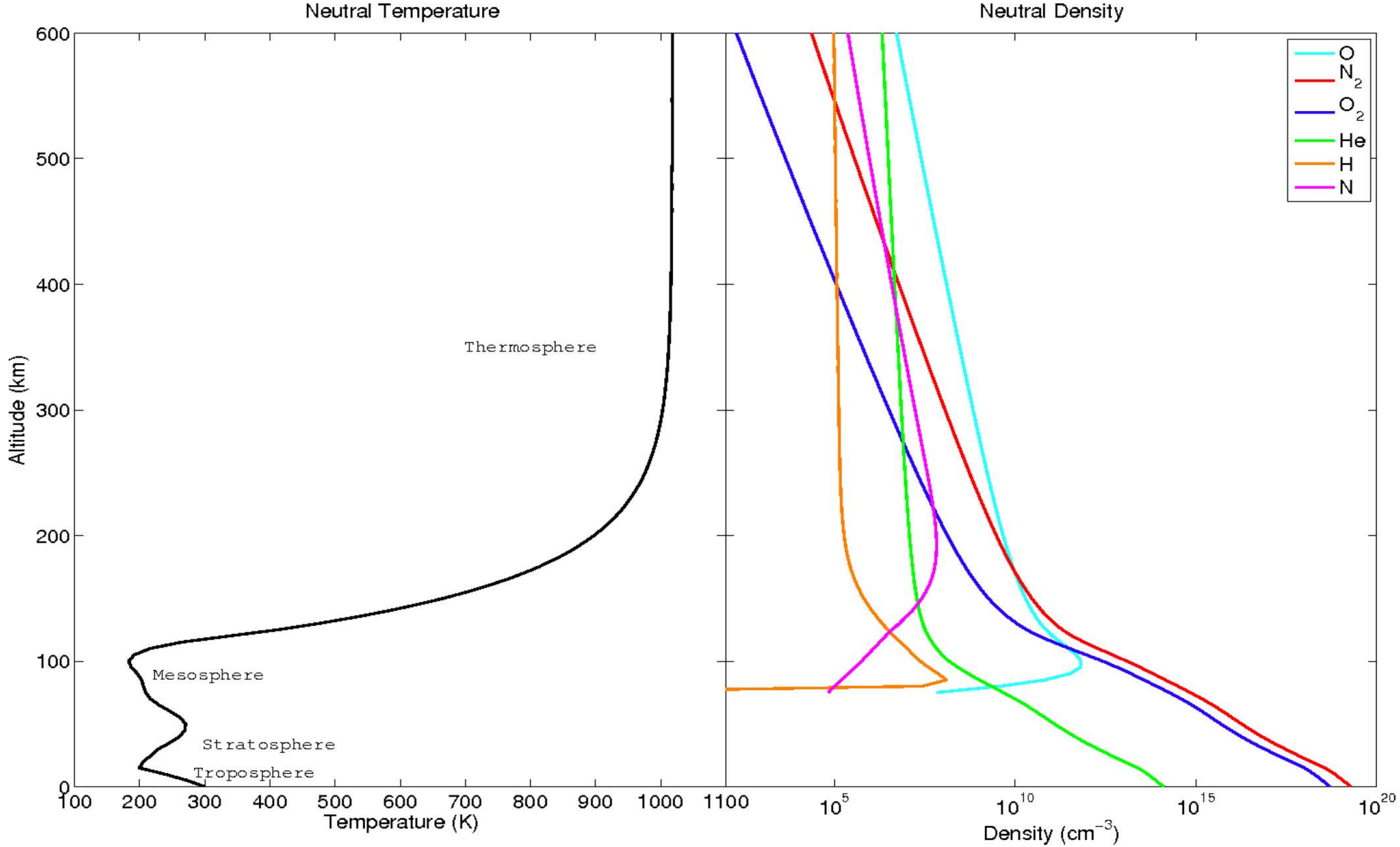
A **scale height** is a term often used in scientific contexts for a distance over which a quantity decreases by a factor of *e*. It is usually denoted by the capital letter *H*.

For planetary atmospheres, it is the vertical distance upwards, over which the pressure of the atmosphere decreases by a factor of *e*. The scale height remains constant for a particular temperature. It can be calculated by

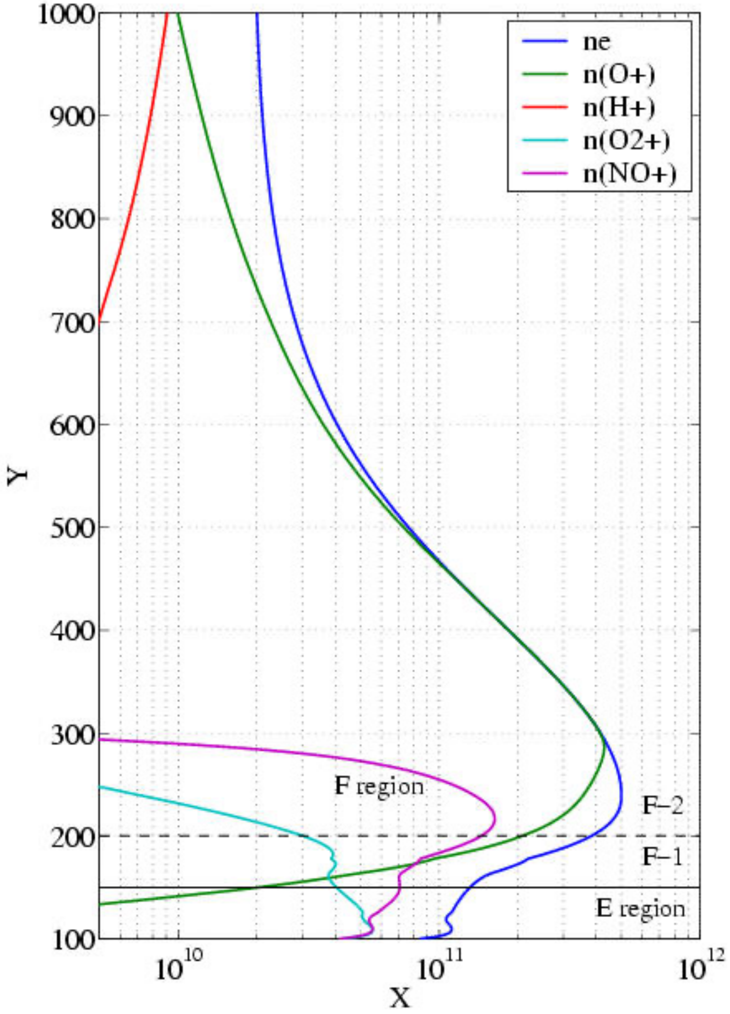
$H = kT/Mg$ where:

k = gas constant = 8.314 J·(mol K)−1
T = mean molecular temperature in kelvins
M = mean molecular mass of dry air (units kg·mol−1)
g = acceleration due to gravity on planetary surface (m/s²)

The Neutral Atmosphere (according to NRLMSISE-00)



Composition



At heights over 100 km, molecular diffusion means that each molecular atomic species has its own scale height.

Dominant Constituent

0-200 Km	Nitrogen
200-1000 Km	Oxygen
1000-2500 Km	Helium
2500 – 8-14 Earth Radii	Hydrogen

Hydrostatic Equilibrium

- The force of gravity on a parcel of air is balanced by the pressure gradient

$$n_n m_n g = \frac{-dp}{dh} = -\frac{d}{dh}(n_n k T_n)$$

- Assume T_n is independent of height and integrate we obtain

$$n_n = n_0 \ \exp[-(h - h_0)/H_n]$$

- The density of an atmosphere falls off (generally) exponentially.

Ionospheric Density Profile

- Photochemical equilibrium assumes transport is not important so local loss matches local production.

$$\frac{\partial n_e}{\partial t} = Q - L = 0$$

- If loss is due to electron-ion collisions, we get a Chapman layer

$$Q = L = \alpha n_e^2$$

$$n_e = (Q/\alpha)^{1/2}$$

- If there is vertical transport

$$\frac{\partial n_e}{\partial t} = Q - L - \frac{\partial (n_e u_{eh})}{\partial h}$$

- Treating the pressure forces of electrons and ions and assuming neutrals are stationary, we obtain

$$n_e u_{pl} = -D\left[\frac{dn_e}{dh} + \frac{n_e}{H_p}\right]$$

- Where $D = k(T_i + T_e)/m_i \upsilon_{in}$ is the ambipolar diffusion coefficient and H_p the plasma scale height

$$k(T_i + T_e)/m_i g$$

- Vertical transport velocity becomes

$$u_{pl} = -(n_e m_i \upsilon_{in})^{-1}\left[\frac{dp_T}{d_h} + n_e m_i g\right]$$

The Earth’s Ionosphere

- For historical reasons, the ionospheric layers are called D, E, F
  - D layer, produced by x-ray photons, cosmic rays
  - E layer, near 110 km, produced by UV and solar x-rays
  - F_1 layer, near 170 km, produced by EUV
  - F_2 layer, transport important

Ion composition

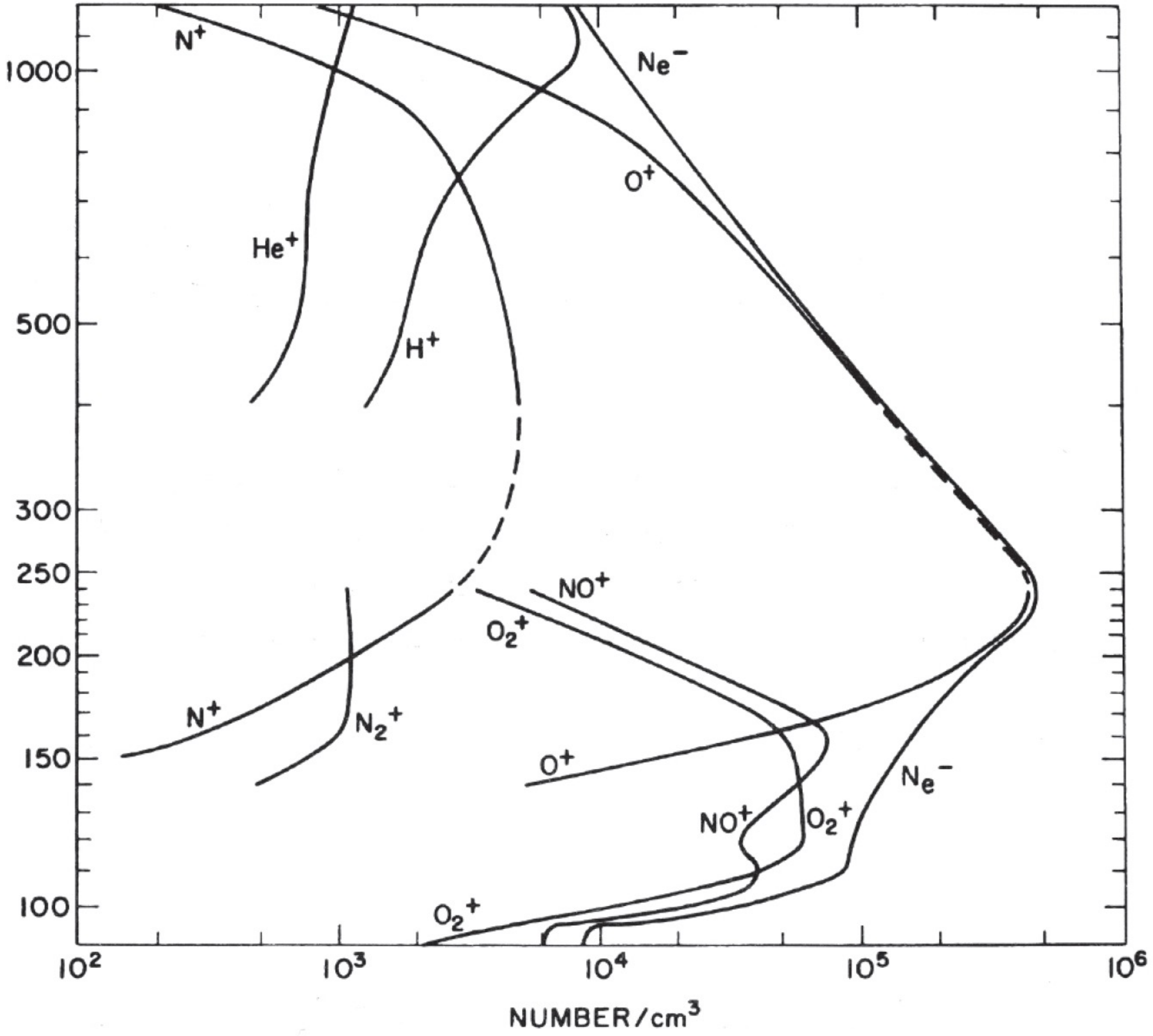


Figure: Daytime solar minimum ion profiles.

- O^+ dominates around F region peak and H^+ starts to increase rapidly above 300 km.
- NO^+ and O_2^+ are the dominant ions in E and upper D regions (Ion chemistry: e.g. $N_2^+ + O \longrightarrow NO^+ + N$).
- D-region (not shown) contains positive and negative ions (e.g. O_2^-) and ion clusters (e.g. $H^+(H_2O)_n$, $(NO)^+(H_2O)_n$).

Ionospheric regions

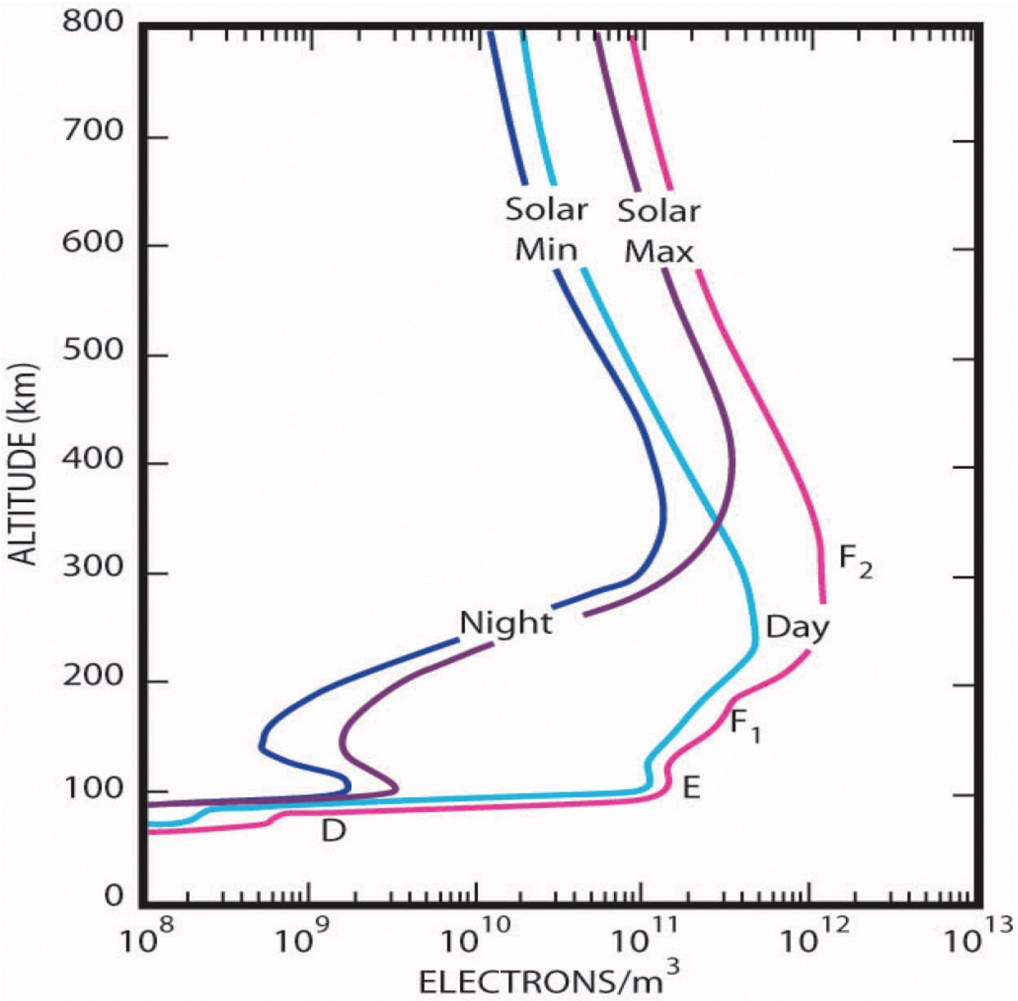


Figure: Typical ionospheric electron density profiles.

Ionospheric regions and typical daytime electron densities:

- D region: 60–90 km, $n_e = 10^8$–10^{10} m^{-3}
- E region: 90–150 km, $n_e = 10^{10}$–10^{11} m^{-3}
- F region: 150–1000 km, $n_e = 10^{11}$–10^{12} m^{-3} .

Ionosphere has great variability:

- Solar cycle variations (in specific upper F region)
- Day-night variation in lower F, E and D regions
- Space weather effects based on short-term solar variability (lower F, E and D regions)

Why do we care about conductivities?

Ionosphere is a plasma with an embedded magnetic field.

$$\nabla \cdot [\sigma \cdot (\mathbf{E}(\mathbf{r},t) + \mathbf{U}(\mathbf{r},t) \times \mathbf{B}] = 0$$

"The resulting electric field is as rich and complex as the driving wind field and the conductivity pattern that produce it", Kelley, Ch. 3

Equations of Motion

Parallel equation of motion

$$\mathrm{q}\,\mathrm{E} = \mathrm{m}_{\mathrm{i}} \nu_{\mathrm{in}} \mathrm{u}_{\mathrm{i}} \qquad -\mathrm{eE} = \mathrm{m}_{\mathrm{e}} \nu_{\mathrm{en}} \mathrm{u}_{\mathrm{e}}$$

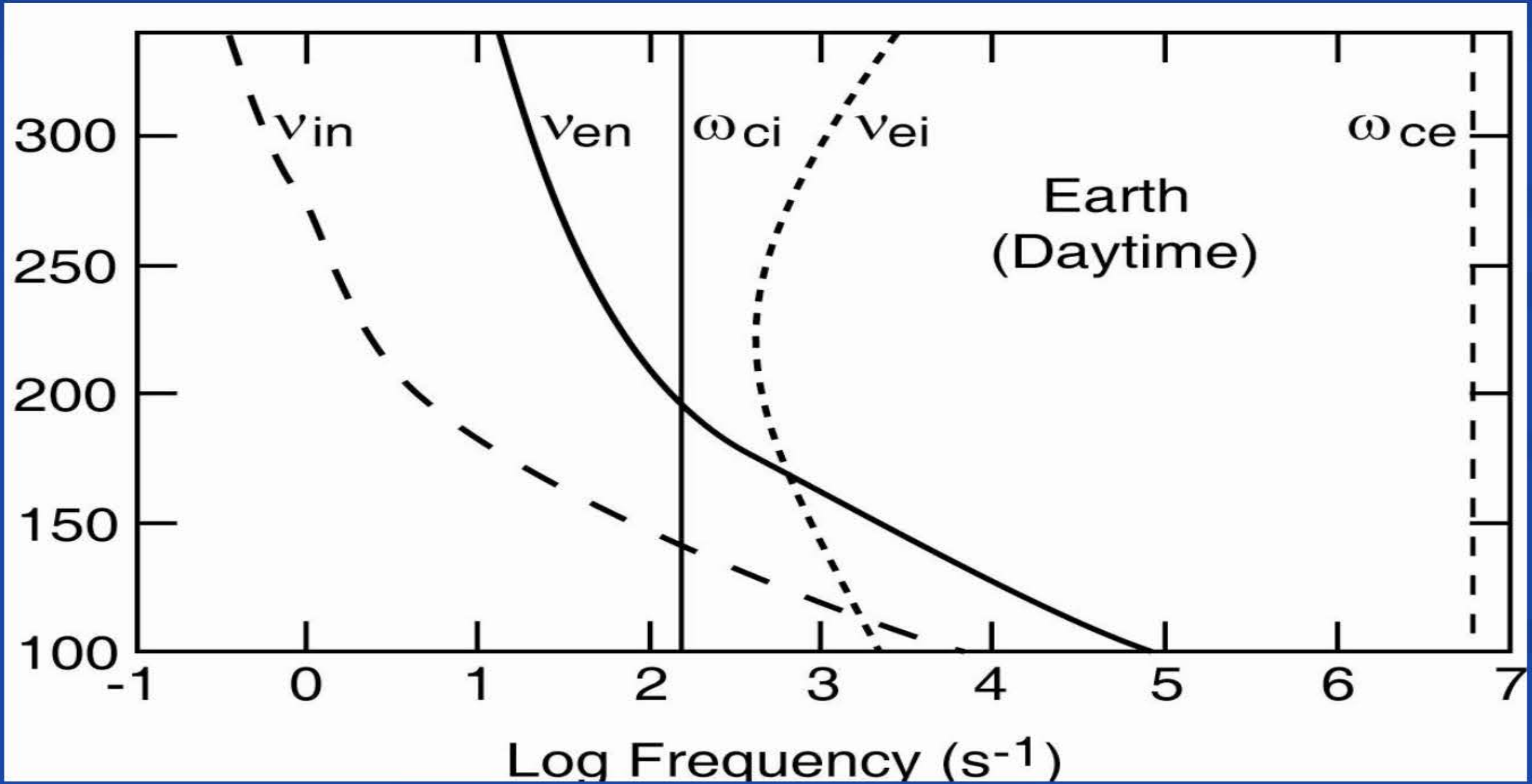
Perpendicular equation of motion

$$\mathrm{q}\left(\mathbf{E}_{\perp} + \mathbf{u}_{i} \times \mathbf{B}\right) = \mathrm{m}_{\mathrm{i}} \nu_{\mathrm{in}} \mathbf{u}_{\perp i}$$

$$-e\left(\mathbf{E}_{\perp} + \mathbf{u}_{e} \times \mathbf{B}\right) = \mathrm{m}_{\mathrm{e}} \nu_{\mathrm{en}} \mathbf{u}_{\perp e}$$

Collision Frequencies

Ion and electrons collide with neutrals as they gyrate. How they move in response to electric fields depends very much on the collision frequency relative to the gyro-frequency.



Conductivity

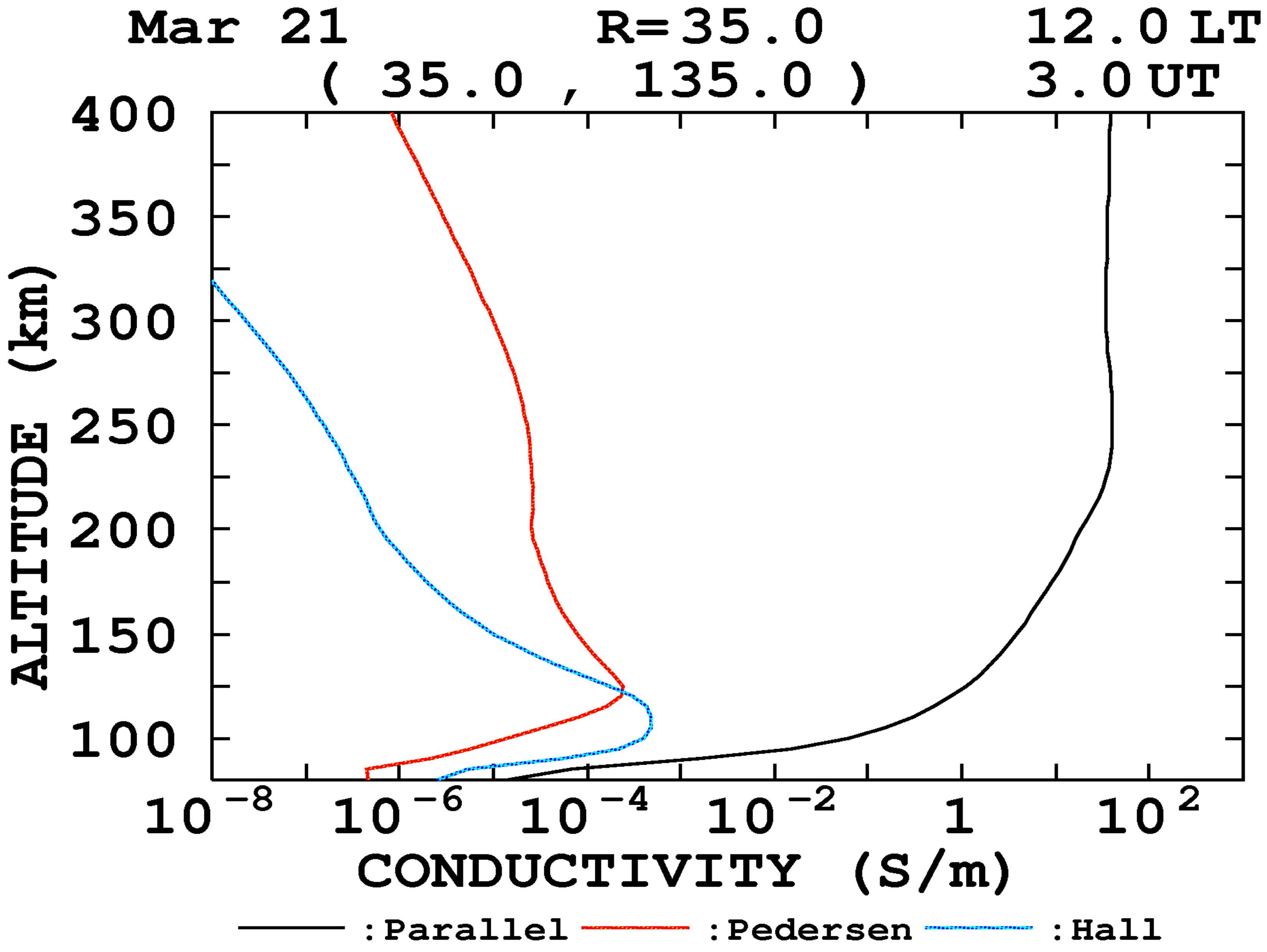
$$\sigma_1 = [\frac{1}{m_e \nu_{en}}(\frac{\nu_{en}{}^2}{\nu_{en}^2 + \Omega_e^2}) + \frac{1}{m_i \nu_{in}}(\frac{\nu_{in}{}^2}{\nu_{in}^2 + \Omega_i^2})] n_e e^2$$

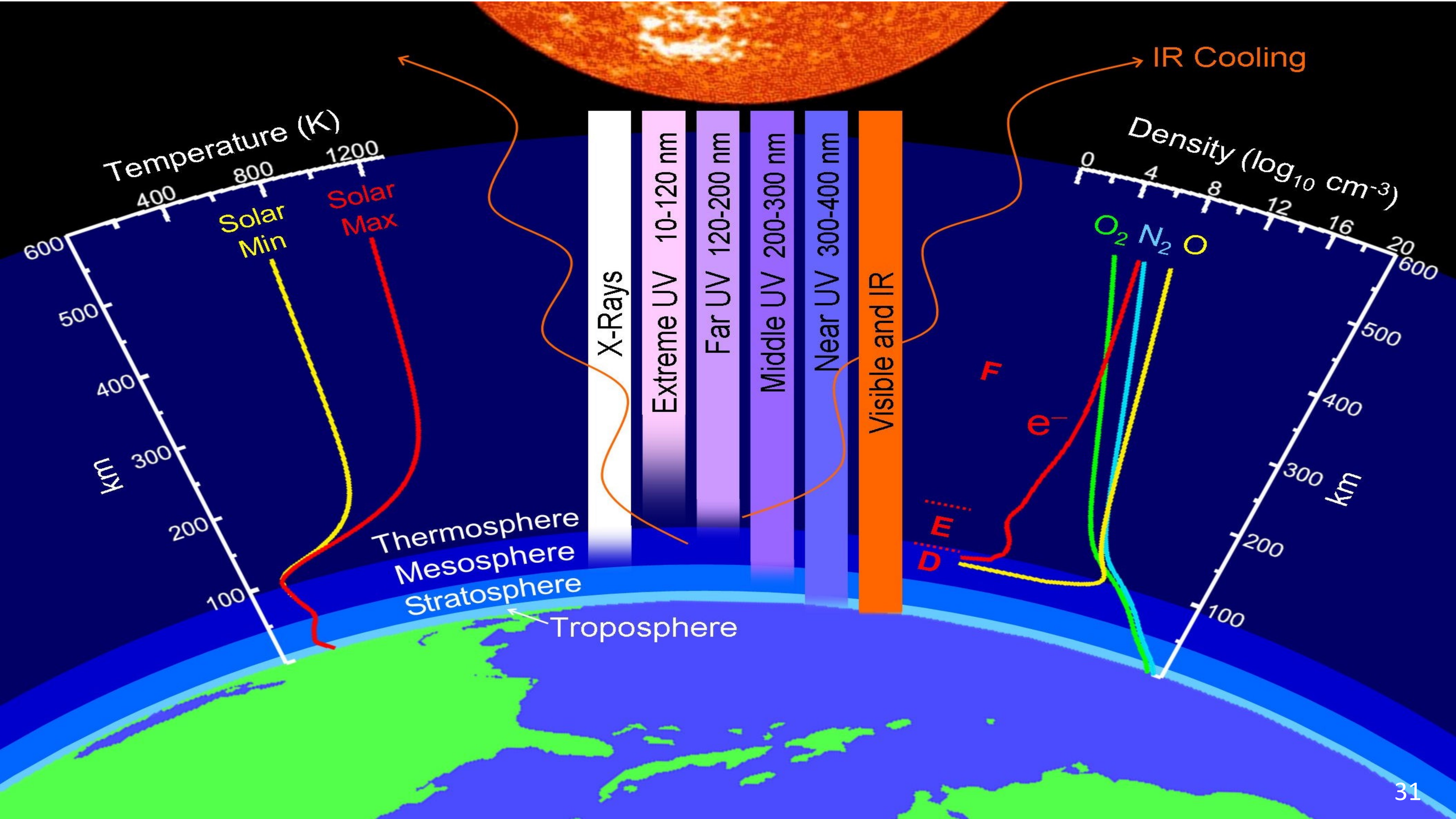
$$\sigma_2 = [\frac{1}{m_e \nu_{en}}(\frac{\Omega_e \nu_{en}}{\nu_{en}^2 + \Omega_e^2}) - \frac{1}{m_i \nu_{in}}(\frac{\Omega_i \nu_{in}}{\nu_{in}^2 + \Omega_i^2})] n_e e^2$$

$$\sigma_0 = [\frac{1}{m_e \nu_{en}} + \frac{1}{m_i \nu_{in}}] n_e e^2$$

$$j = \begin{pmatrix} \sigma_1 & \sigma_2 & 0 \\ -\sigma_2 & \sigma_1 & 0 \\ 0 & 0 & \sigma_0 \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix}$$

- **Pedersen conductivity (along $E_\perp$) perpendicular B, parallel E; horizontal**
- **Hall conductivity (along E x B)**
- **Parallel conductivity**
- Conductivity tensor


Mar 21
R=35.0
12.0 LT
(35.0 , 135.0)
3.0 UT
ALTITUDE (km)
400
350
300
250
200
150
100
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
CONDUCTIVITY (S/m)
:Parallel
:Pedersen
:Hall


IR Cooling
Temperature (K)
400
800
1200
Solar Min
Solar Max
600
500
400
300
200
100
km
X-Rays
Extreme UV 10-120 nm
Far UV 120-200 nm
Middle UV 200-300 nm
Near UV 300-400 nm
Visible and IR
Thermosphere
Mesosphere
Stratosphere
Troposphere
Density ($\log_{10}$ cm^{-3})
0
4
8
12
16
20
O_2
N_2
O
F
e^-
E
D
600
500
400
300
200
100
km

Ionosphere at high, middle and low latitudes

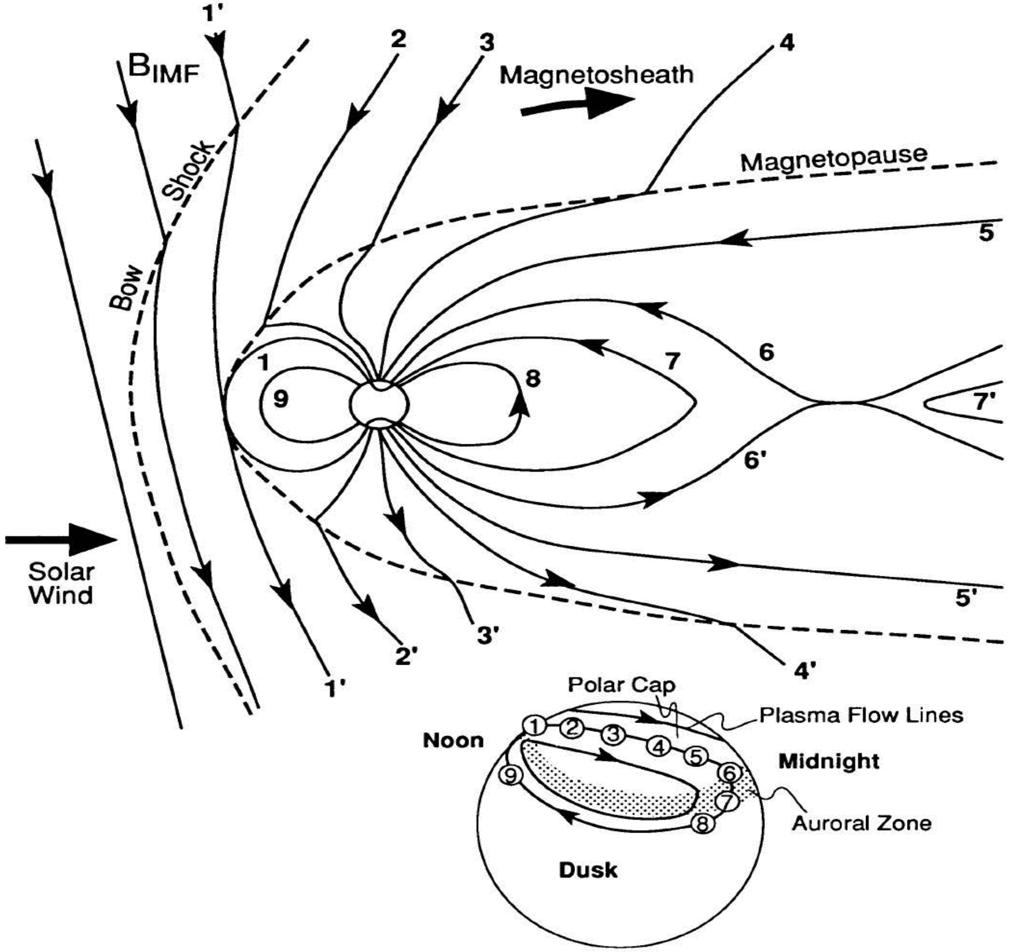
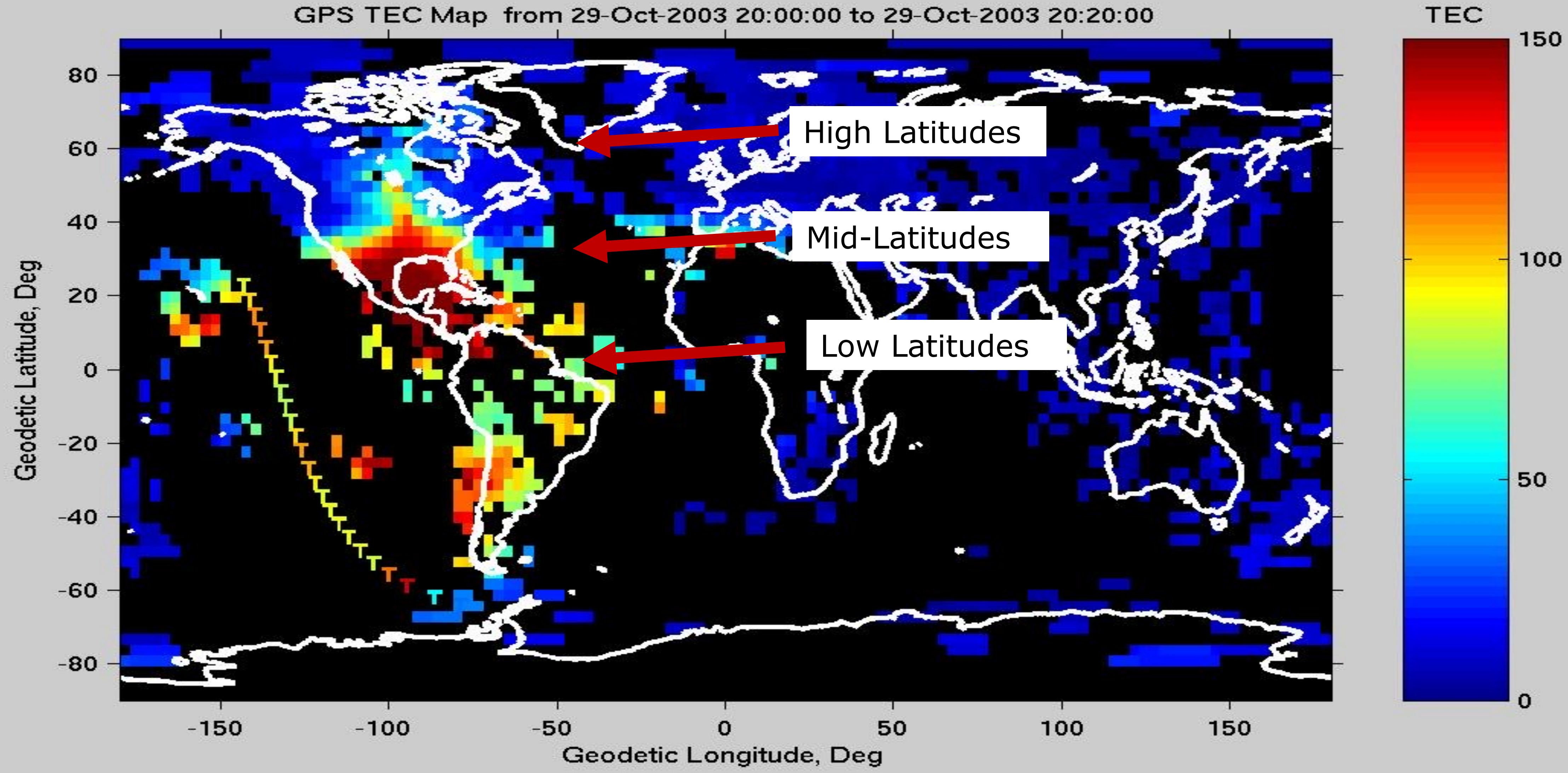


Figure: IMF coupling to the magnetosphere.

- High-latitude ionosphere (polar cap, cusp, auroral oval): intense electric fields mapping from the magnetosphere, particle precipitation, effects of magnetospheric substorms.
- Mid-latitude ionosphere: occasionaly high-latitude electric fields may penetrate to mid-latitudes, effects of magnetic storms.
- Low-latitude ionosphere: small electric fields, high day-time conductivities due to solar radiation (equatorial electrojet).

Day302 PM

MIT Haystack Observatory

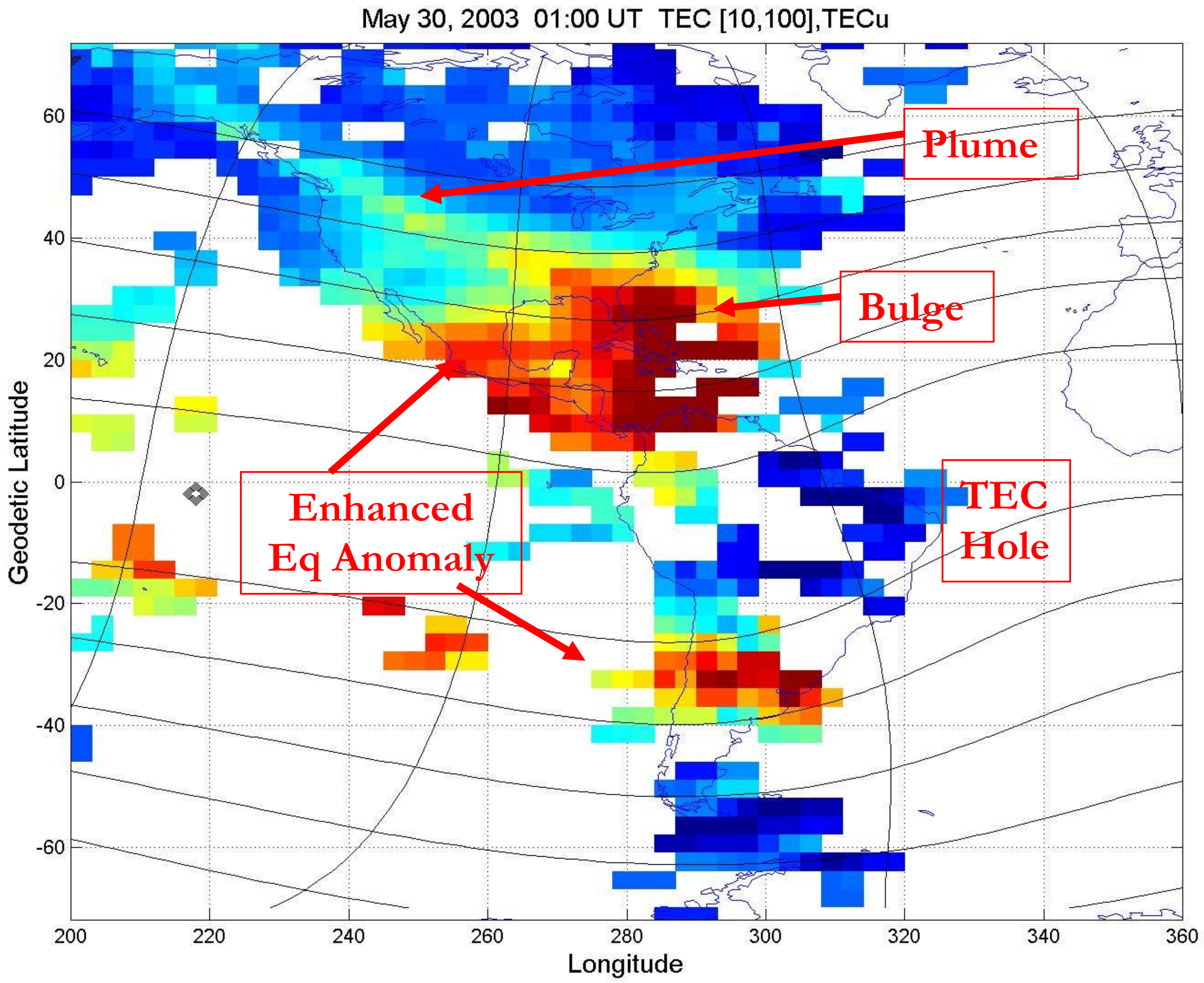


High Latitudes

Mid-Latitudes

Low Latitudes

Enhanced TEC Region observed in the Mid-Latitudes



Plume

Bulge

Enhanced Eq Anomaly

TEC Hole

Aurora observed over Venetie, Alaska

But how to explain these next two photographs? Answer in chat

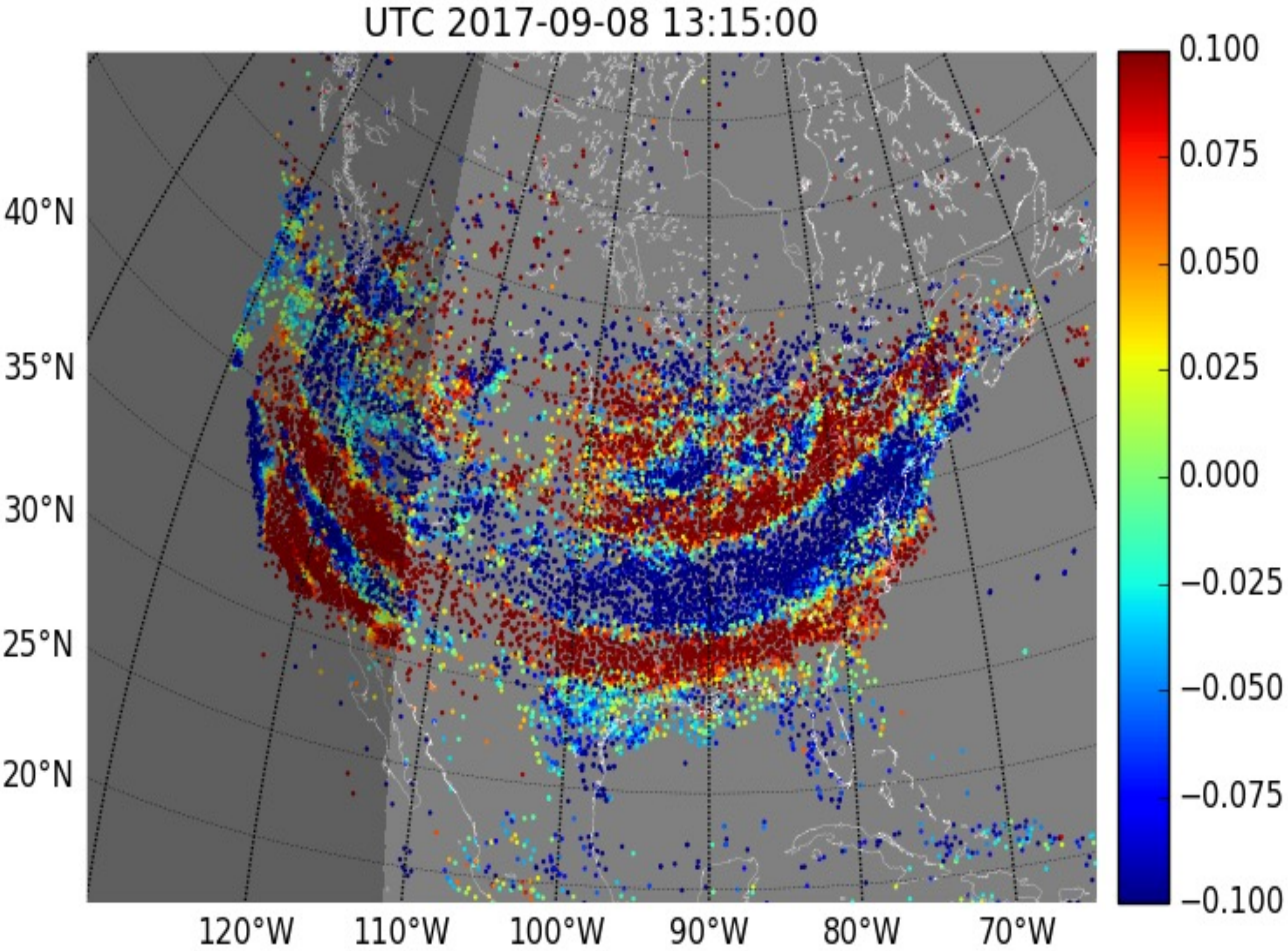
Socorro New Mexico 20 Nov 2003

(from astronomy picture of the day)

West Texas 15 Sept 2000 near El Paso Texas

(from astronomy picture of the day)

The last few slides are to provide excitement about the ionosphere !!!


UTC 2017-09-08 13:15:00
40°N
35°N
30°N
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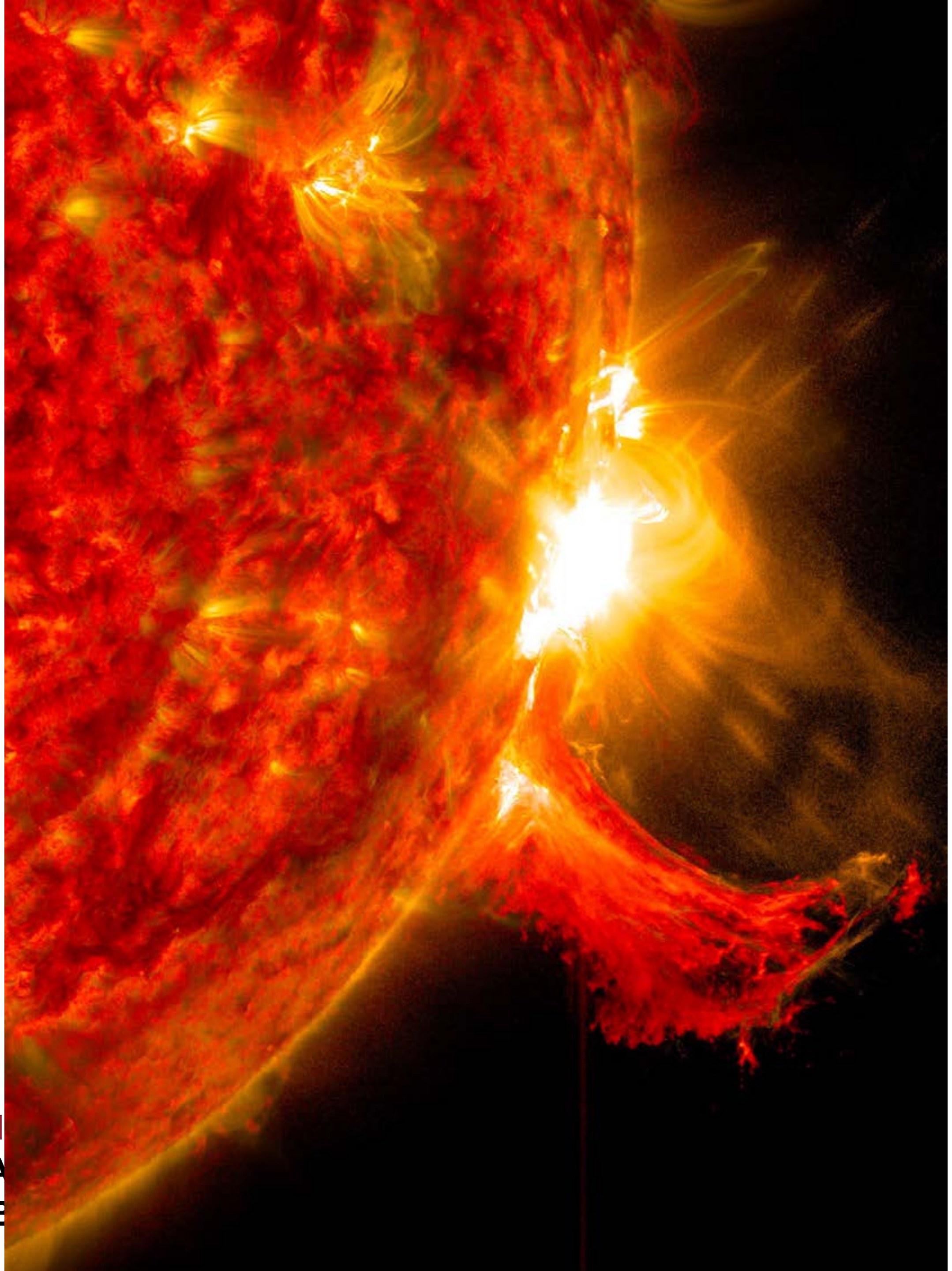
20°N
120°W
110°W
100°W
90°W
80°W
70°W
0.100
0.075
0.050
0.025
0.000
−0.025
−0.050
−0.075
−0.100

MI
HA
OE

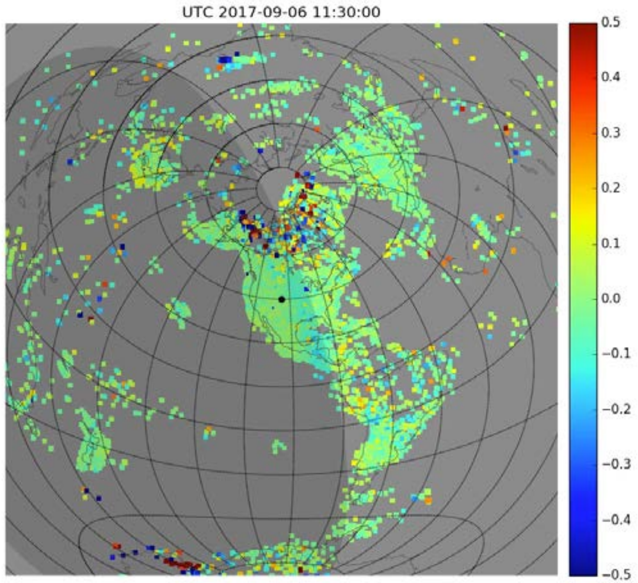
Solar Flare

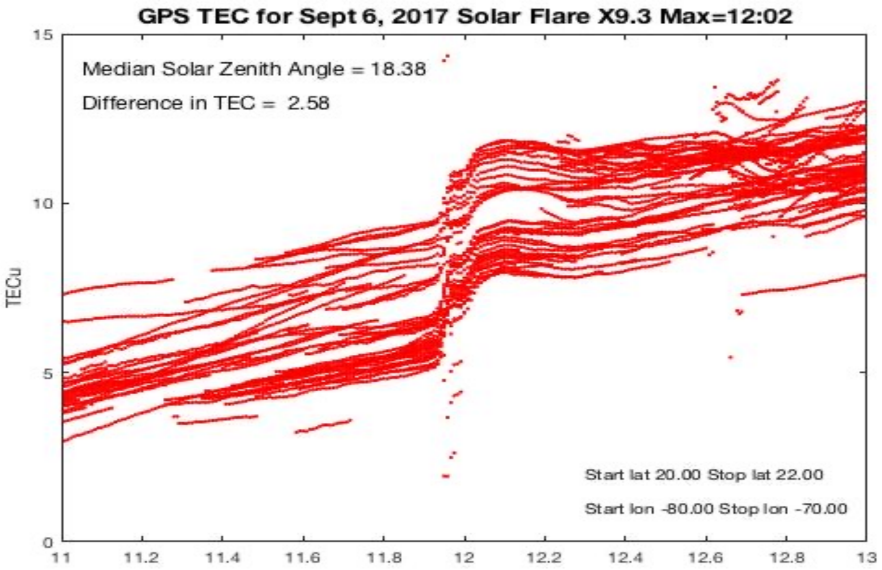


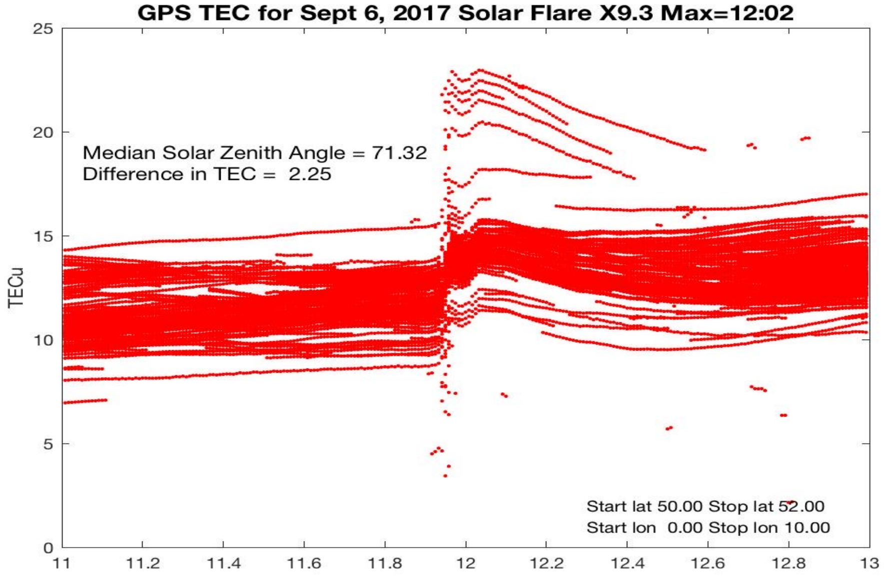
A violent explosion in the Sun's atmosphere; energy equivalent of a hundred million hydrogen bombs. Giant bursts of X-rays and energy which travel at the speed of light

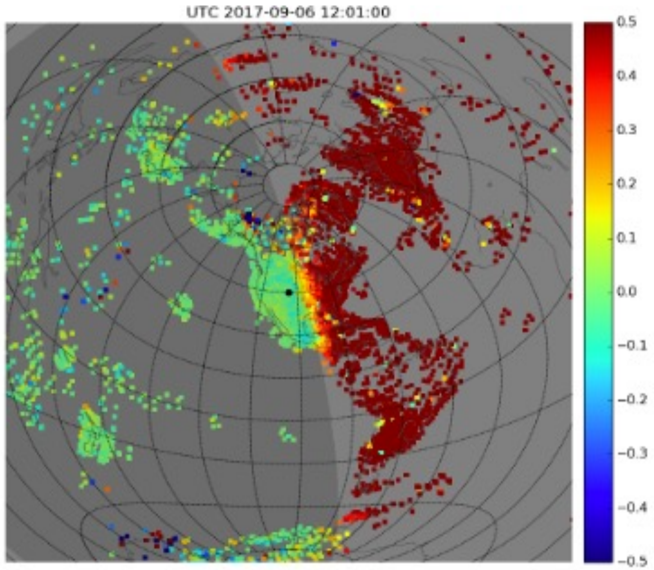
- **Arrival: 8 min from Sun to Earth (149.6 million km)**
- **Duration: minutes to 3 hrs**
- **Daylight-side impact**

Sept 6, 2017









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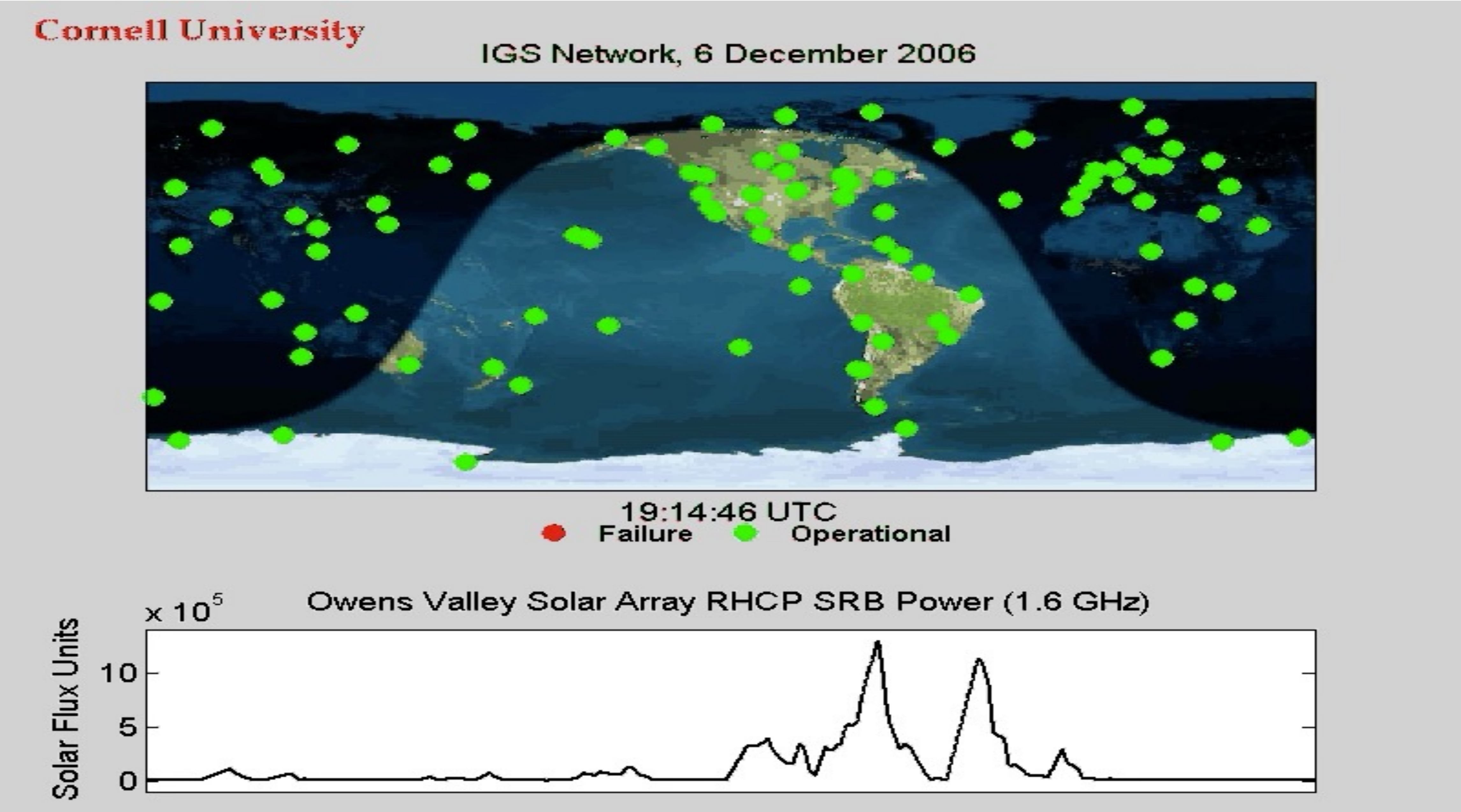
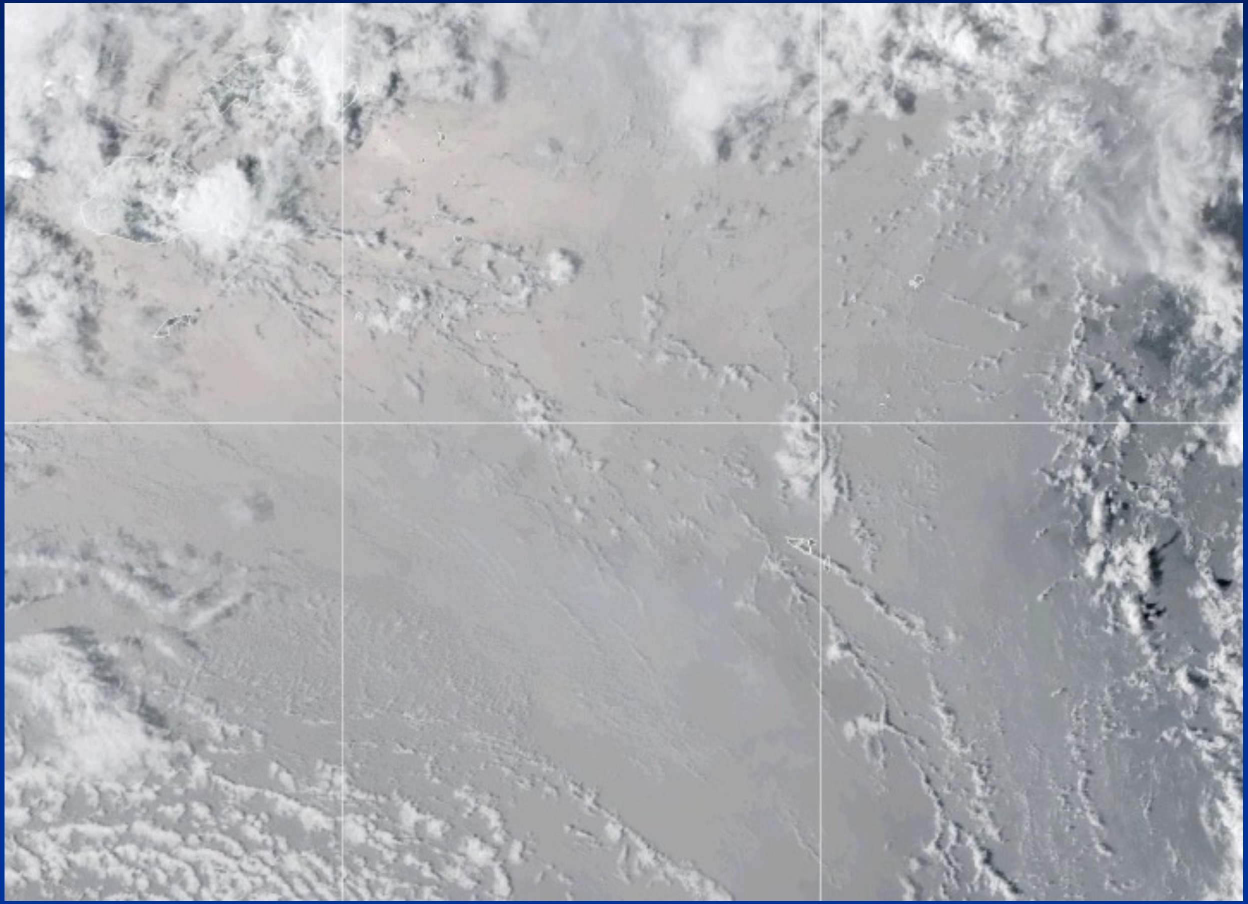

Cornell University
IGS Network, 6 December 2006
19:14:46 UTC
● Failure
● Operational
Owens Valley Solar Array RHCP SRB Power (1.6 GHz)
x 10^5
Solar Flux Units
10
5
0

2022 Tonga volcanic eruption induced TID global propagation



This looping video shows a series of GOES-17 satellite images that caught an umbrella cloud generated by the underwater eruption of the Hunga Tonga-Hunga Ha'apai volcano on Jan. 15, 2022.

Crescent-shaped bow shock waves and numerous lighting strikes are also visible.

Credit: NASA Earth Observatory image by Joshua Stevens using GOES imagery courtesy of NOAA and NESDIS
words from https://www.jpl.nasa.gov/news/tonga-eruption-sent-ripples-through-earths-ionosphere)

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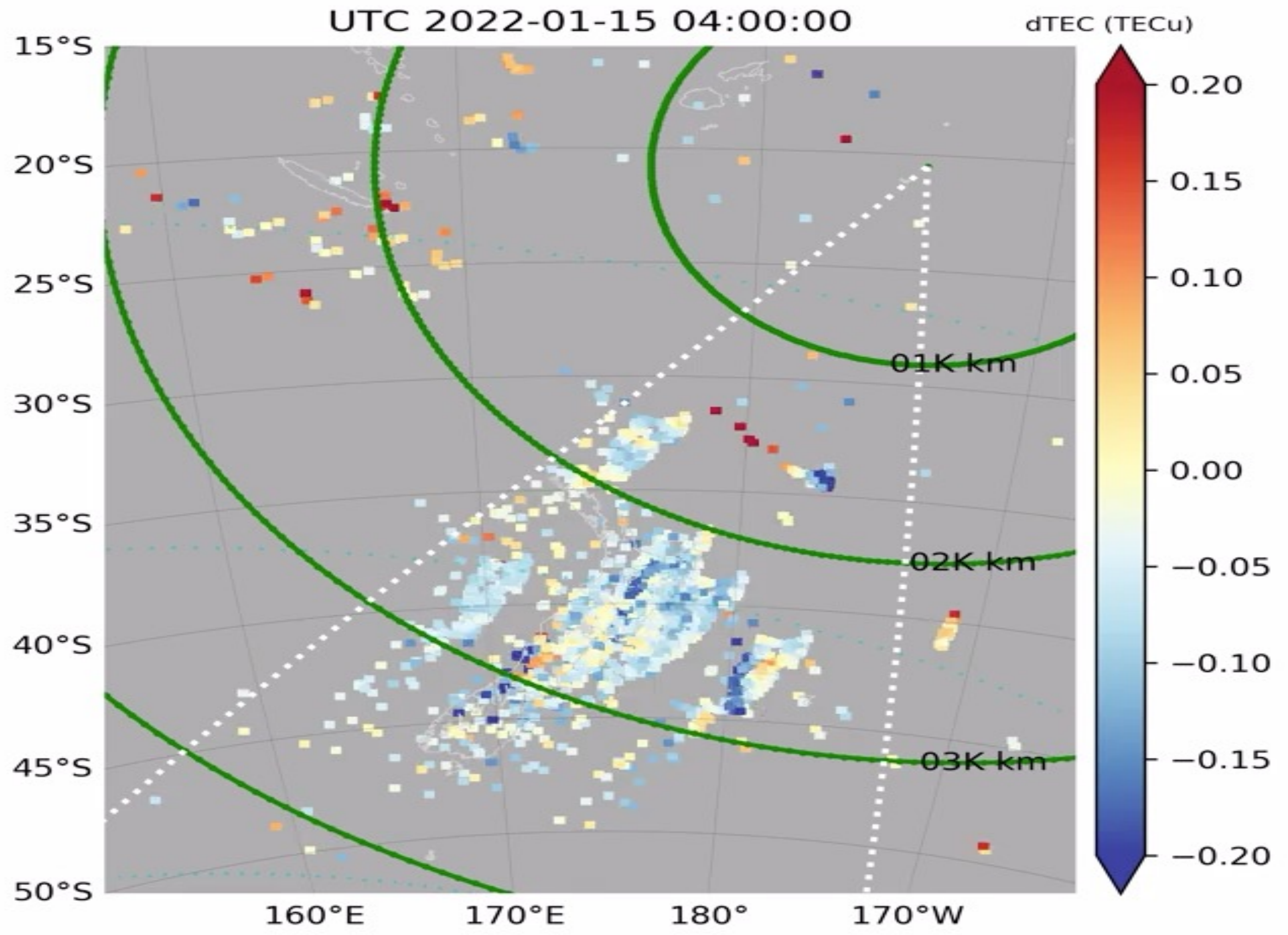
New Zealand (Animation)

Initial waves had huge amplitudes and wavelengths (~ 2K km!)

Subsequent waves had 300-500 km wavelengths



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Summary

Ionospheric science continues to provide us with a wealth of new and exciting observations (e.g. the Steve phenomena)
It is a major contributor to space weather effects on radio wave propagation and on PNT systems (positioning, navigation, and timing).

> **“The resulting electric field is as rich and complex as the driving wind field and the conductivity pattern that produce it”, Kelley, Ch. 3**

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