Space Weather In the Ionosphere and Upper Atmosphere

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NASA/Goddard Space Flight Center,

Space Weather “Bootcamp”
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Goals of this talk…

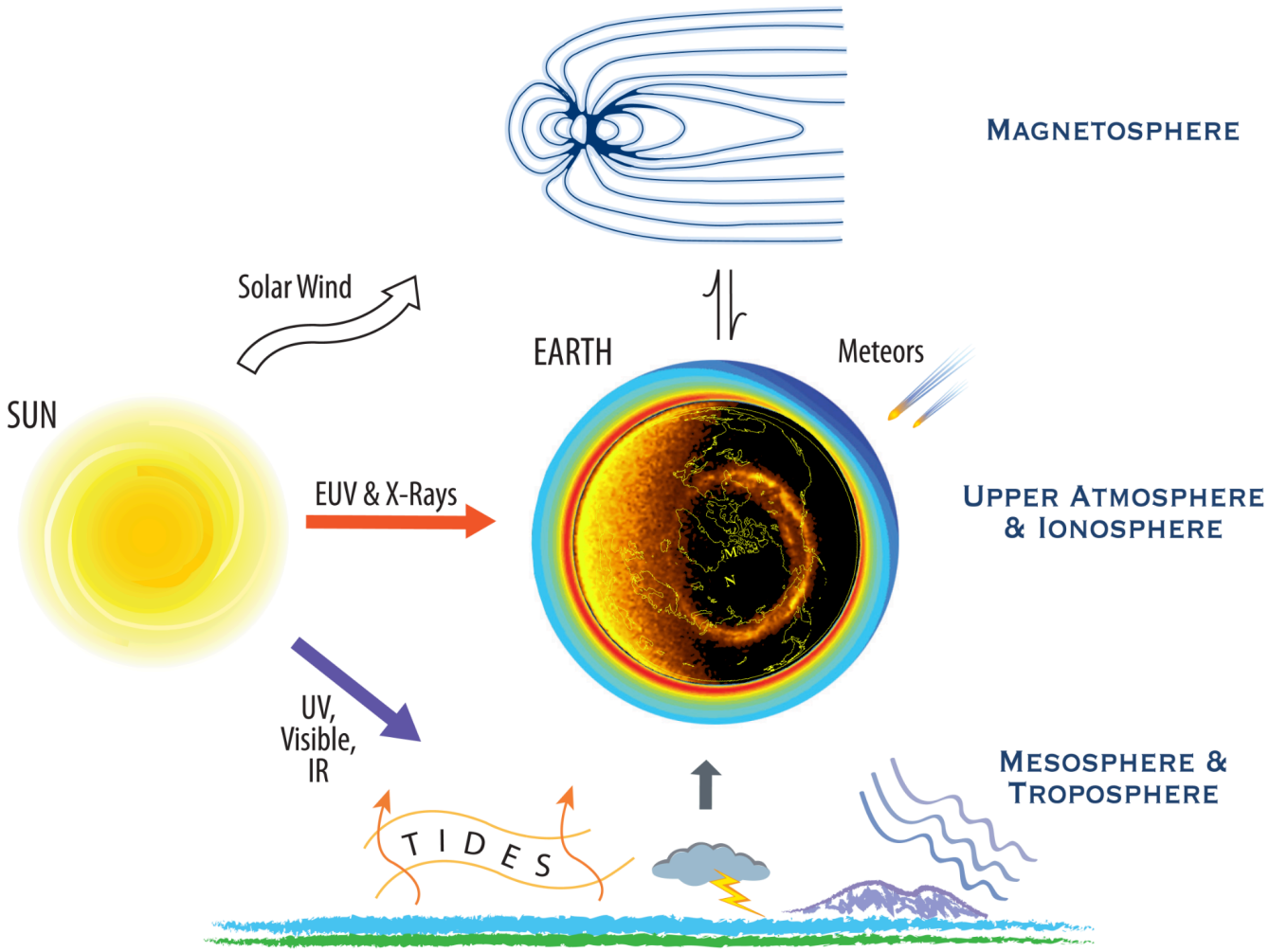
1. Provide an overview of the earth's ionosphere and upper atmosphere, including how dynamic and unpredictable they are…

2. Outline some of the main Space Weather processes that are intrinsic to the ionosphere/upper atmosphere

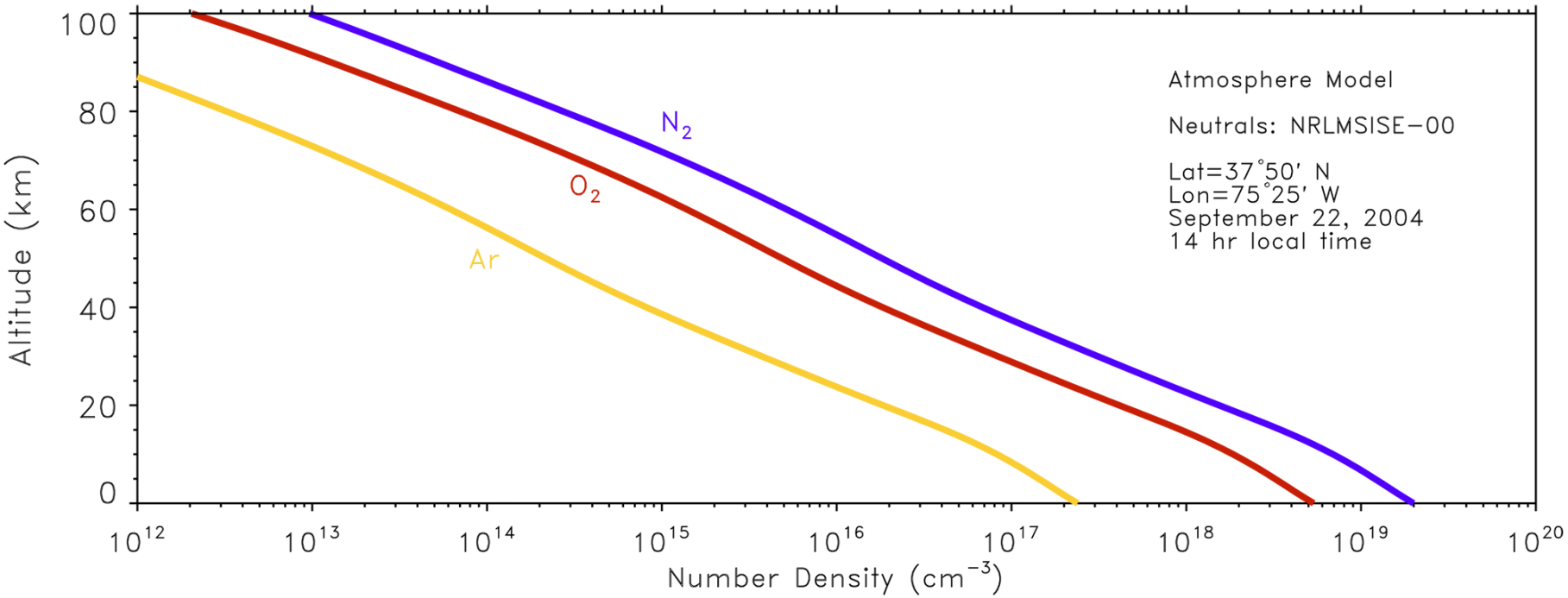
3. Underscore how poorly these regions are understood and why observations are needed to improve our knowledge and space weather models

We focus on the region of 50 to 500 km

Pathways of solar energy to the Upper Atmosphere and Ionosphere

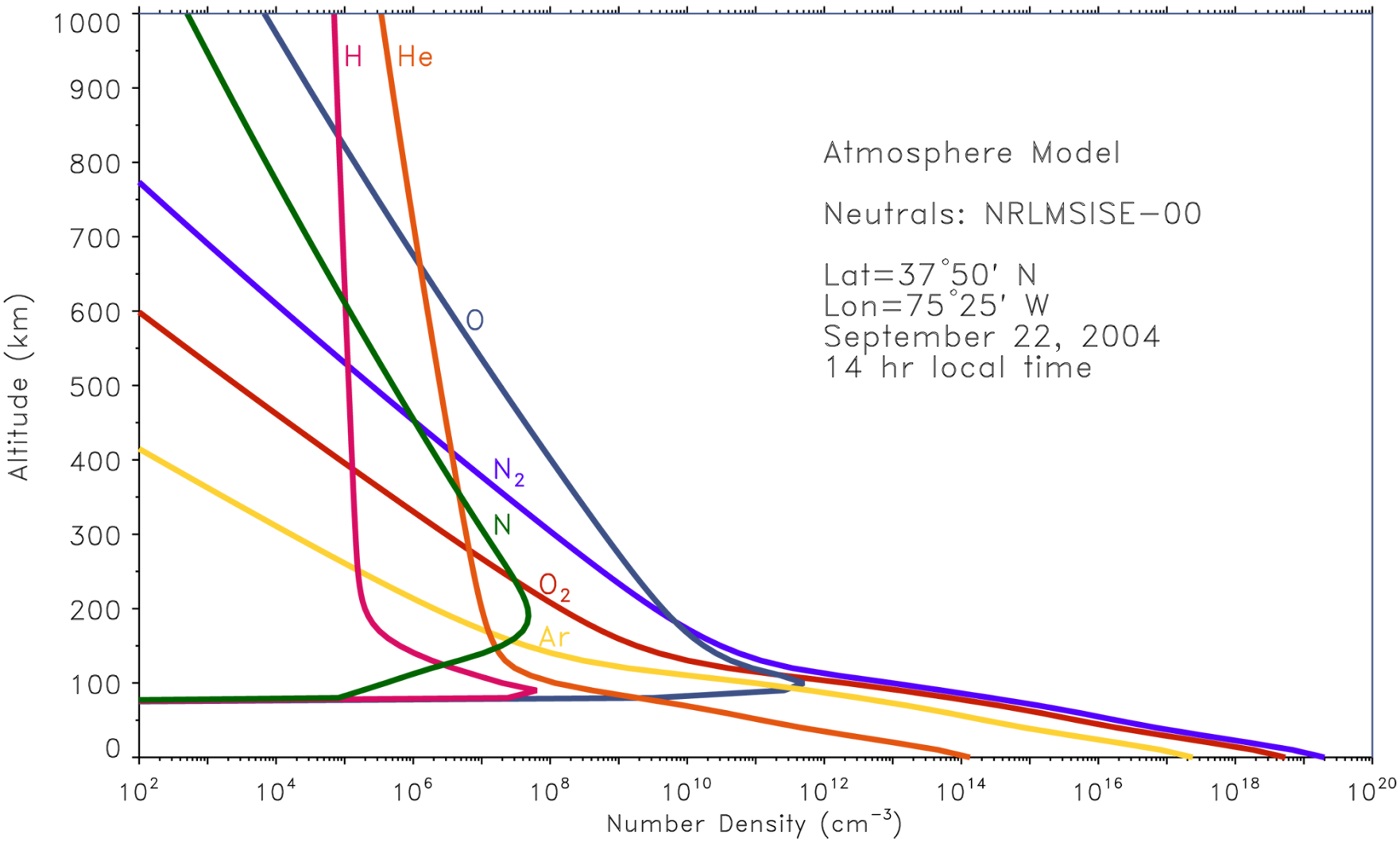


How high does the atmosphere extend?

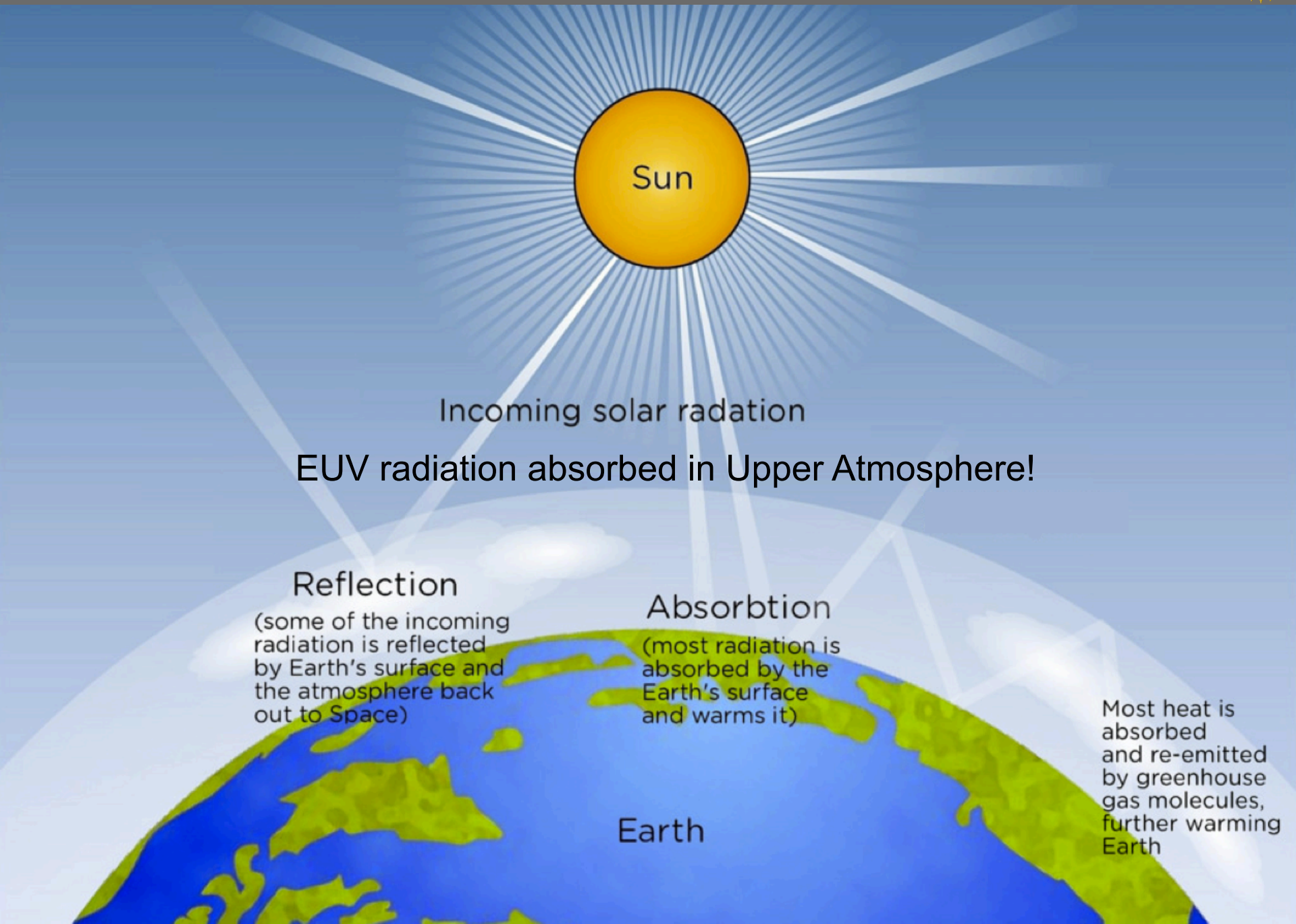


The atmosphere at the surface of the earth is 78% nitrogen, 21% oxygen, and 1% argon and other gases.

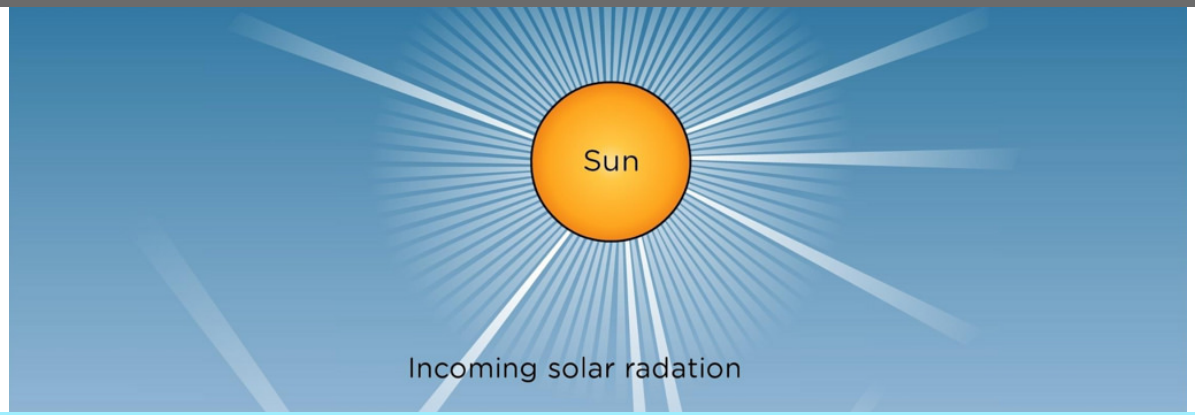
This mixture extends in altitude until…?


Atmosphere Model
Neutrals: NRLMSISE−00
Lat=37°50′ N
Lon=75°25′ W
September 22, 2004
14 hr local time
H
He
O
N2
N
O2
Ar
Altitude (km)
Number Density (cm−3)
1000
900
800
700
600
500
400
300
200
100
0
10^2
10^4
10^6
10^8
10^10
10^12
10^14
10^16
10^18
10^20

Graphic shows atmosphere extending to 1000 km



EUV radiation absorbed in Upper Atmosphere!

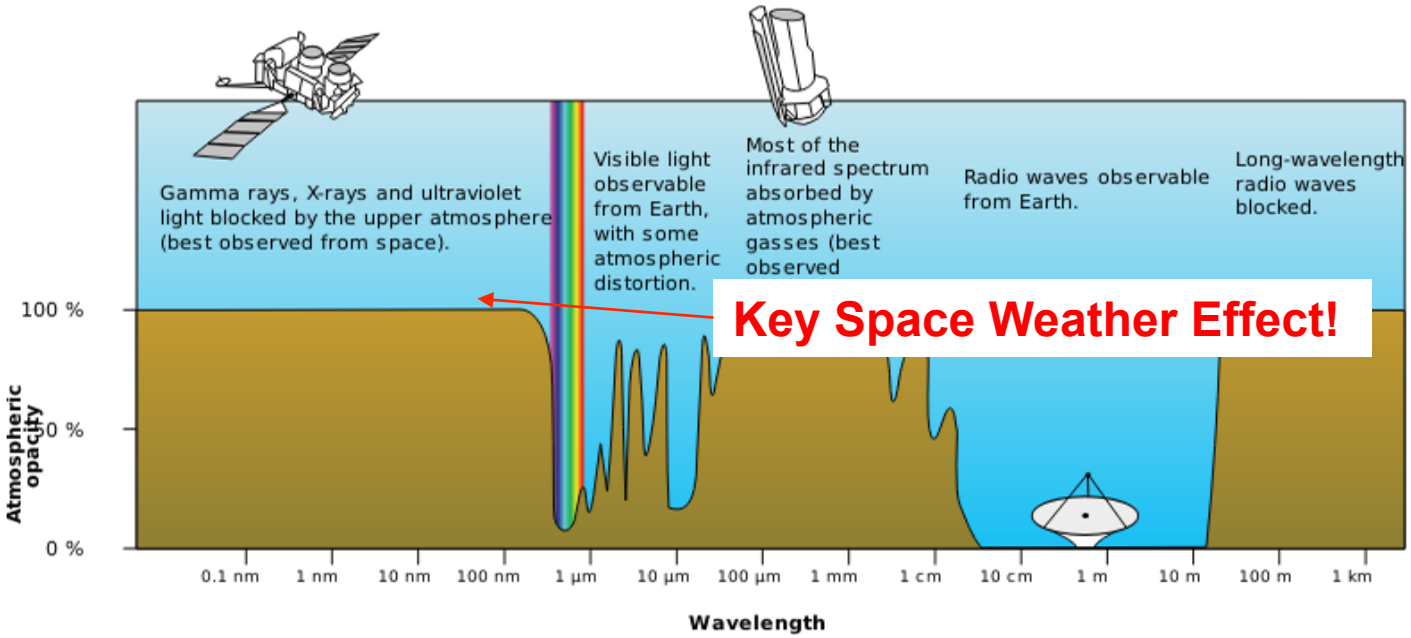


EUV radiation absorbed in Upper Atmosphere!

→ Heats the upper atmosphere (via dissociation of O_2 → O + O)

→ and thereby *sets it in motion*

→ Ionizes a small fraction



Earth's Upper Atmosphere Density

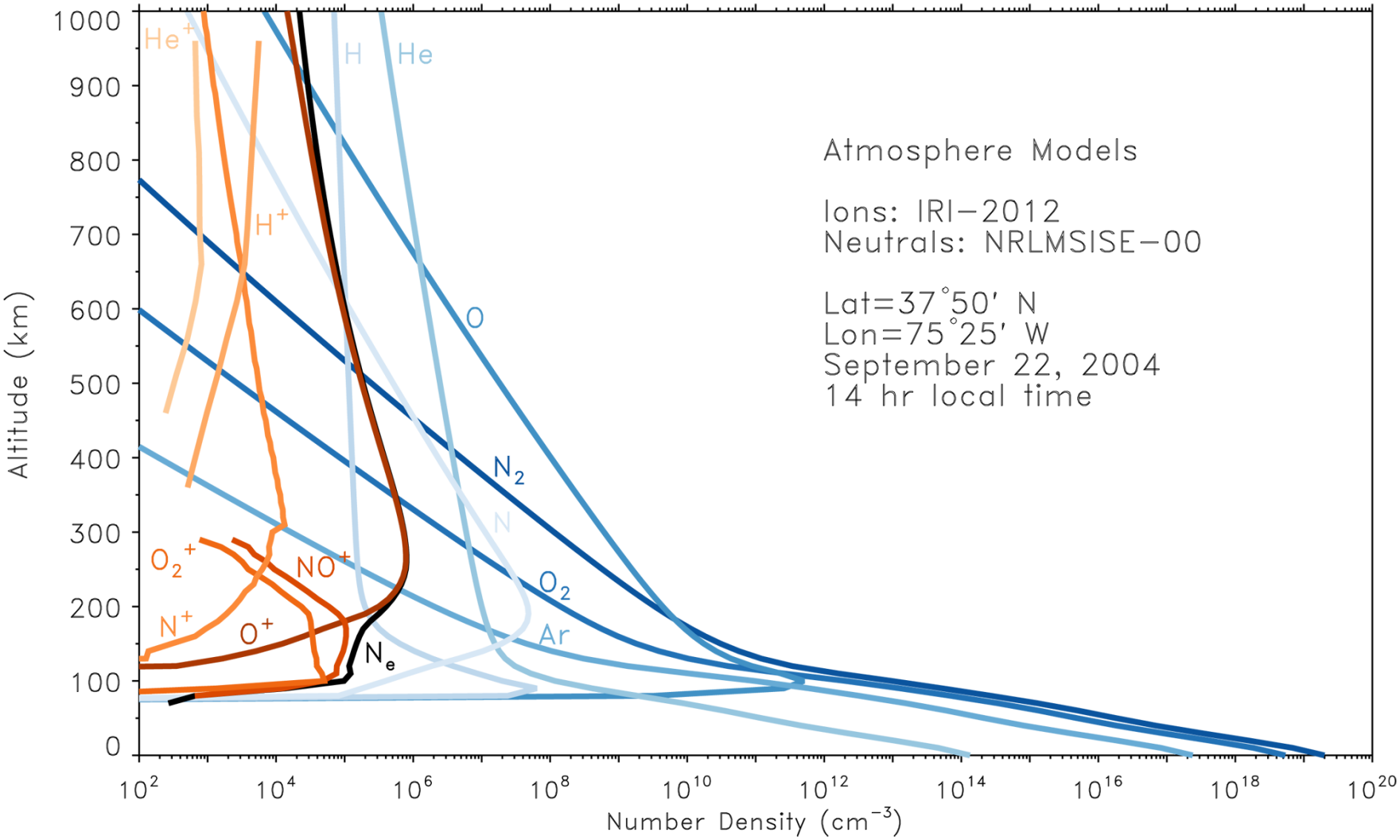
→ Life's "Shield"

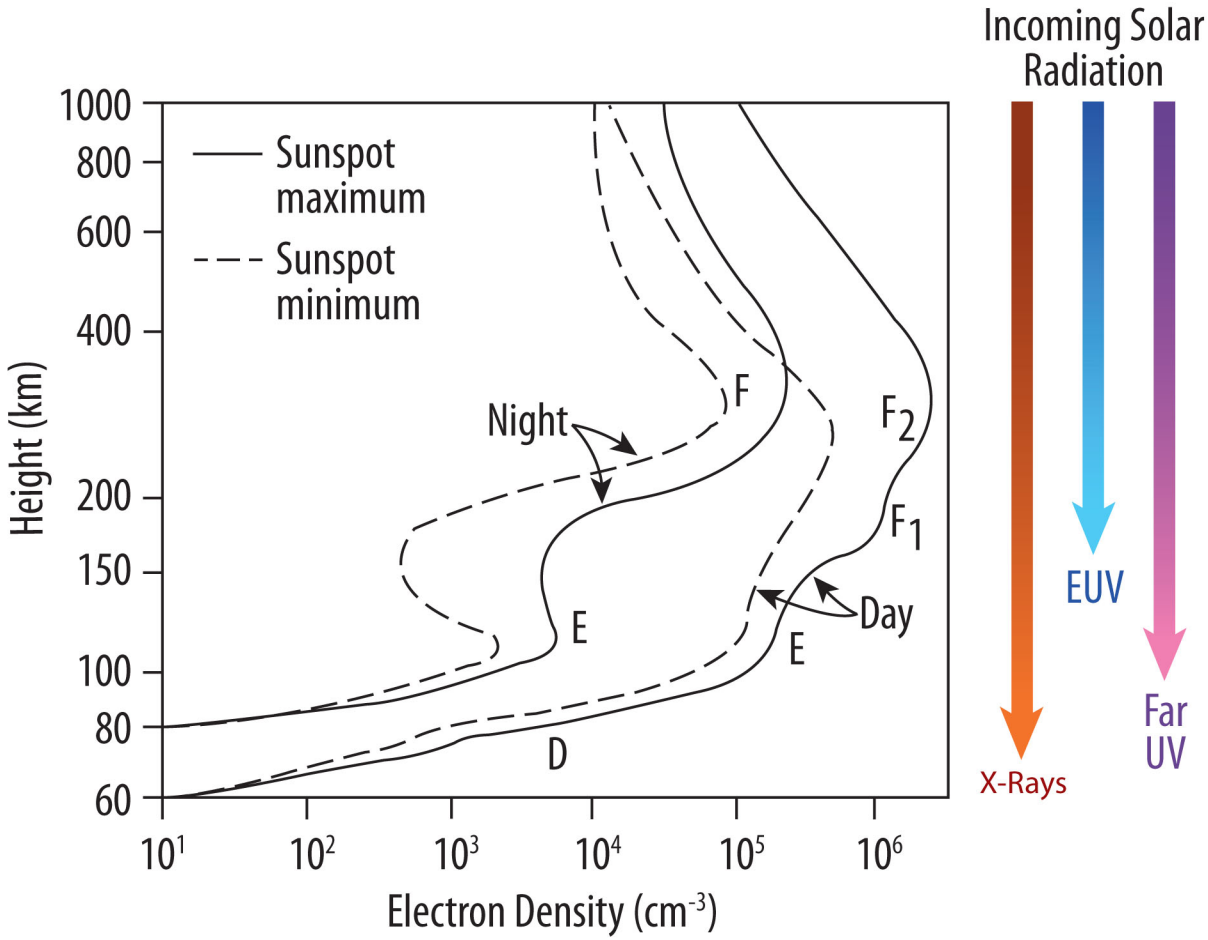
Key Space Weather variable

→ • Absorbs solar EUV and hence protects life

• Very important for understanding life on other planets such as Mars

Solar EUV radiation ionizes a small fraction of certain neutral density constituents above about 100 km




Incoming Solar Radiation
Sunspot maximum
Sunspot minimum
Height (km)
1000
800
600
400
200
150
100
80
60
Night
F
F2
F1
E
Day
E
D
X-Rays
EUV
Far UV
10¹
10²
10³
10⁴
10⁵
10⁶
Electron Density (cm⁻³)

Earth's Upper Atmosphere Density → Absorbs solar EUV

The main process by which the upper atmosphere absorbs EUV energy from the sun is that of photo-dissociation. Diatomic oxygen is the primary molecule in the upper atmosphere that dissociates. This occurs when it is struck by photons with wavelengths of 242 nm or less, as as expressed by the reaction

$$O_2 + h\nu\ (\lambda < 242\ \text{nm}) \rightarrow O + O + \text{energy}$$

The main mechanism that creates the ionosphere is the photo-ionization of a tiny fraction of the earth's extended, tenuous neutral upper atmosphere during the daytime. Essentially, incoming solar EUV and X-ray radiation penetrate the upper atmosphere with sufficient energy to detach an electron from a neutral atom to create an ion and electron pair, as depicted here for oxygen, the main atmospheric gas that is ionized in this manner:

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

Charge exchange readily occurs between the oxygen ions and the ambient nitrogen and oxygen molecules (N_2 and O_2), creating NO^+ and O_2^+:

$$O^+ + N_2 \rightarrow NO^+ + N$$

$$O^+ + O_2 \rightarrow O_2^+ + O$$

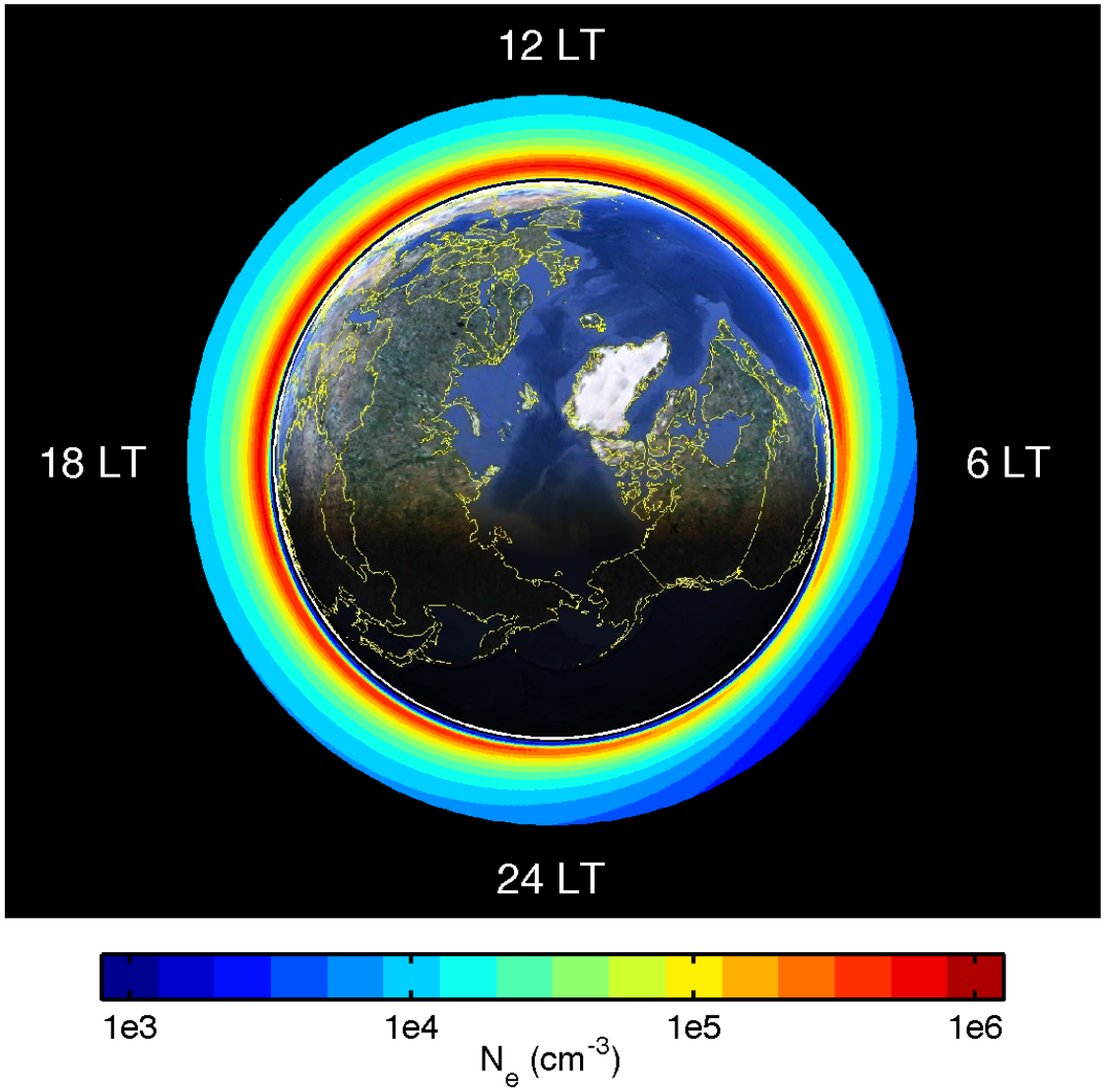
Dissociative recombination which is important for the E-region molecular ions and greatly reduces the density of the low altitude (< 250 km) nighttime ionosphere:

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

$$NO^+ + e^- \rightarrow N + O$$

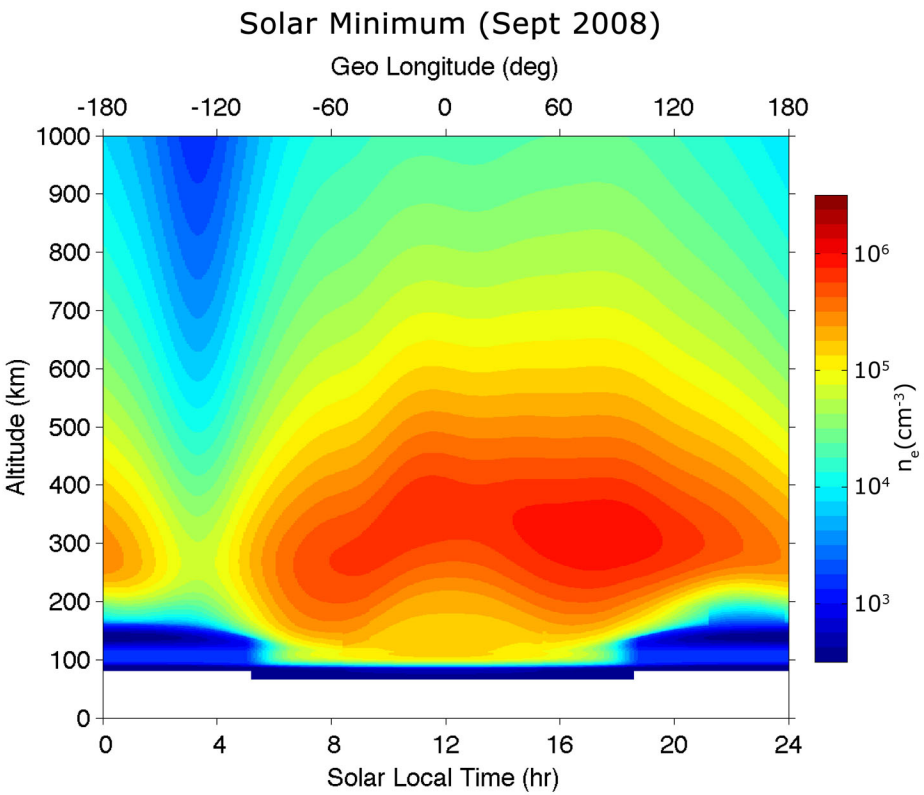
Remember: Ionosphere is charge neutral → Ne = Ni

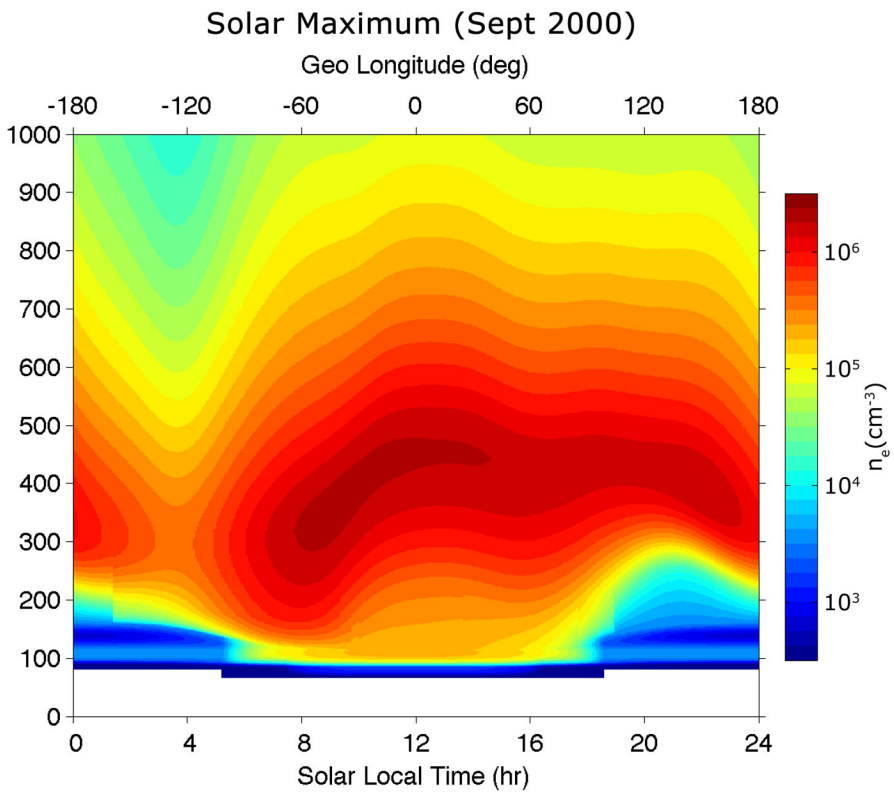
Plasma Density at the Magnetic Equator - IRI-2007 Model
22 Sep 2004



Electron Density Along Magnetic Dip Equator

IRI-2007 Model





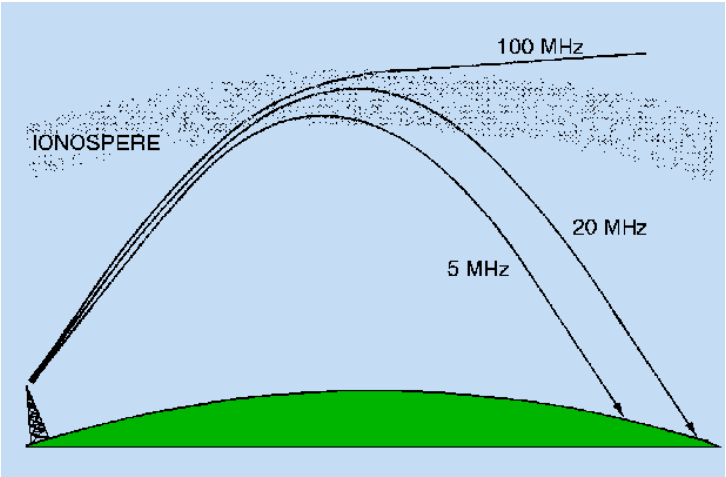
Ionospheric Density

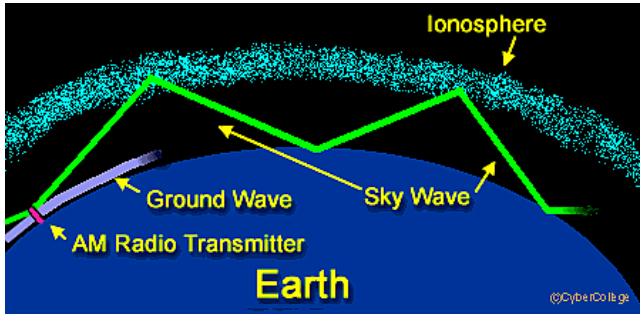
Key Space Weather variable

→ • Affects radiowave propagation, particularly below several MHz

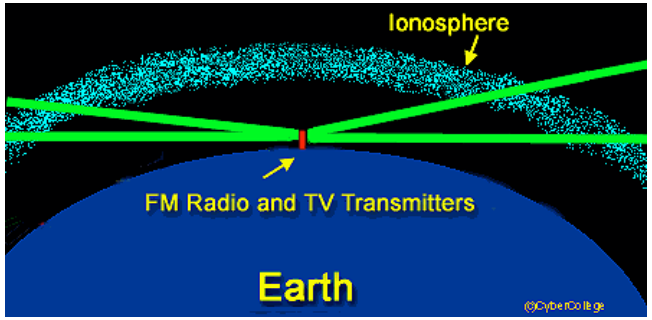
• Affects ionosphere/atmosphere “coupling” everywhere

The ionosphere reflects radio waves below the plasma frequency (about 10 MHz) and allows higher frequencies (microwaves) to pass through!





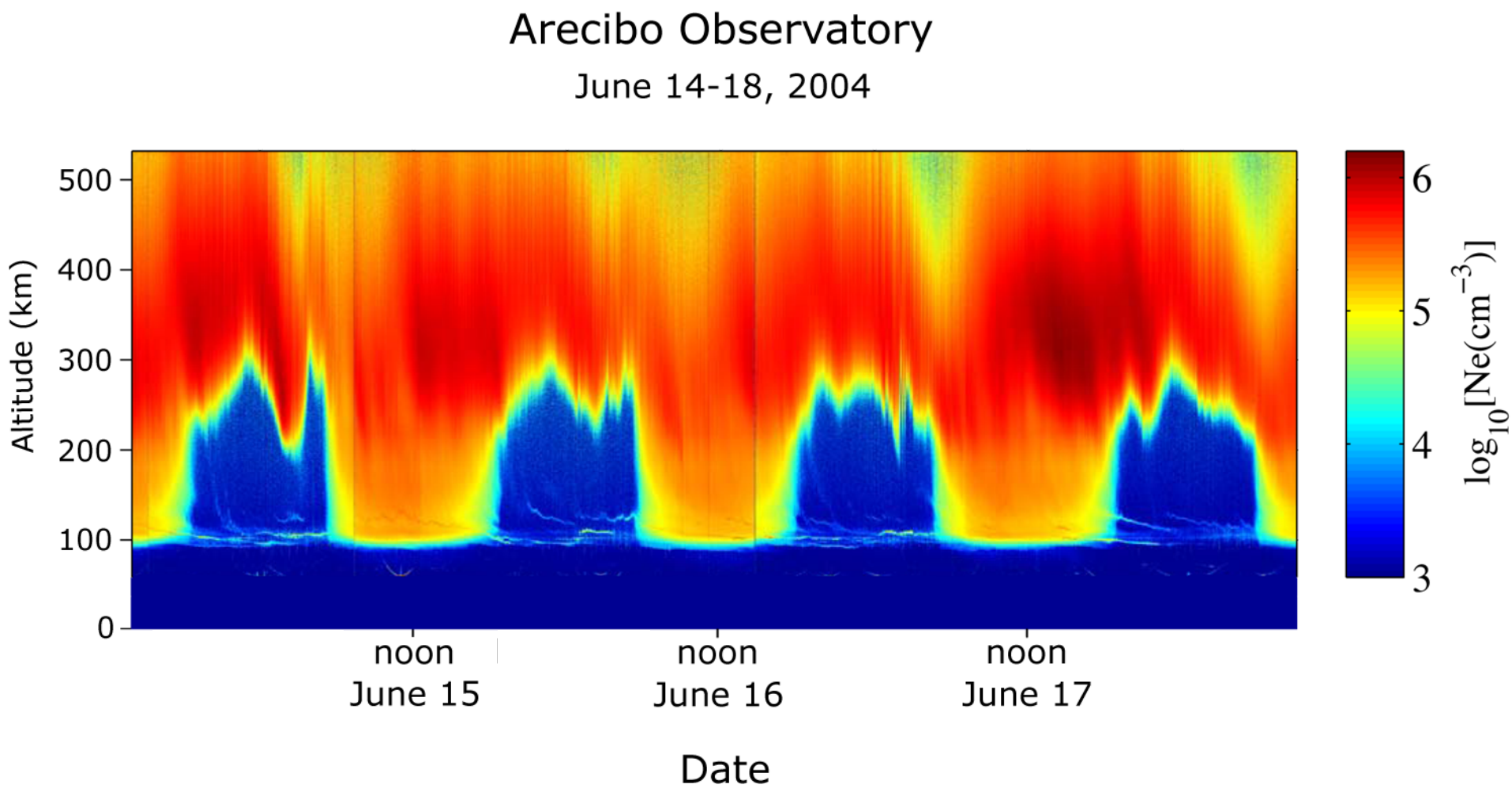
AM Radio (< a few MHz) is trapped in the earth's "waveguide"

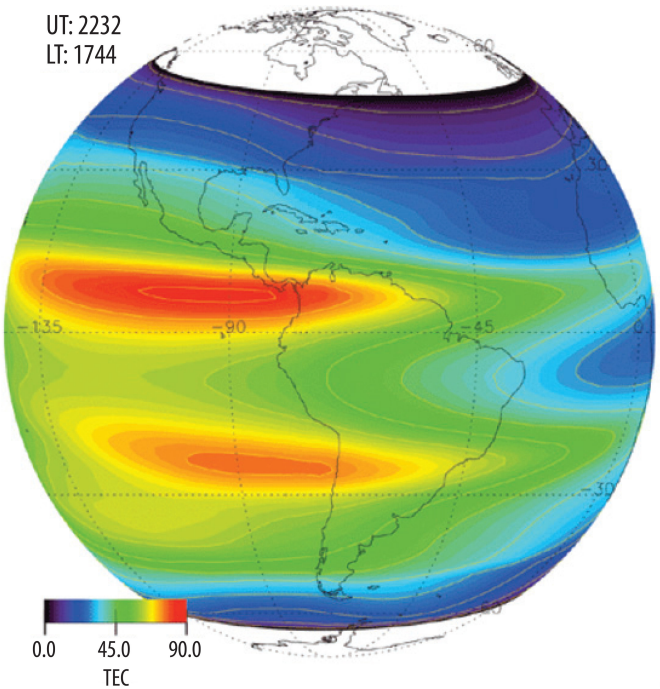


FM Radio + TV (< a few 100 MHz) passes through the ionosphere as do satellite communications!

Arecibo Observatory

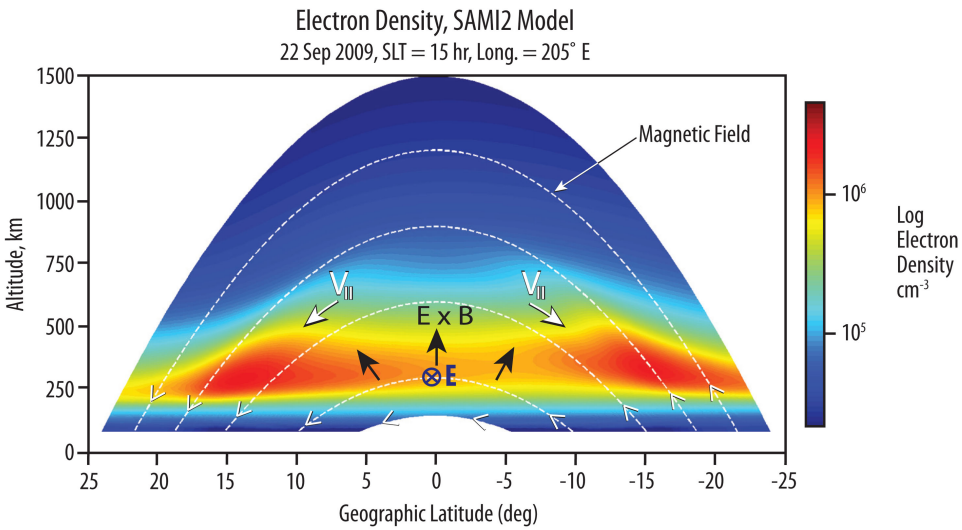
Provides exceedingly high quality measurements of the ionospheric density versus altitude

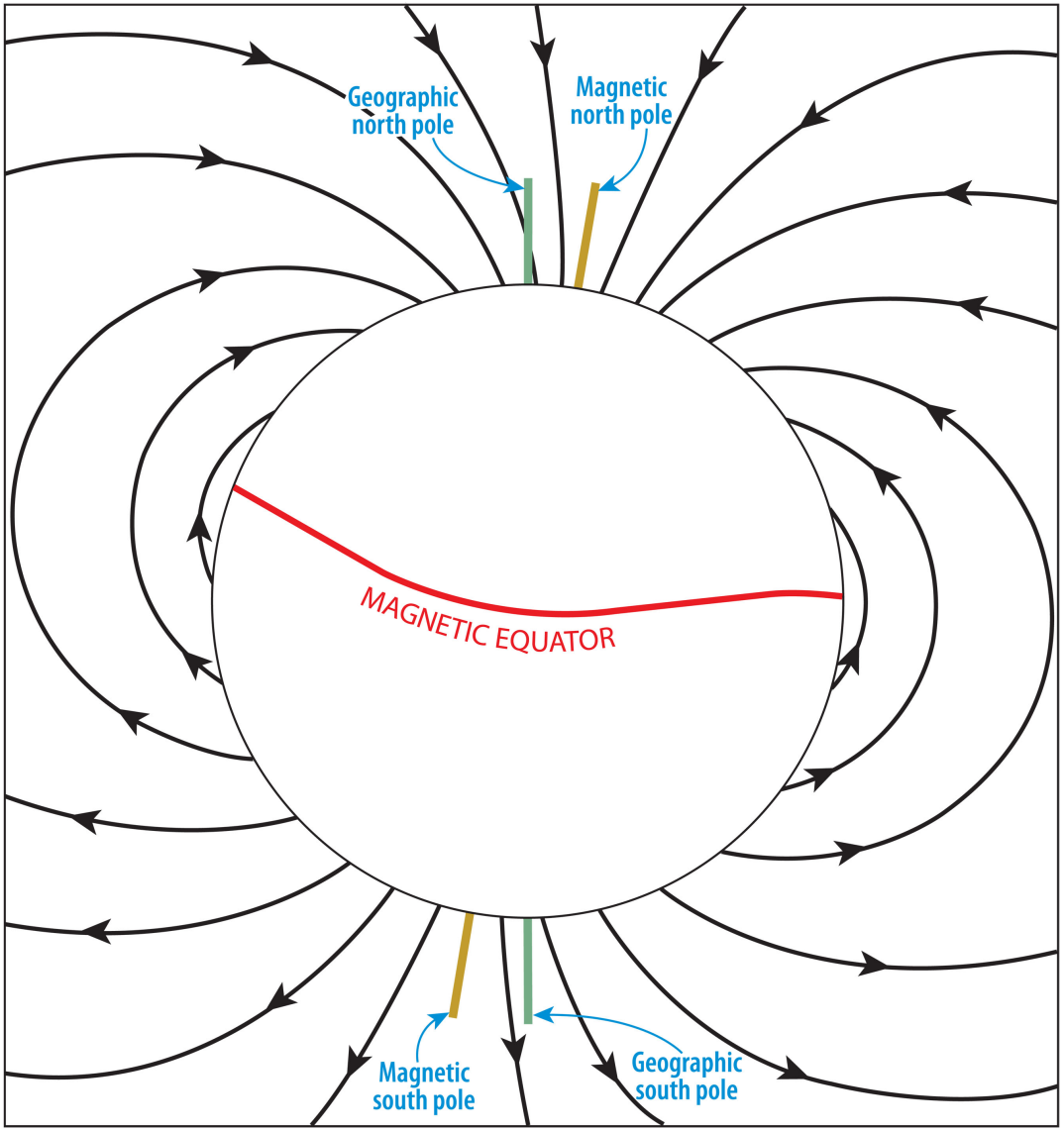

Arecibo Observatory
June 14-18, 2004
Altitude (km)
500
400
300
200
100
0
noon
June 15
noon
June 16
noon
June 17
Date
6
5
4
3
$\log_{10}[Ne(cm^{-3})]$



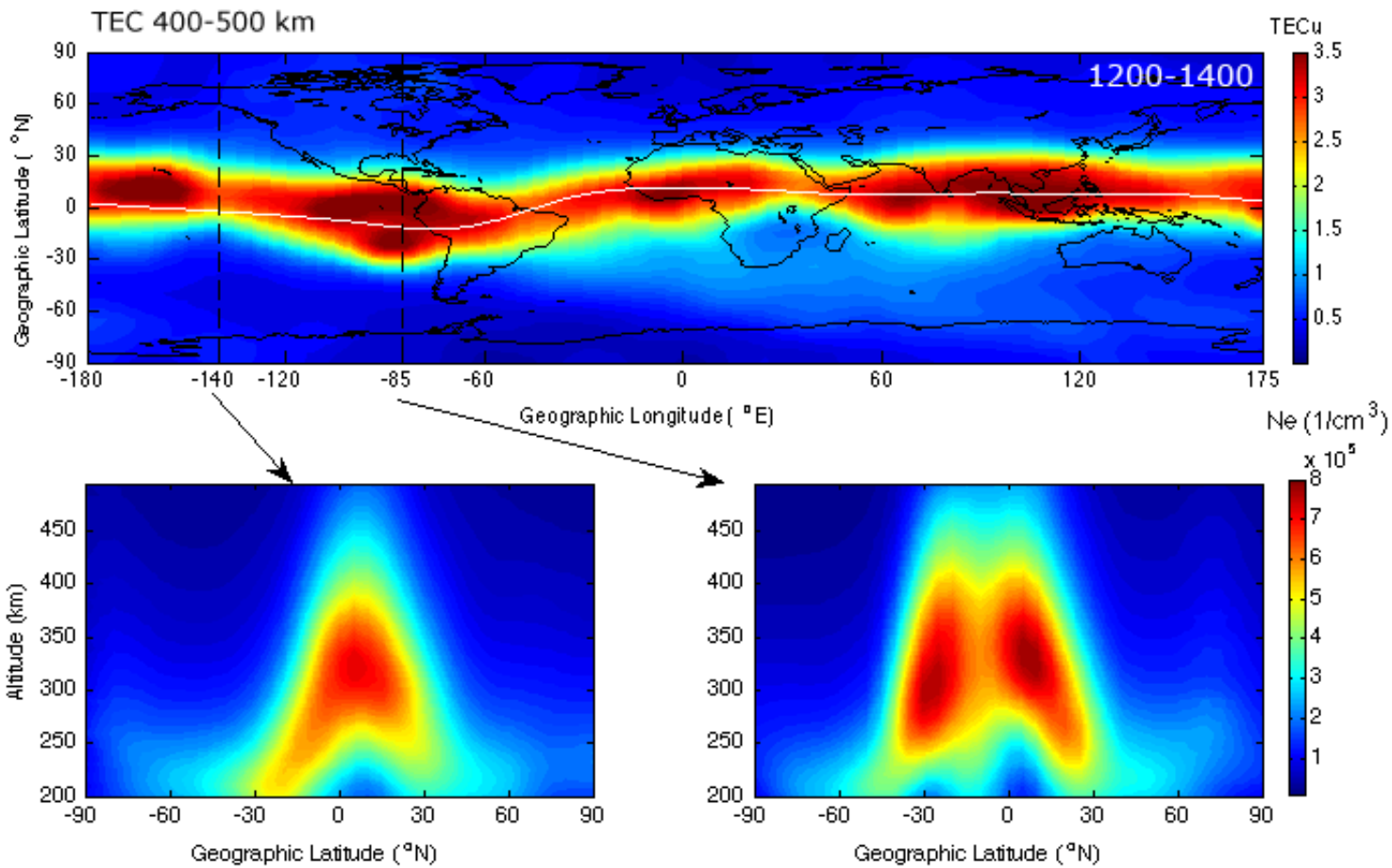
The earth's ionosphere is not strongest at the sub-solar point!

Electric fields at the magnetic equator drive the ionosphere where it then "slides" down magnetic fields lines (the "Fountain Effect"




Geographic north pole
Magnetic north pole
MAGNETIC EQUATOR
Magnetic south pole
Geographic south pole

But the plasma density is shown to vary with longitude!



Perhaps the electric field (or neutral winds?) that drives the Fountain Effect varies with longitude? → tidal effects from below?

COSMIC-2 Satellite (Lin et al., 2007)

Ionospheric Density Irregularities

Key Space Weather variable

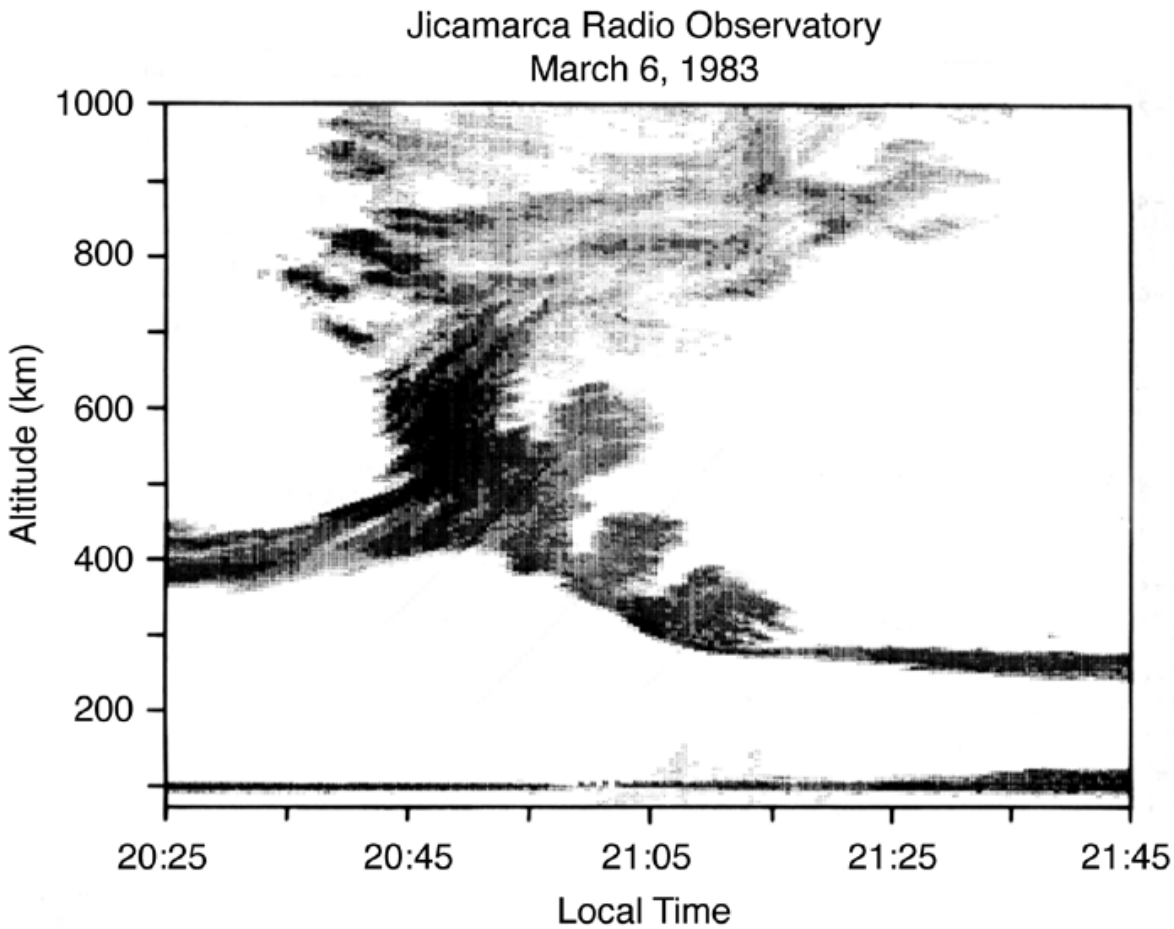
→ • Affects communication/navigation systems, particularly above several MHz

Jicamarca Radio Observatory, Peru

Premier scientific facility in the world for studying the equatorial ionosphere

- 50 MHz
- 18432 three-meter crossed dipoles
- 288m by 288m

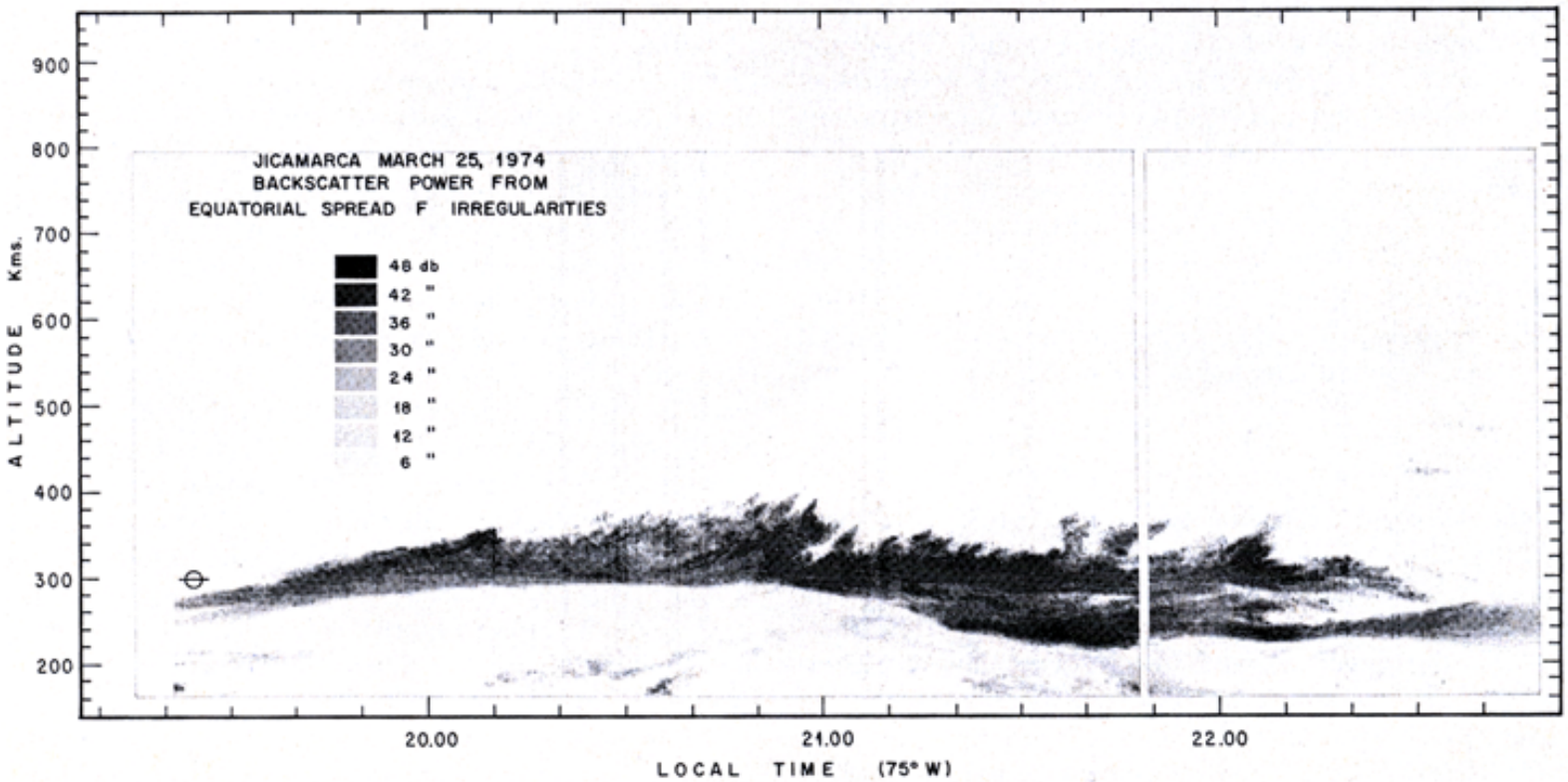
Backscatter radar shows the ionosphere is highly irregular particularly at the magnetic equator after sunset



Kelley et al., 1986

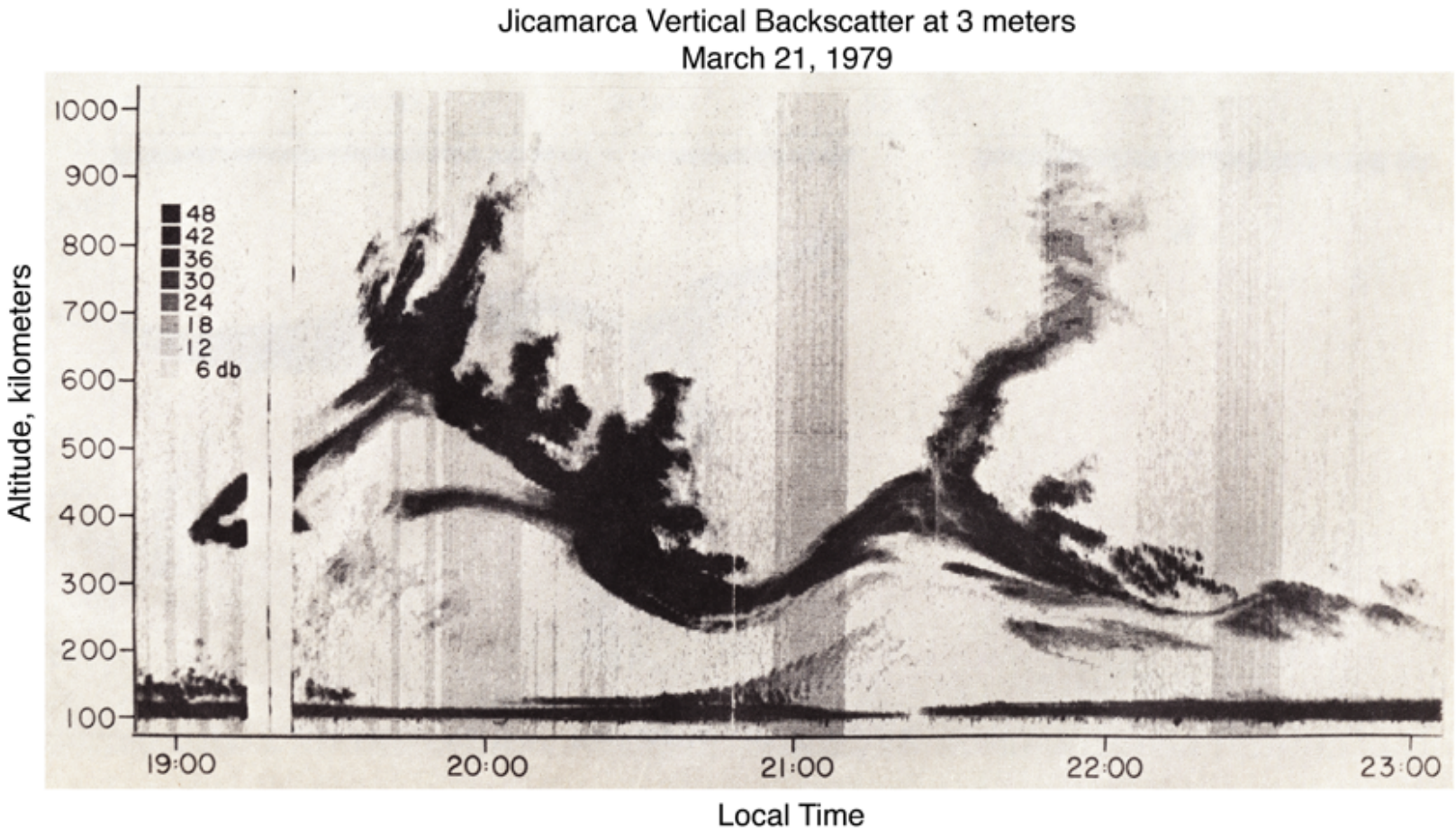
Sometimes the irregularities are only present at the bottom of the ionosphere

Jicamarca Radio Observatory
25 March 1974



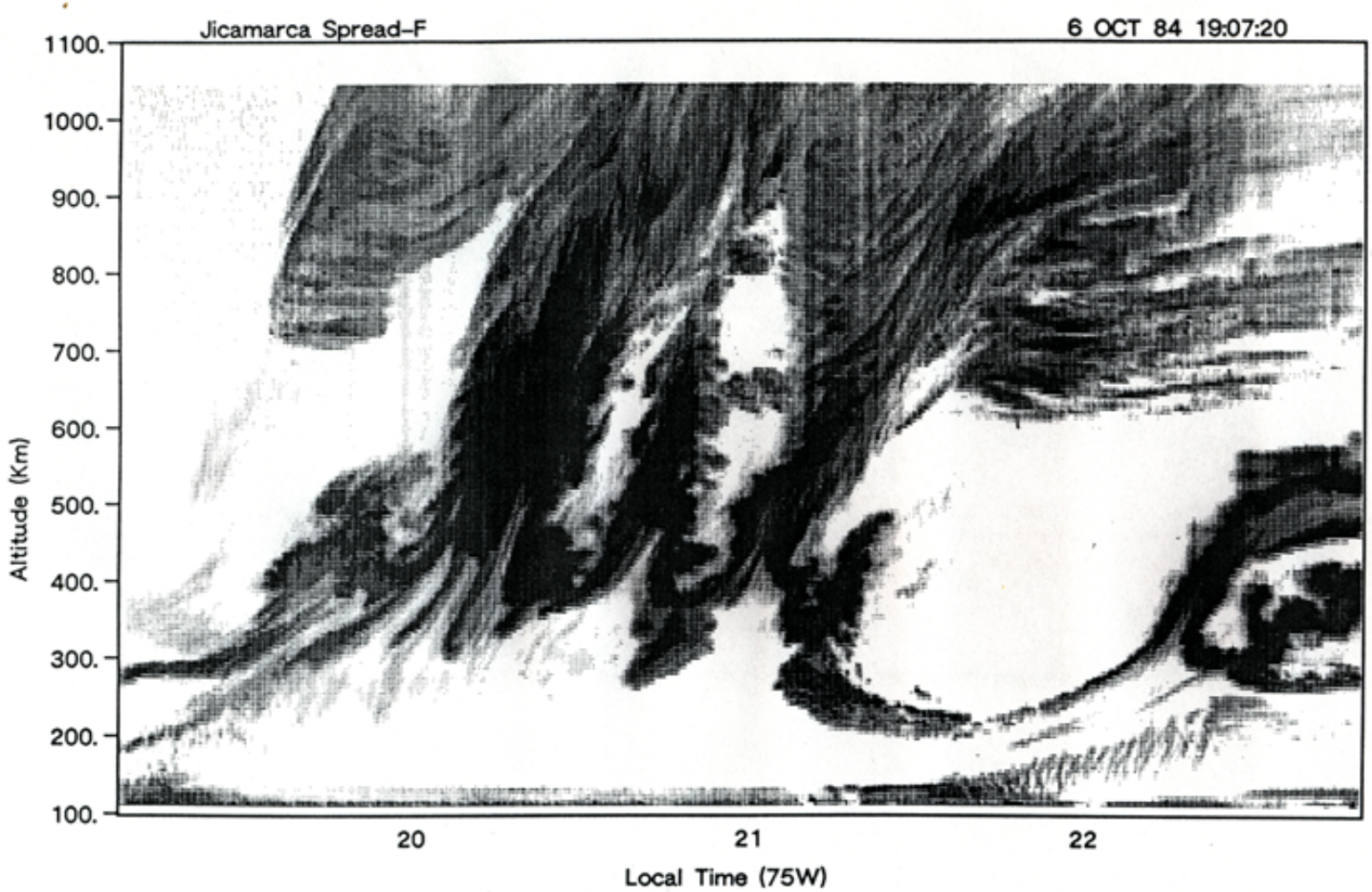
Woodman and LaHoz, 1976

Spread-F radar displays are often very dramatic -- indicating plasma density is disturbed on planetary scales.



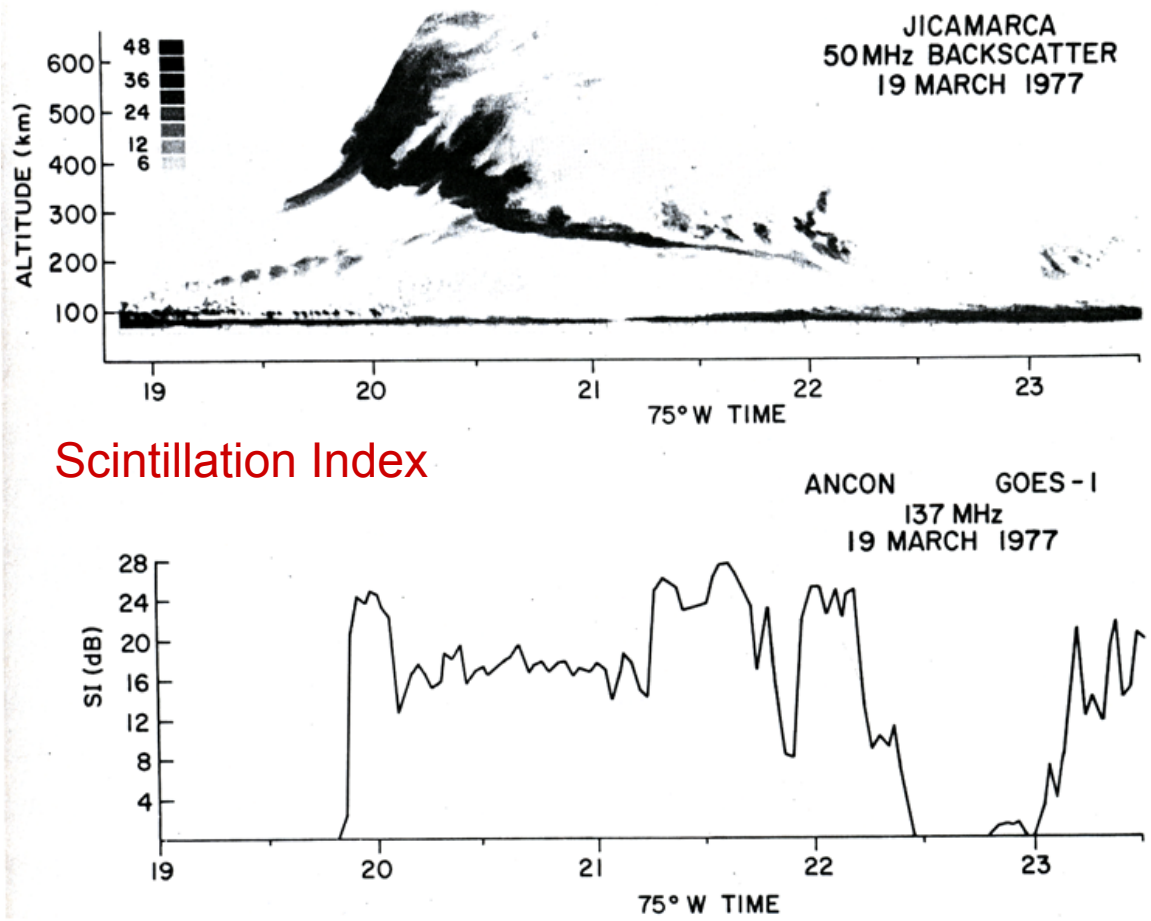
Kelley et al., 1981

Spectacular Spread-F radar displays from Jicamarca associated with magnetic storm

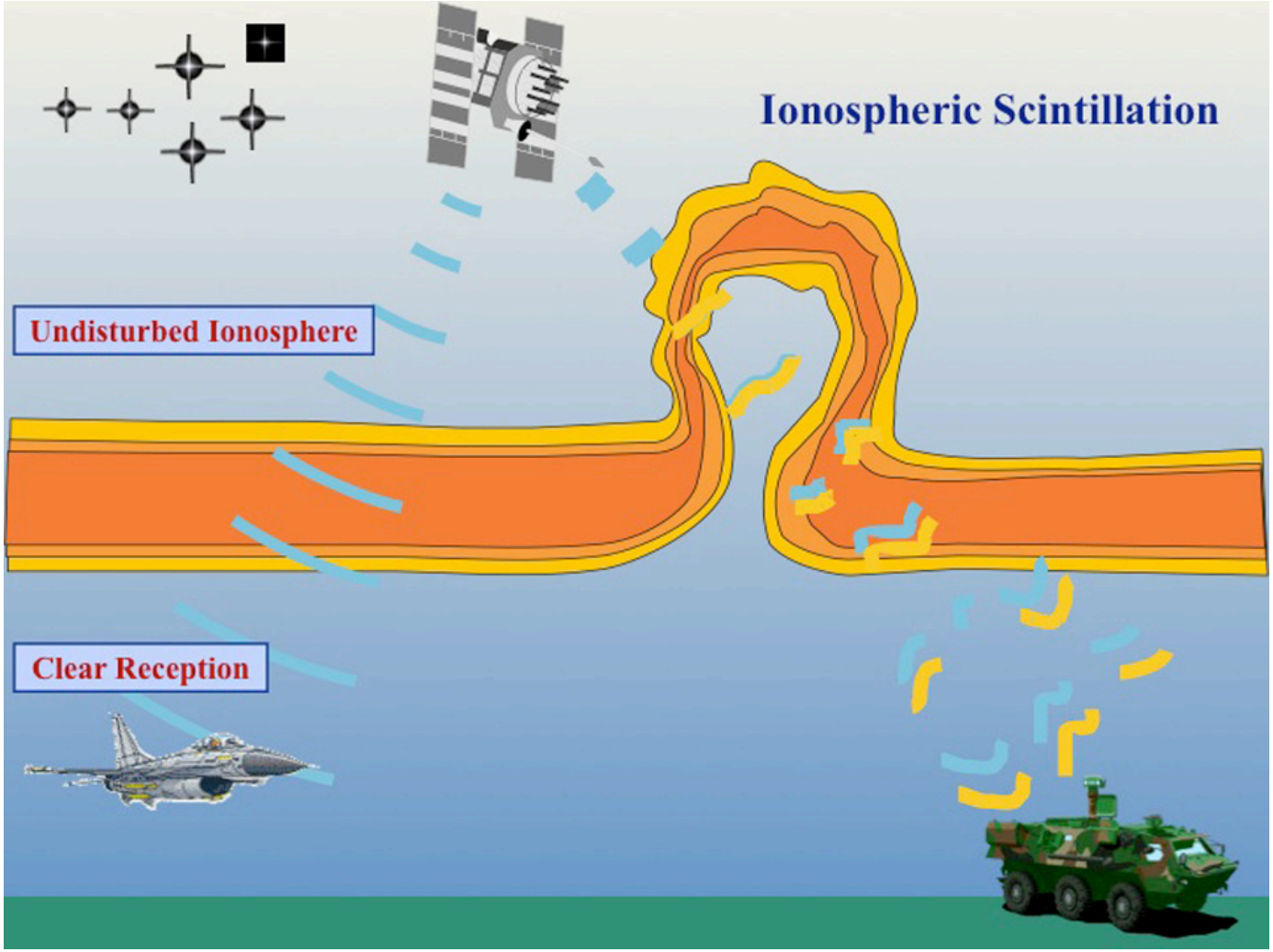


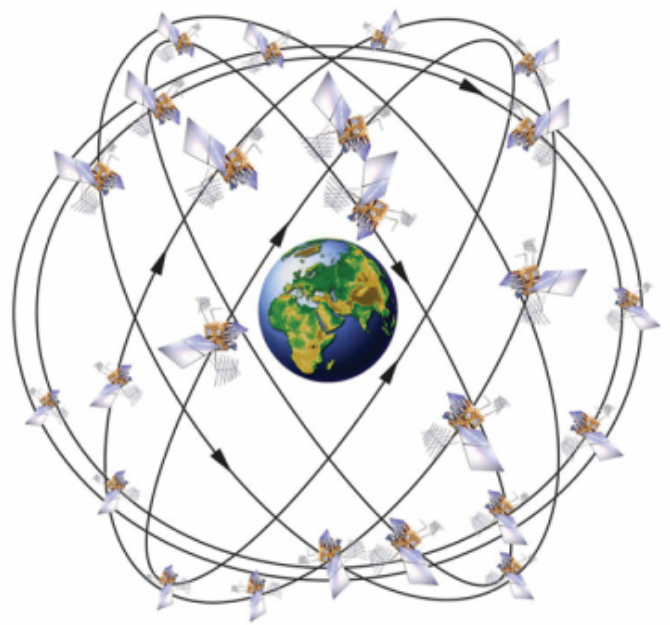
Data courtesy R. Woodman, JRO

Irregularities disrupt radiowaves, particularly at high frequencies!

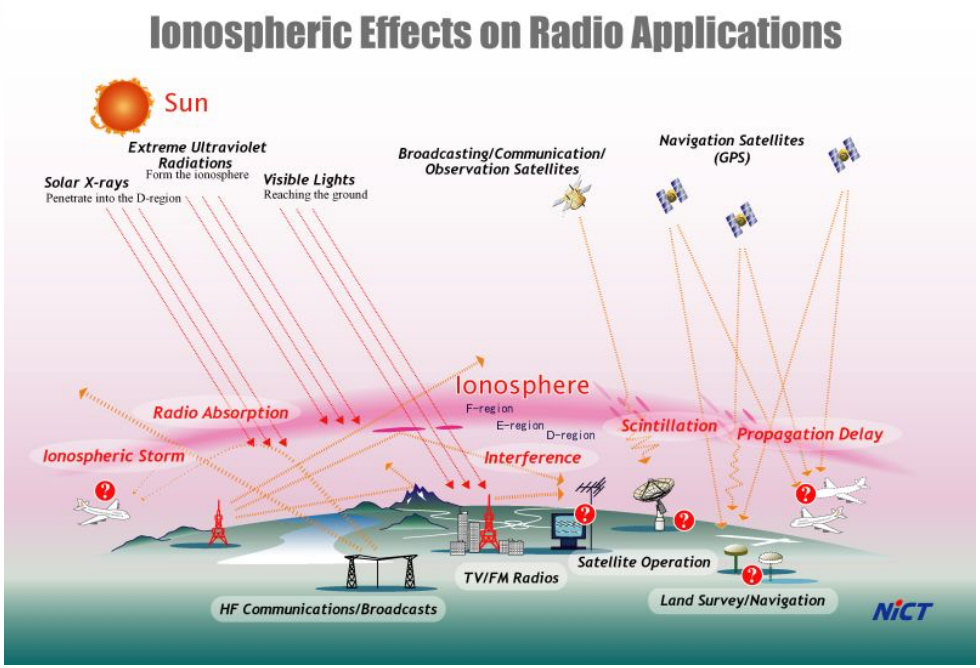


Basu et al., 1978


Ionospheric Scintillation
Undisturbed Ionosphere
Clear Reception



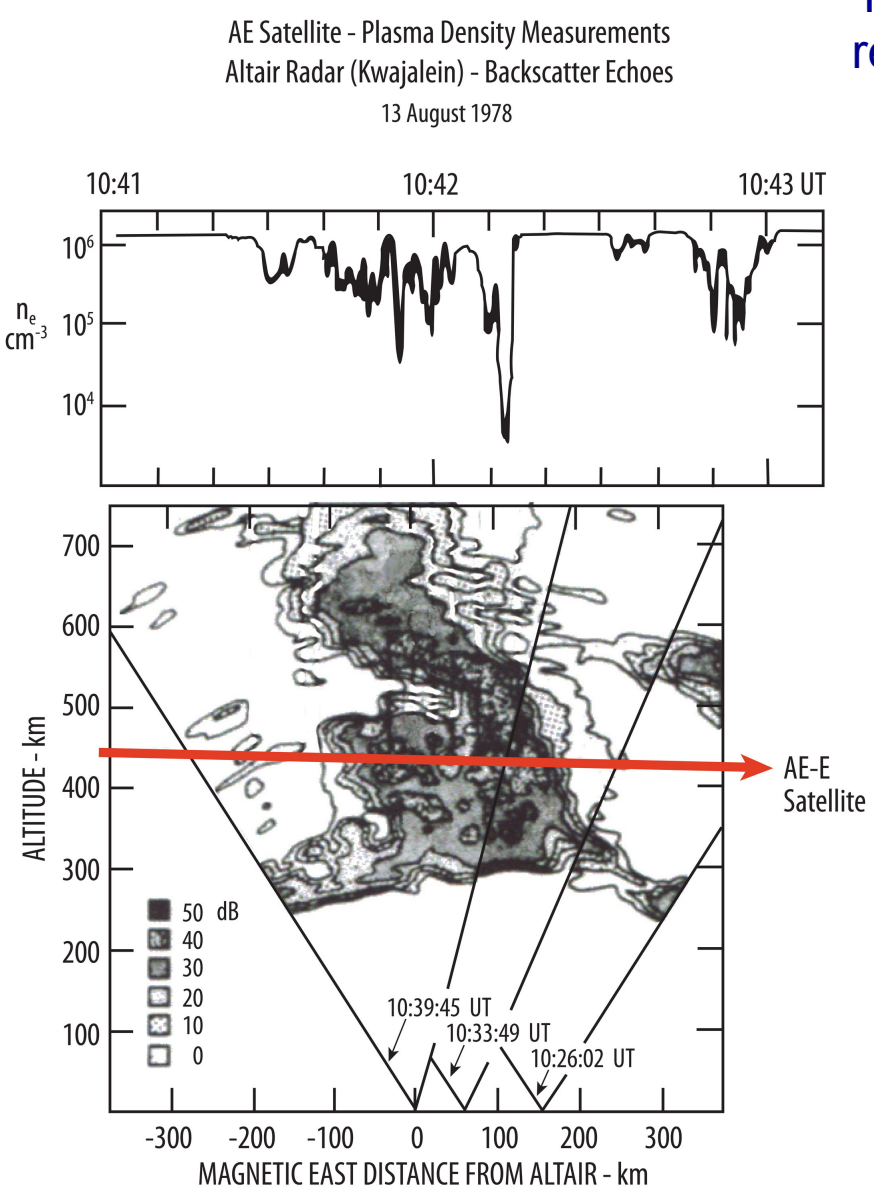
GPS Navigation Signals are Susceptible to Errors due to Ionospheric Scintiallations



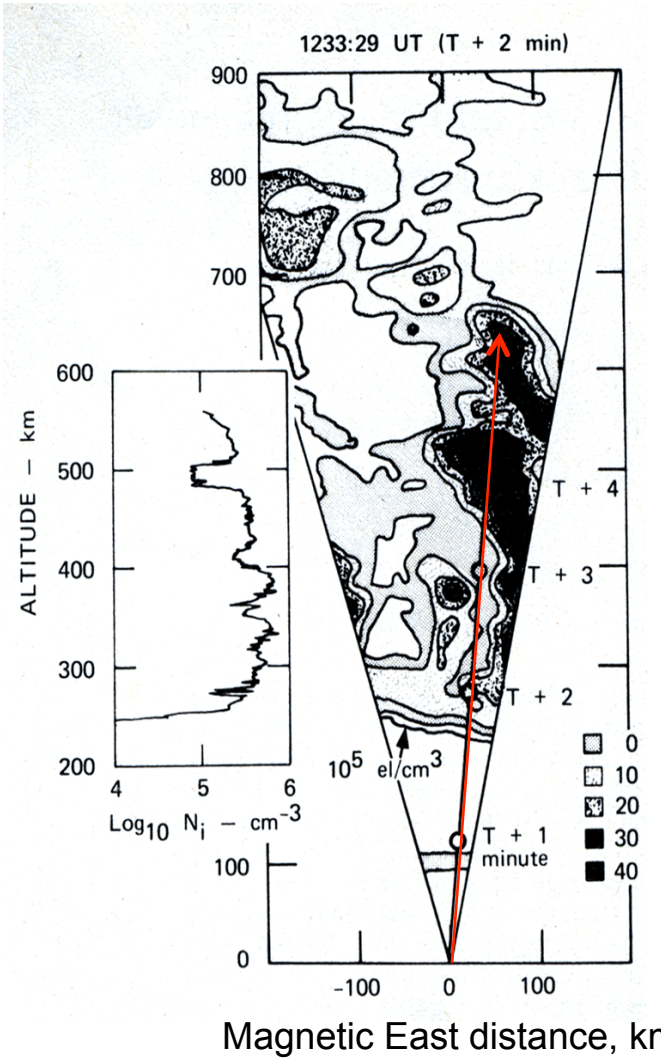
Fresnel scattering

Plasma density irregularities with horizontal scale lengths of 100 m in a thin screen at 400 km altitude create scattering effects at GHz radio wave frequencies.

In situ measurements (satellites, rockets) reveal deep plasma depletions associated with spread-F backscatter



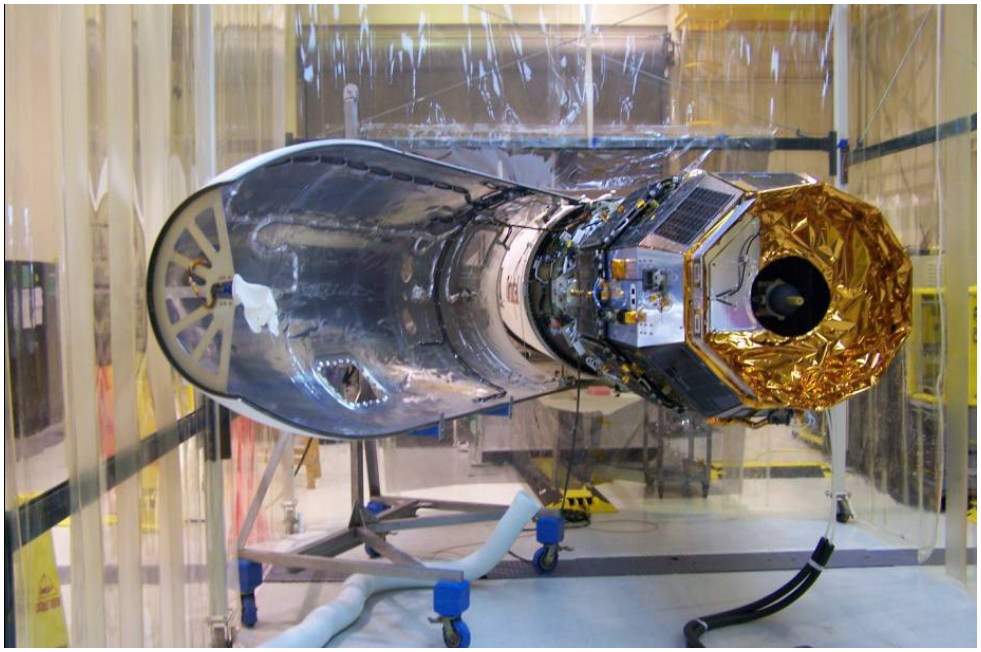
After Tsunoda et al., 1982

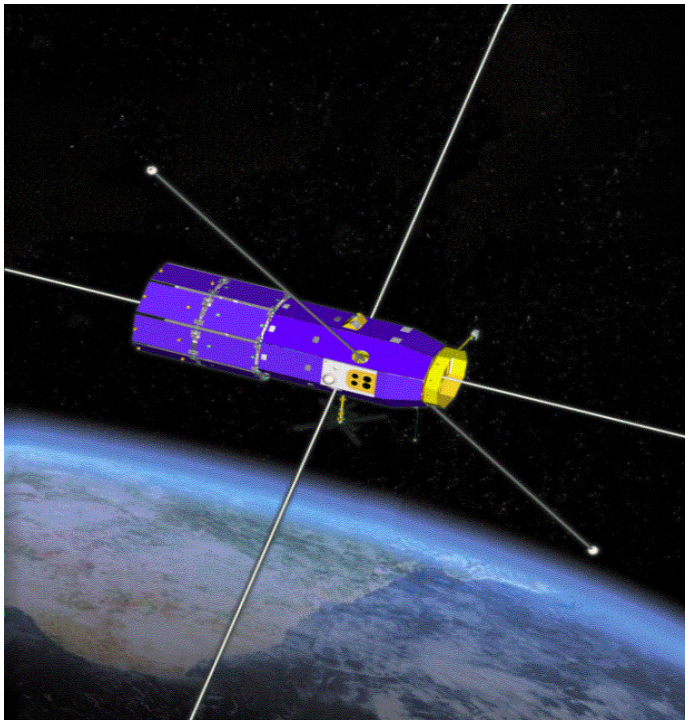


Rino et al., 1981

Communications/Navigation Outage Forecast System Satellite (C/NOFS)

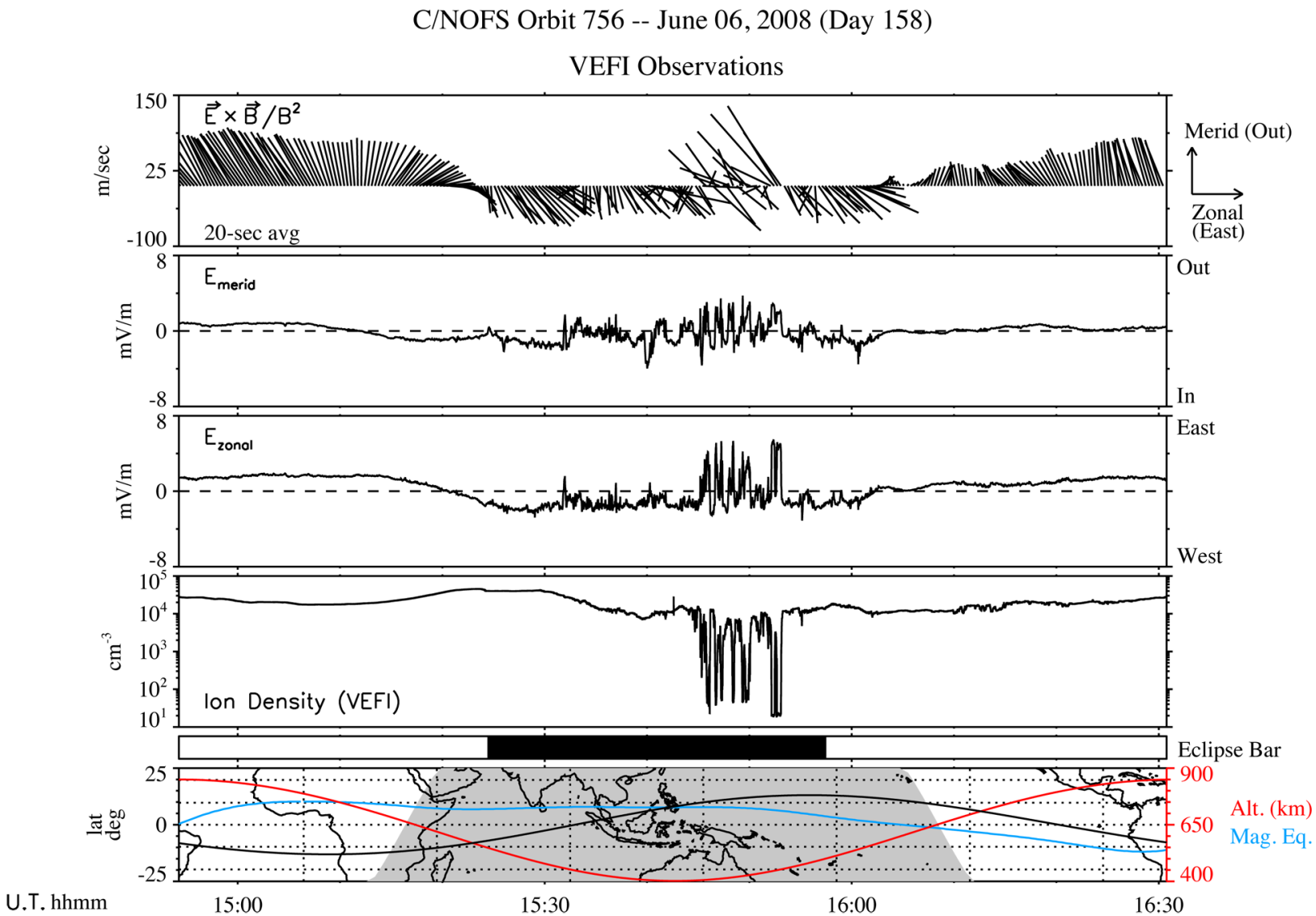
designed and built to study equatorial scintillation → a space weather satellite!





Air Force C/NOFS Satellite

Full Orbit of C/NOFS electric field and plasma density measurements

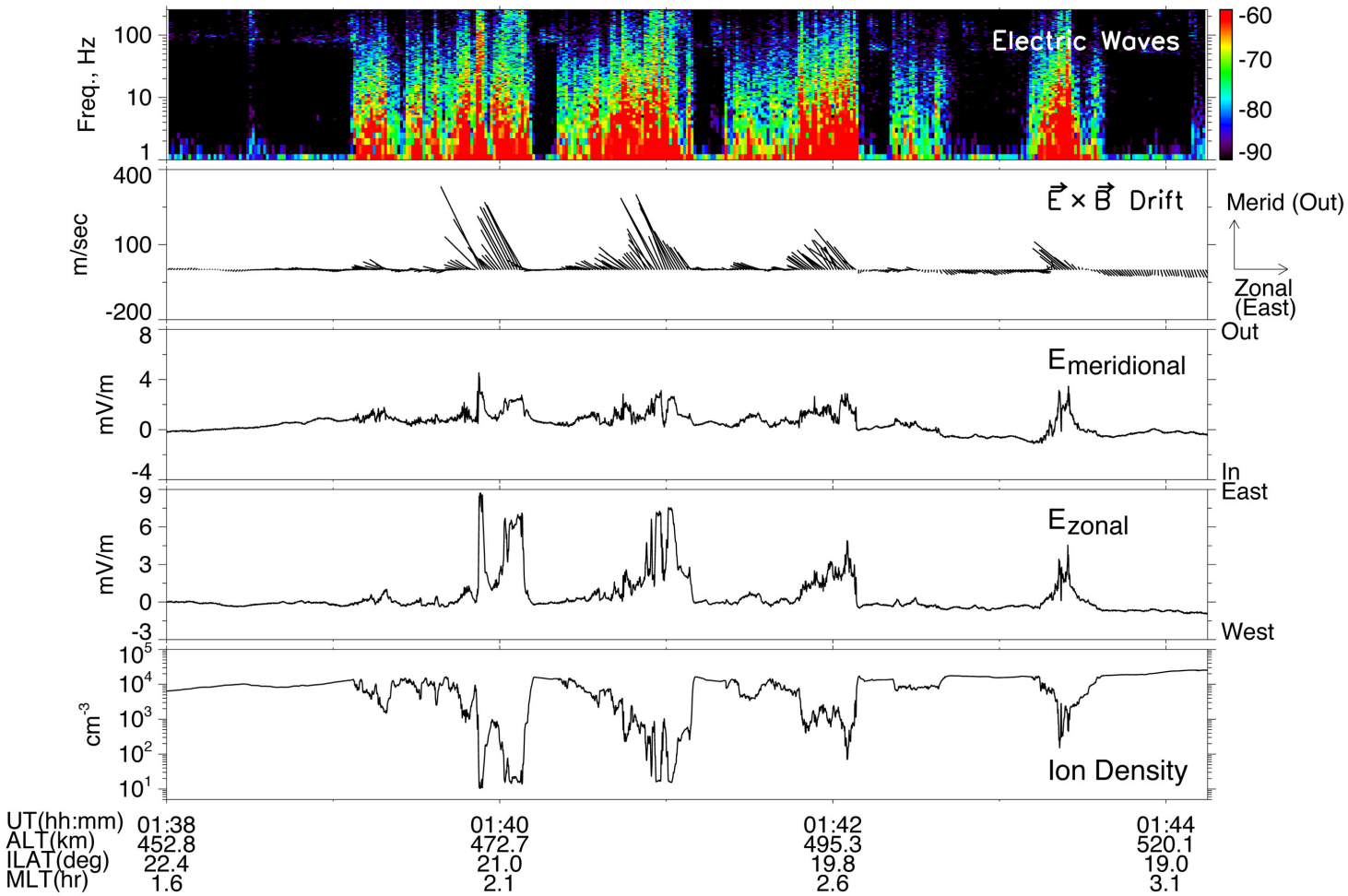


Notice large plasma depletions at night with large electric fields!

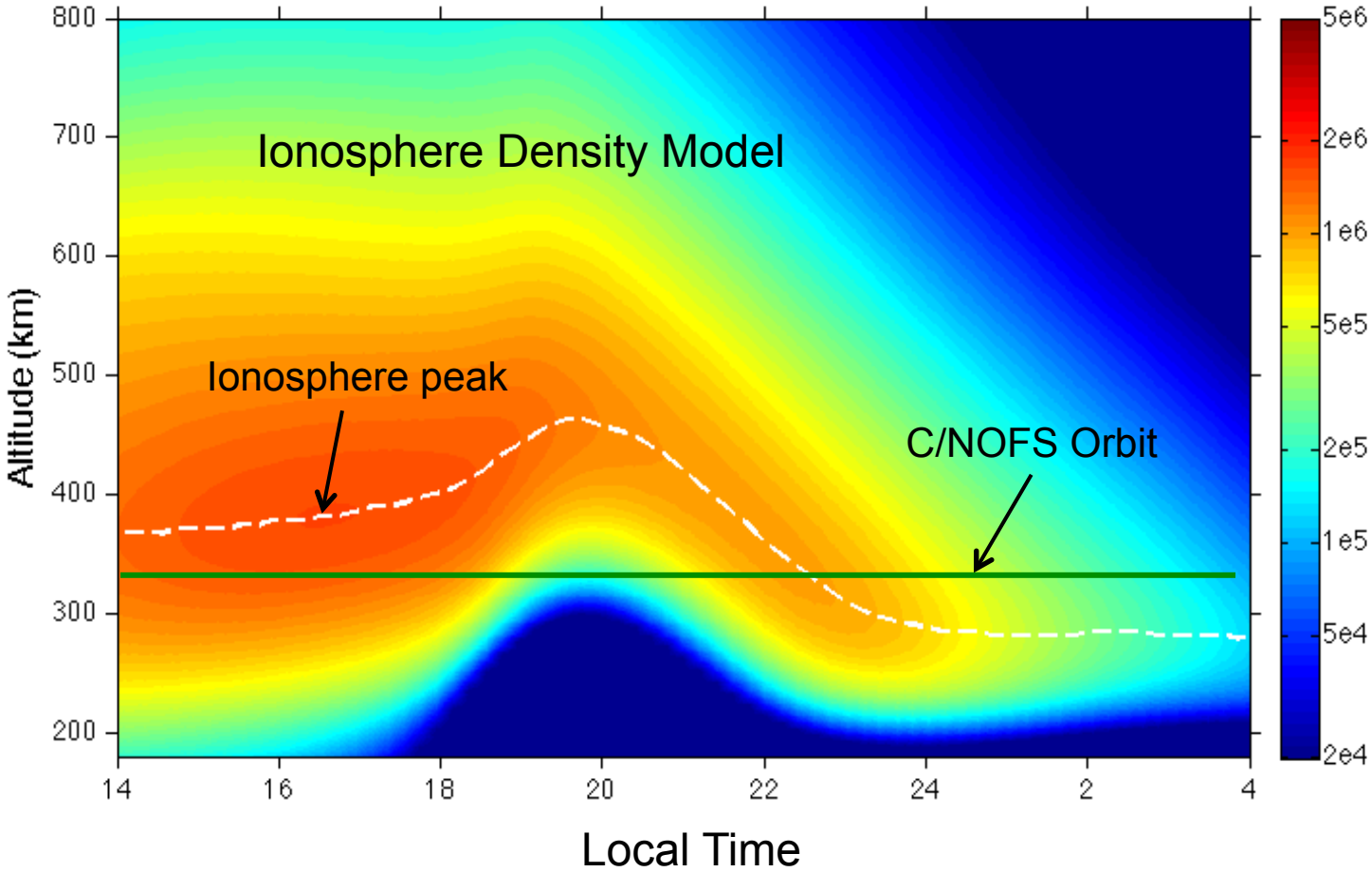
High resolution measurements show irregularities, highly correlated fields and density depletions

C/NOFS Orbit 688 -- June 02, 2008

VEFI Observations

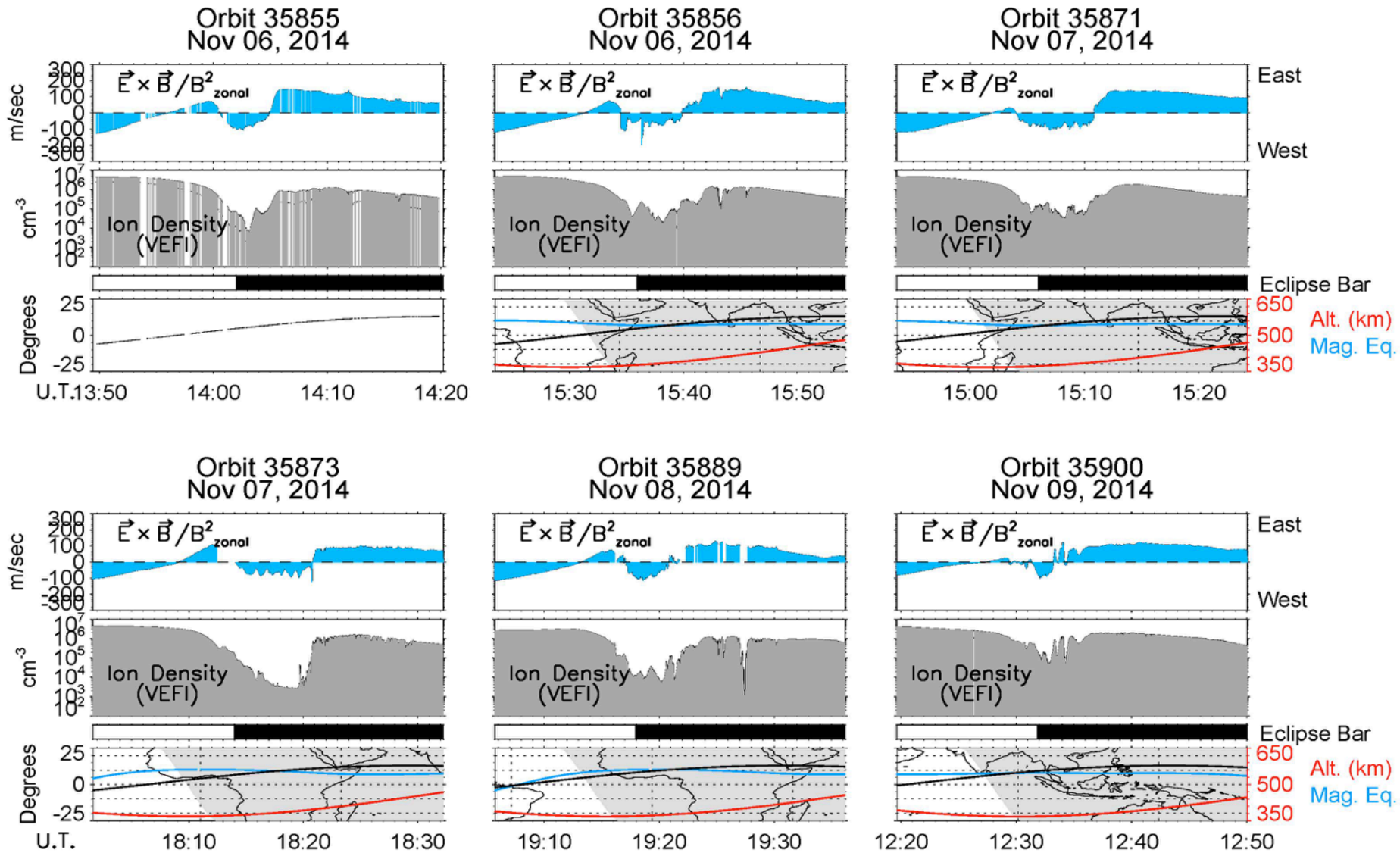


Spacecraft traversals below the Base of the F-region Reveals new physics

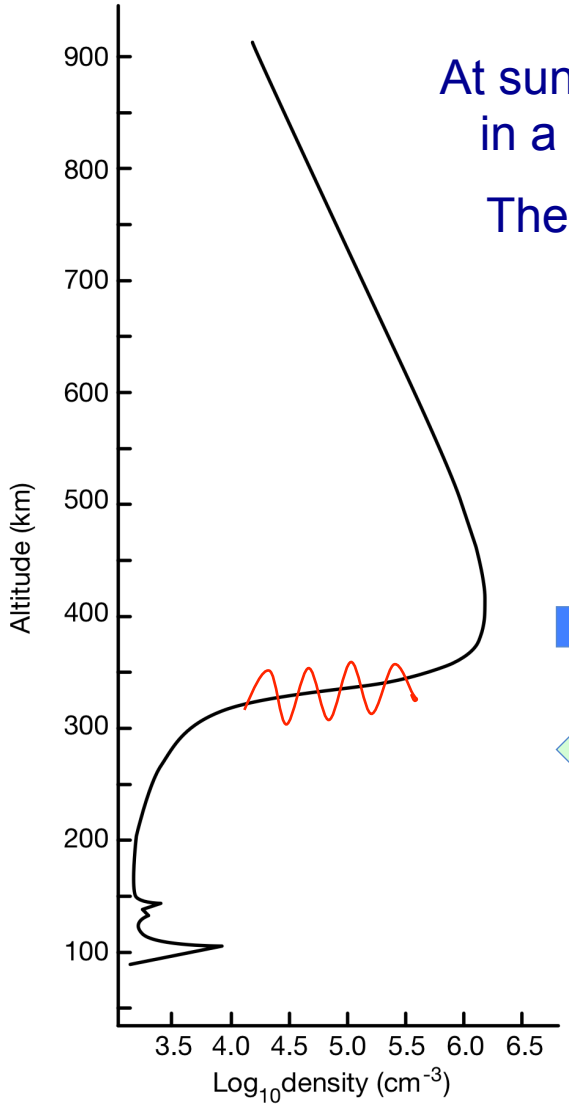


Ionosphere density is elevated at sunset

C/NOFS VEFI Observations



CN-4312-0248-5878-60R-DGH-02-N, CN-4312-0429-5879-70R-DGH-00-N
c:\cnofs\carmen\plots\2014-11-07_18_01_36_to_2014-11-07_18_32_15_35873_Esolved_DP_2-axis_solution_Robs_Request_259_ExB.ps
Tue Feb 10 15:09:38 2015 cl



At sunset, the ionosphere below the F-peak flows in a reversed zonal direction than the topside.

The implications for the creation of instabilities are very important…

Does the shear drive instabilities?

Search for large scale undulations on bottomside…

Evidence of 400-500 km "Undulations" Below F-peak

Shears in the "Background" Zonal **E** x **B** Drifts suggest Kelvin-Helmholtz Instability Seeds Spread-F Depletions

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may be damaged. Try closing other applications and restarting your computer, and then open the image file again. If the red x still appears, you may need to delete the image and then insert it again.

Plasma density

- Data support theories (e.g., Hysell and Kudeki, 2004) that Kelvin-Helmholtz shear drives bottomside F-region unstable, "seeding" the formation of spread-F depletions, irregularities.

- Explanation also accounts for regular spacing of spread-F depletions

Upper Atmosphere Density

Key Space Weather variable

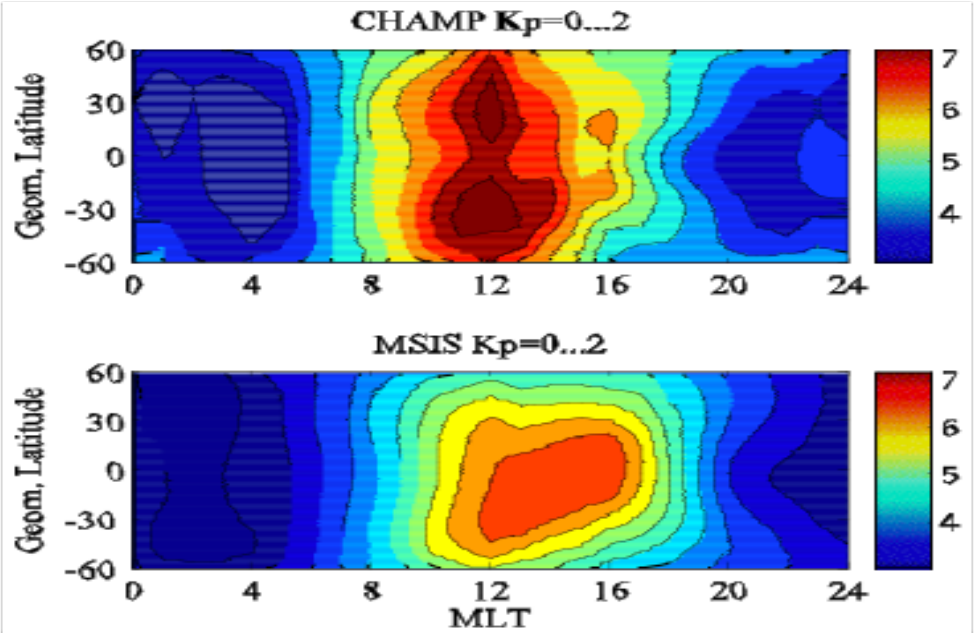
→ • Creates drag on satellites

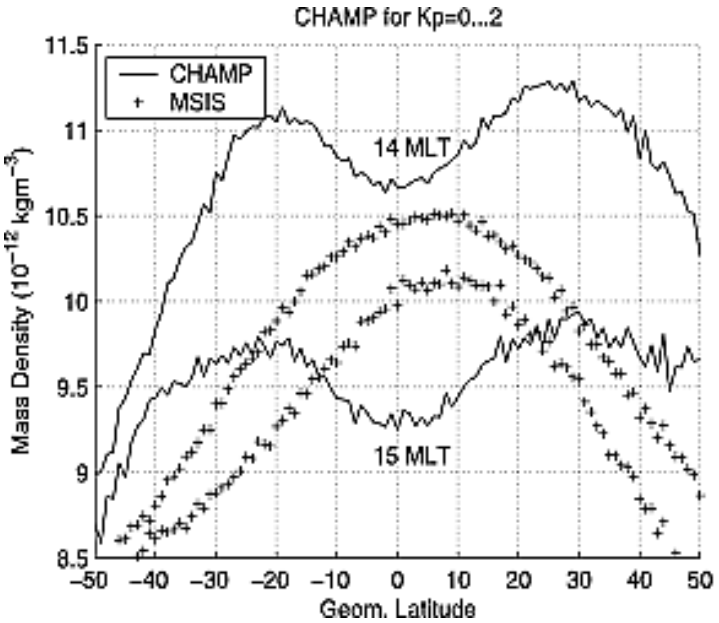
→ • Affects attitude and "pointing" of satellites (particularly non-symmetric ones) and can re-direct sun-pointing solar arrays

→ • Affects incoming meteoroids and debris

Few Existing Neutral density measurements don't agree at all with models!

Neutral Density Variations CHAMP Satellite

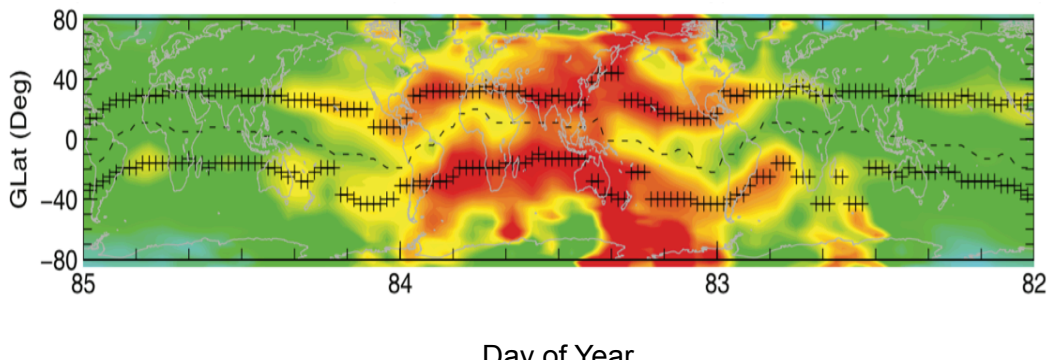




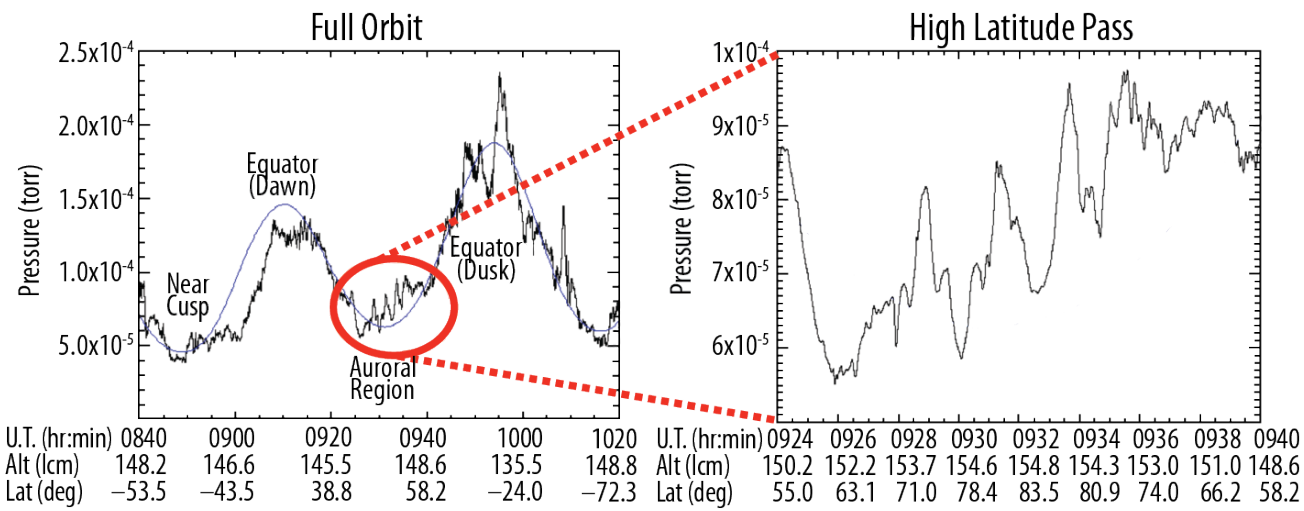
Statistical Survey and Comparison with MSIS Model

Neutral density is highly structured! Why?

CHAMP Neutral density variations near 400 km

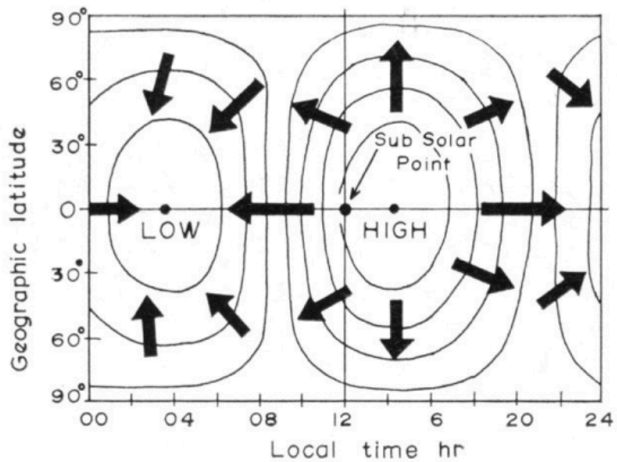


STREAK Satellite -- 28 June 2006

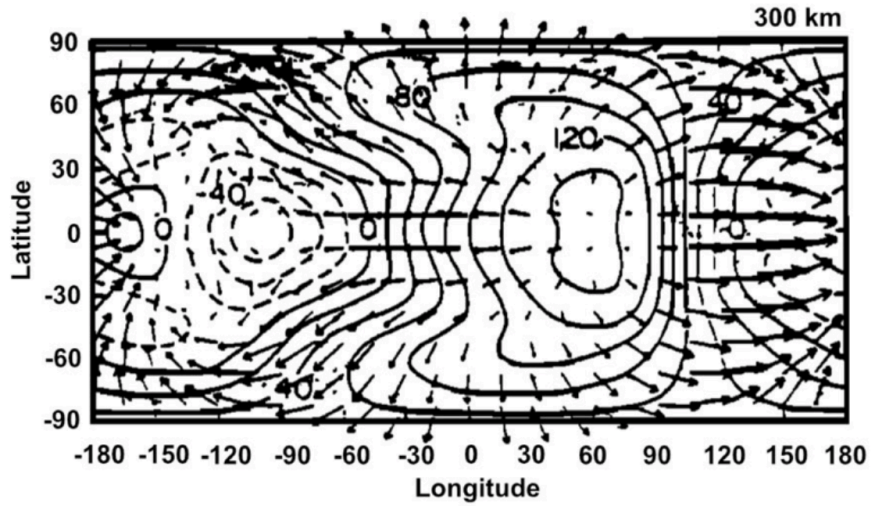


This affects ionospheric structure → affects radiowaves

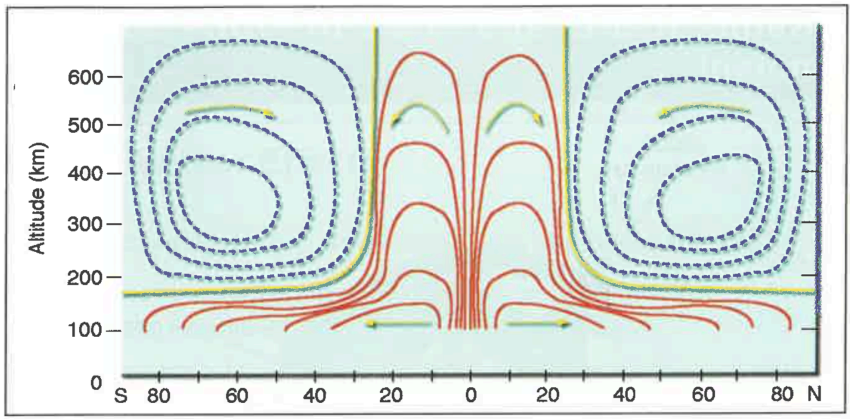
Motions of Upper Atmosphere (winds) affects ionosphere, creates electric fields

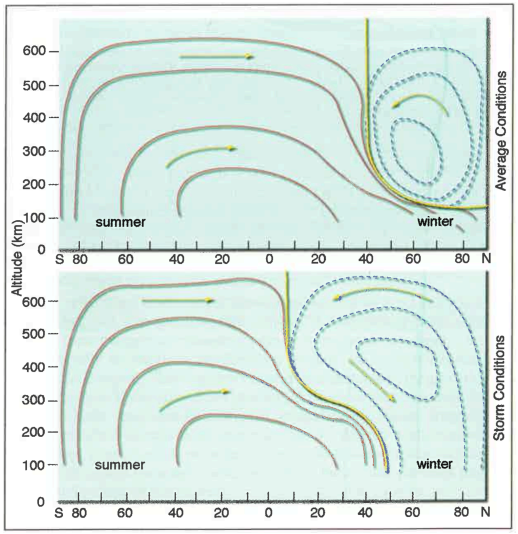


Beer [1976]



Fesen et al. [1986]

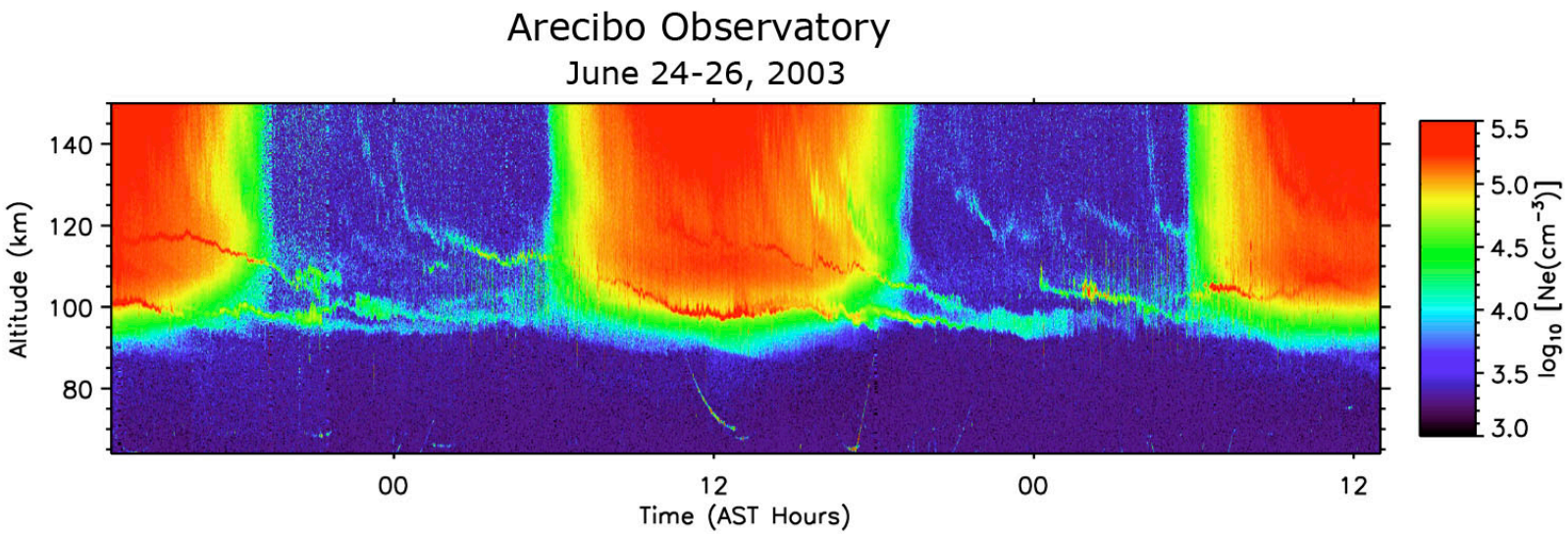


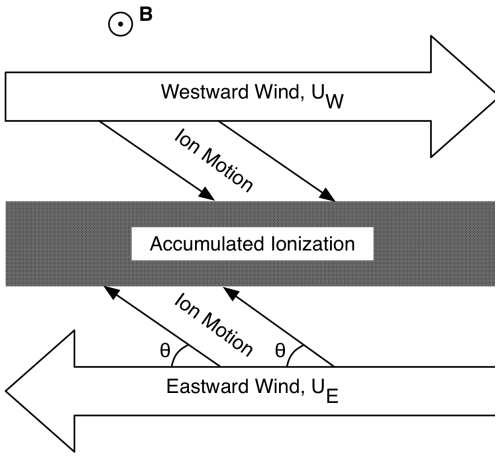


Lower panels from Ray Roble, NCAR

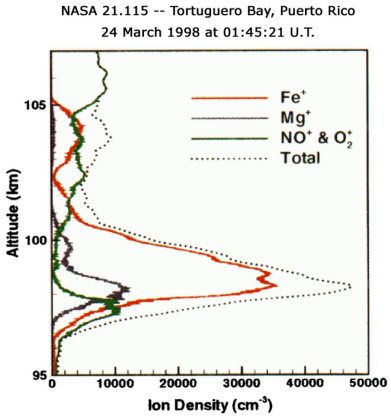
These are all models… We lack systematic, vector wind measurements

Wind shears create enhanced layers of metallic ions from meteoric input





Hines [1964]



Rocket measurements show thin layers of metallic ions

Earle et al. [2000]

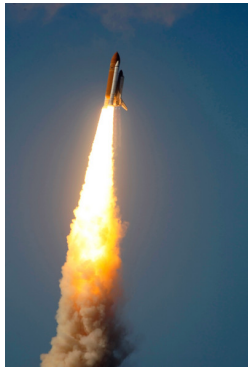
Upper atmosphere winds also affect aerosols, explosion material, exhaust…

Krakatoa Volcanic Eruption, 1883

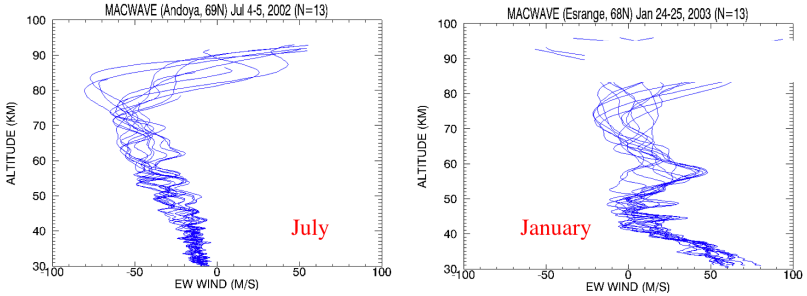
Lithograph, 1888

Noctilucent Clouds (~84 km)

Shuttle Exhaust



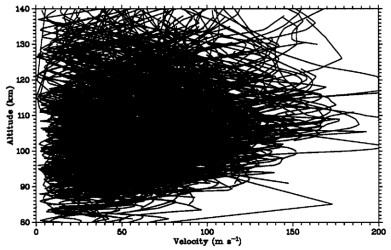
Nuclear Explosion



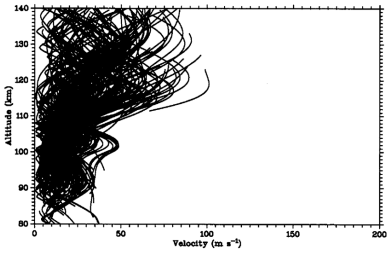
[Courtesy, F. Schmidlin, R.Goldberg, GSFC]

Neutral Winds (80-140 km) -- Large, variable, *not* understood

Wind Data



Model Results



[Larsen et al., 2000]

Upper Atmosphere Winds

Key Space Weather variable

→ Affects plasma distribution, sets up electric fields

→ Also affects distribution of:

-- aerosols
-- volcanic material
-- nuclear explosion material
-- rocket exhaust (e.g., from the Shuttle)
-- meteoroids
-- other

Key Features of the Earth's Upper Atmosphere/Ionosphere

- Neutral and Ionized gases co-exist in the same volume, with the neutral density far exceeding that of the ionized gas below 1000 km

- Ionosphere lower edge extends to ~100 km during day, but recombines at night, with a lower altitude of ~275 km (dependent on solar activity)

- Equal number of ions and electrons, though ion mass varies with altitude

- Plasma gyrates about earth's magnetic field lines, controlled by electric fields with drive currents

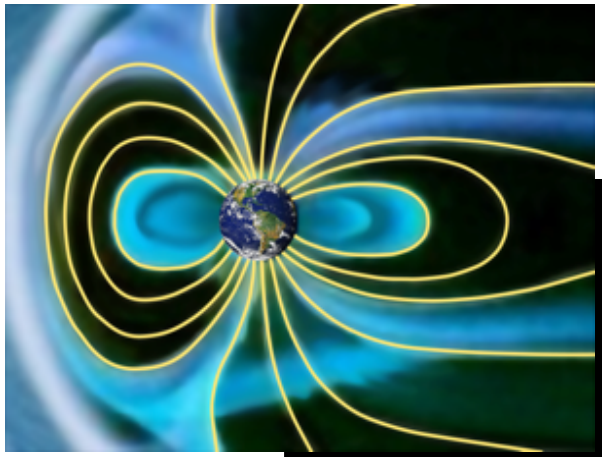
- Neutral gases have a complex motions; Collide with ions, set up electric fields, currents…

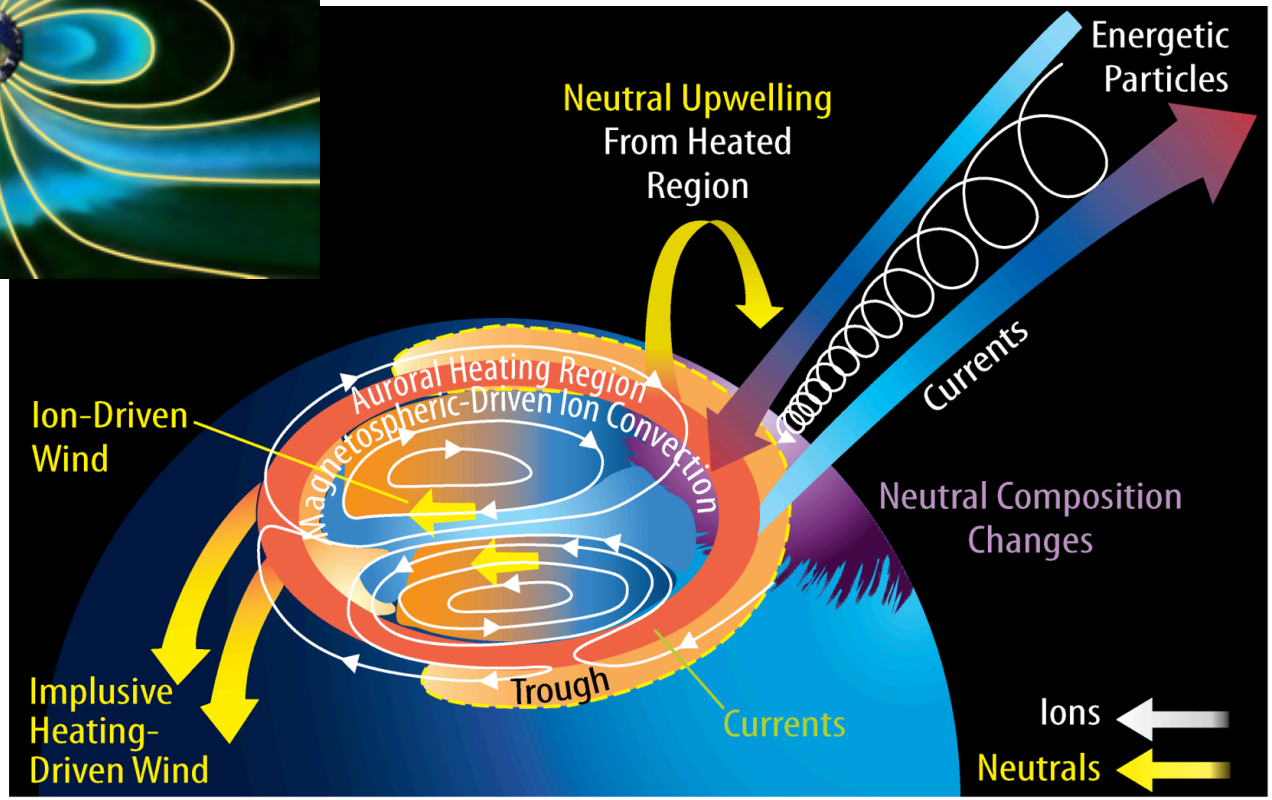
- Partially ionized upper atmosphere has a fascinating physics that we are still in the throes of discovering and understanding…

*Now…*Switch to high latitudes

→ Earth's magnetic field "connects" the upper atmosphere/ionosphere with magnetosphere and ultimately the solar wind energy

Solar wind/magnetosphere “drives” high latitude Ionosphere/Thermosphere ”system” which then feeds back on the magnetosphere!



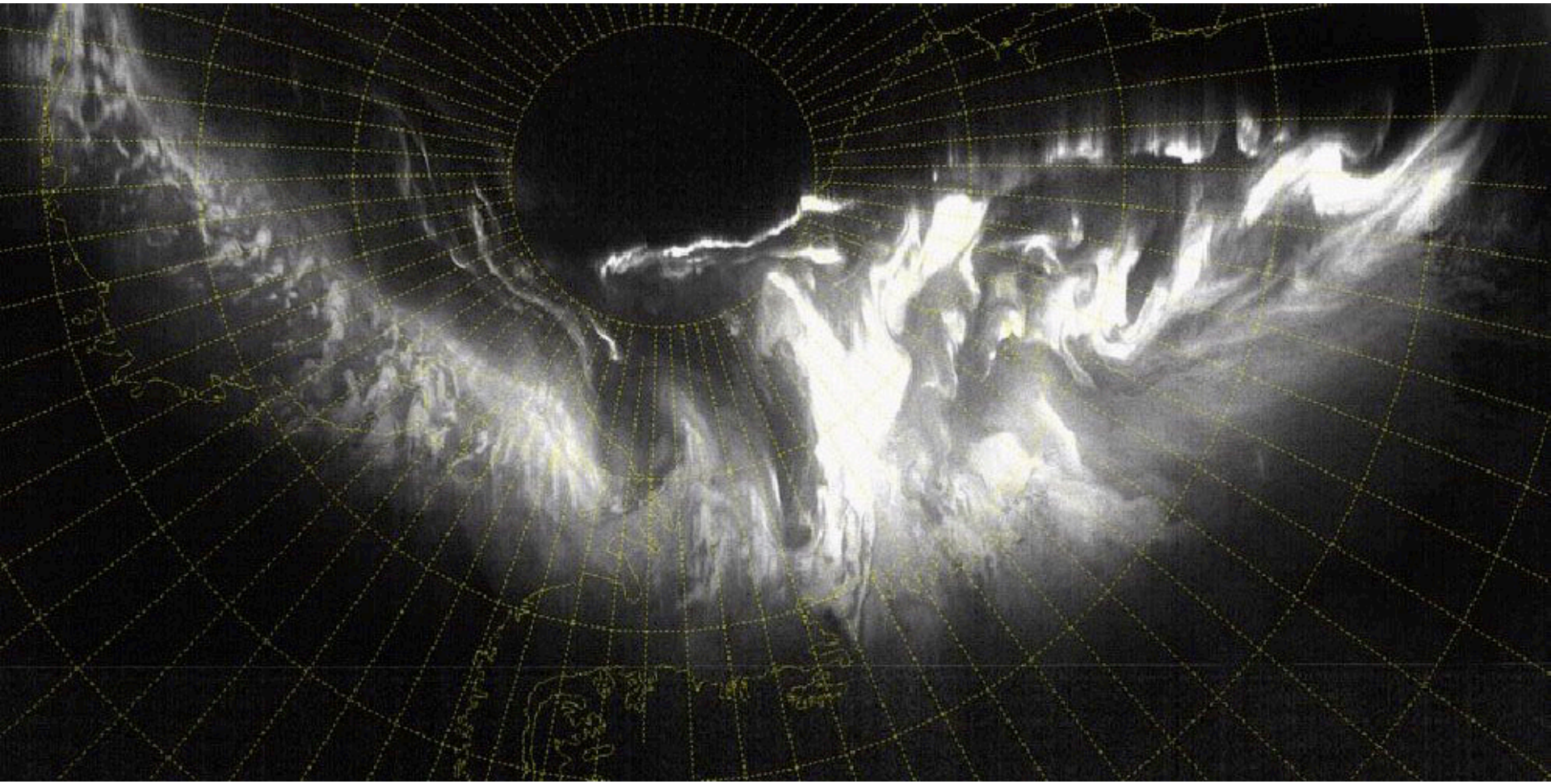


Aurora from the ground…

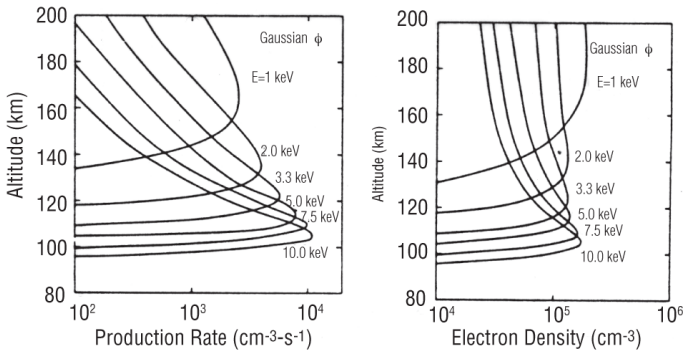
Aurora from space from the side…

Astronaut photograph

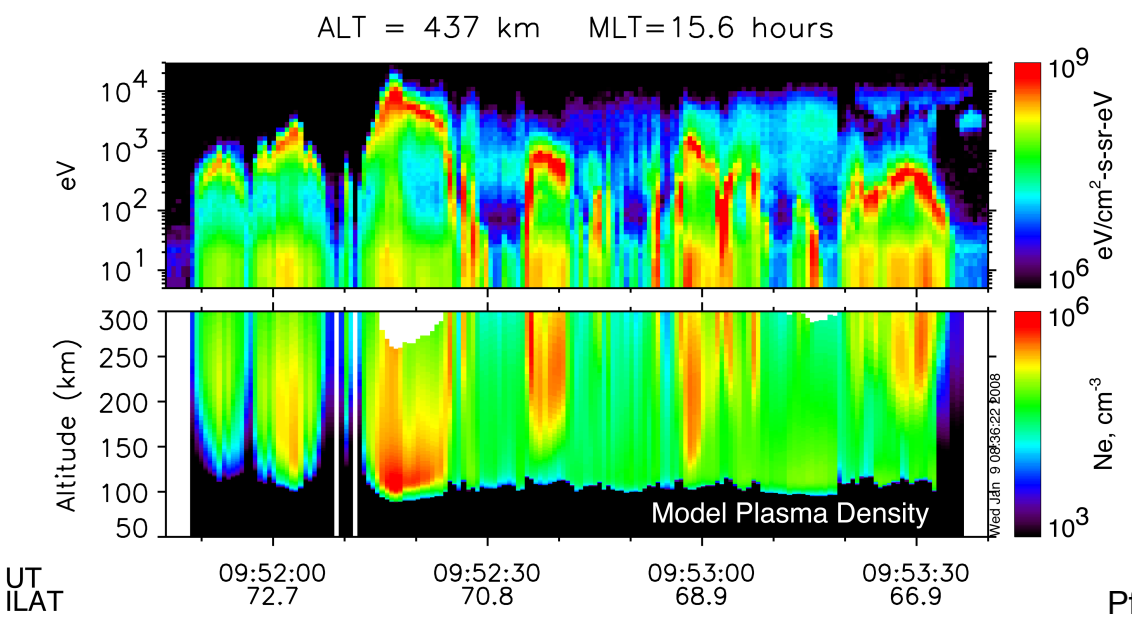
Aurora from satellite looking down…



Energetic auroral electrons are "braked" by the upper atmosphere, create thermal plasma

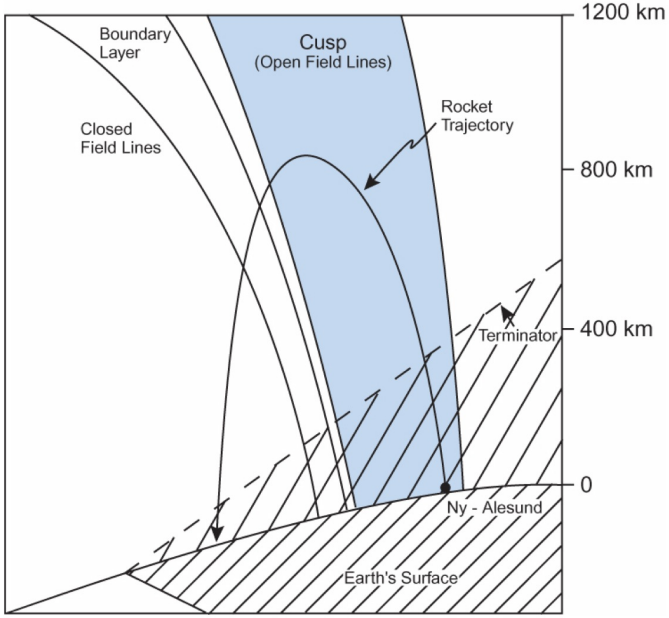


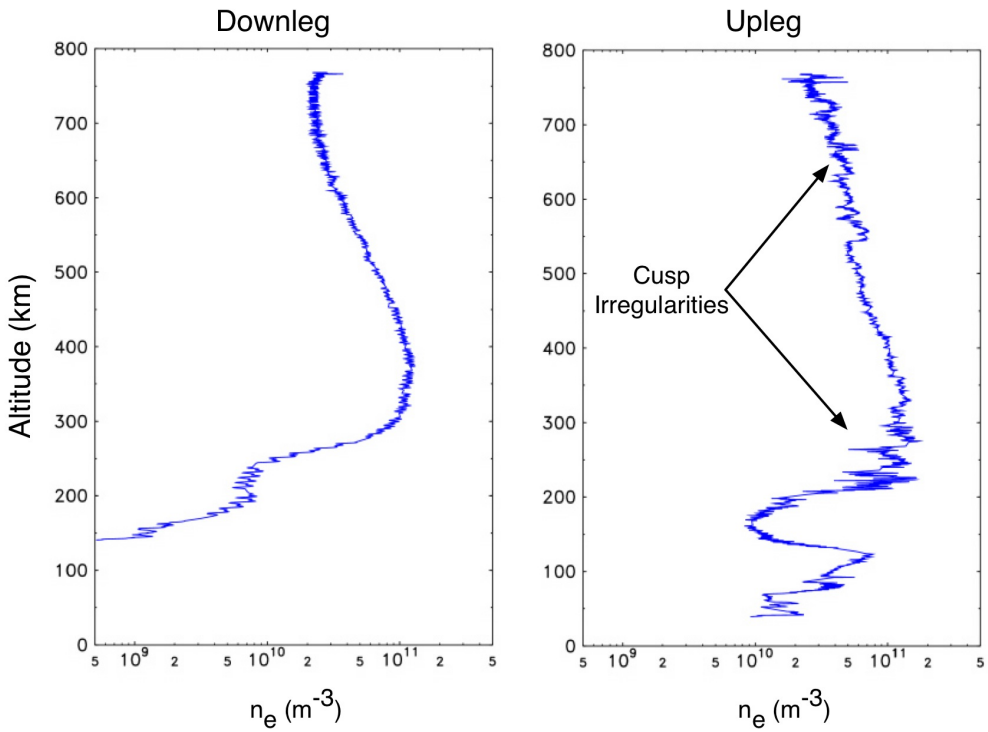
Strickland et al., [1983]



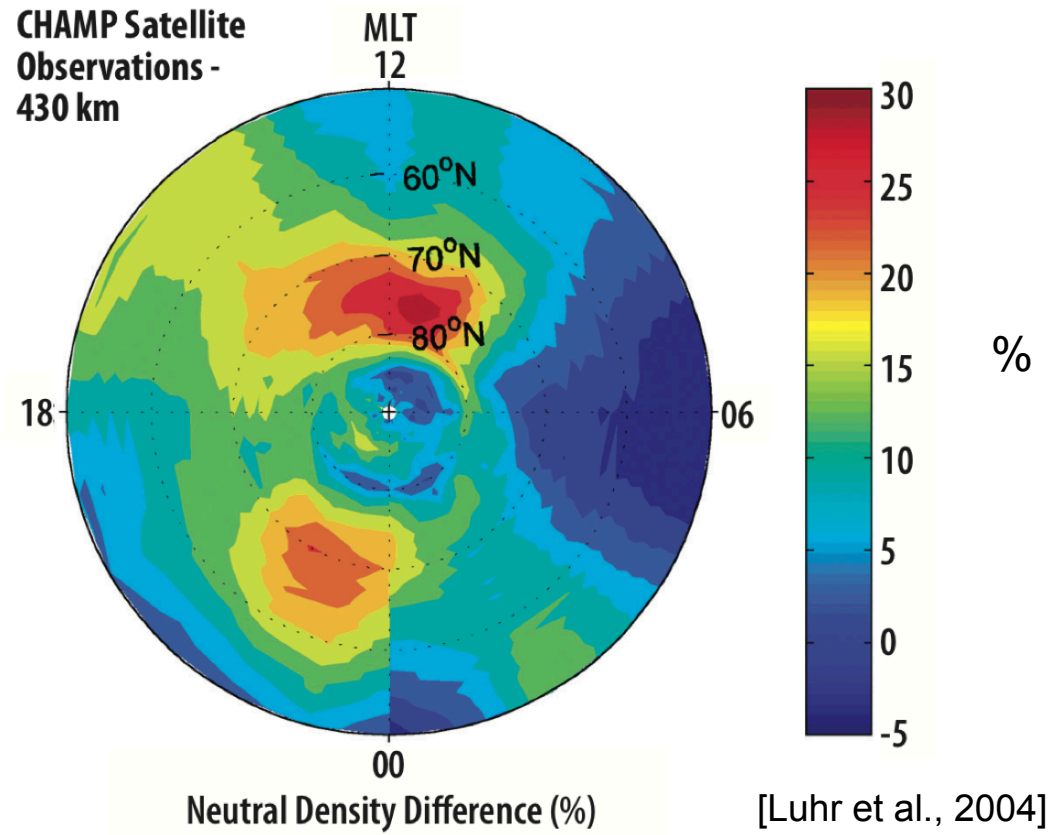
Pfaff [2012]

Ionosphere at high latitudes is replete with density irregularities (causing scintillations) as shown here measured with rocket probes in the cusp…





High Latitude Upper Atmosphere shows strong neutral density variations associated with the cusp, aurora…



[Luhr et al., 2004]

Neutral density variations at high latitudes are poorly understood -- Thermospheric Upwelling? Driven by Joule Heating?

Magnetospheric electric fields drive plasma which drives winds

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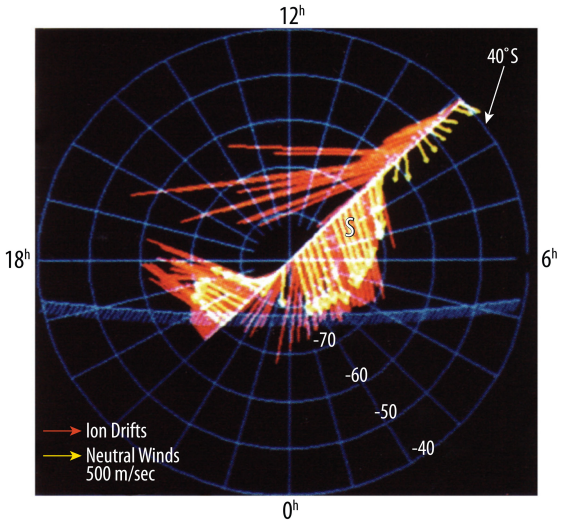
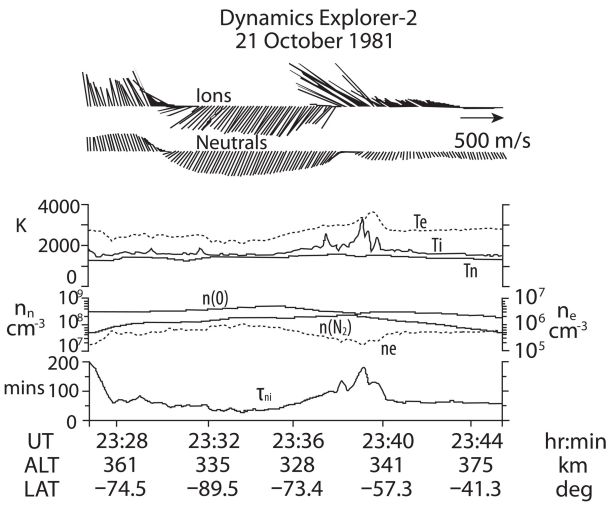
CTIPe

200 km

Neutral Winds

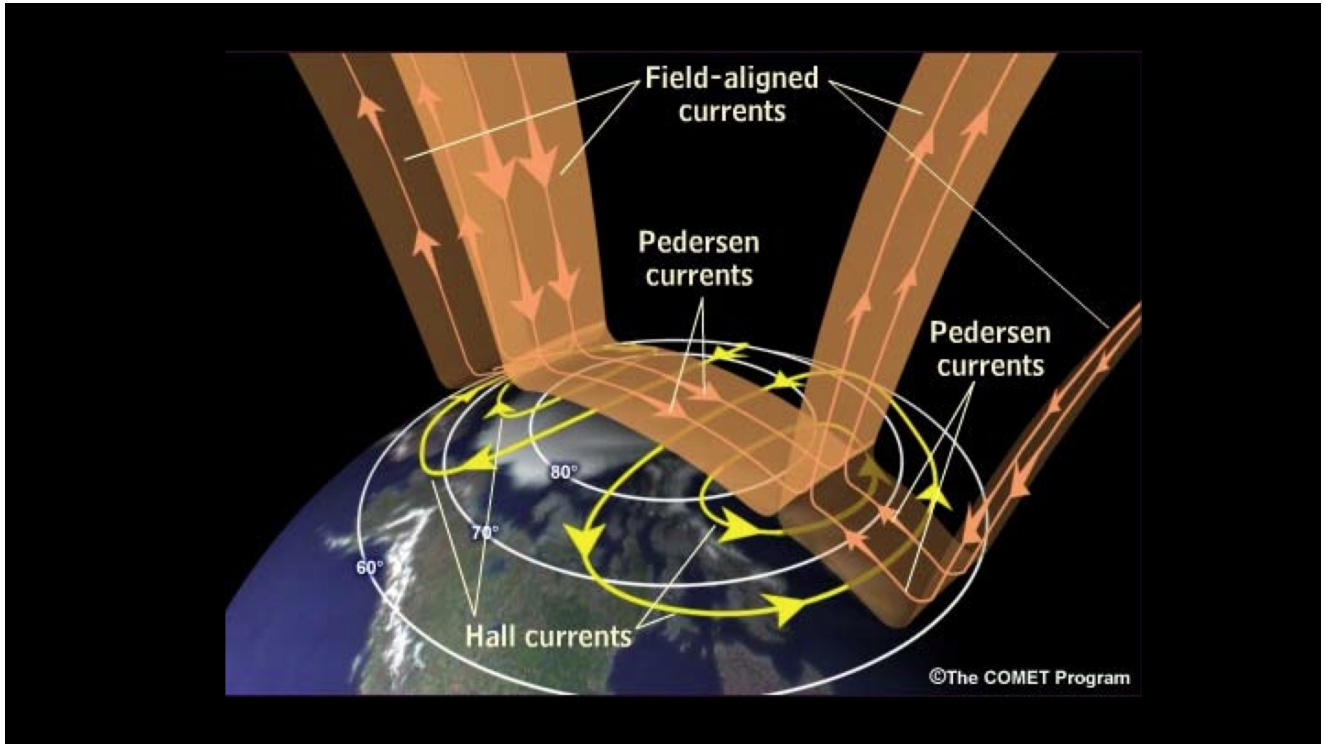
Ion Drifts





Killeen et al., 1984

Field aligned currents, electric fields, conductivity combine to create Geomagnetically Induced Currents (GIC)



Electrical Currents in the Ionosphere

Key Space Weather variable

→ • Induces Currents in the ground

→ • Affects power systems and grids

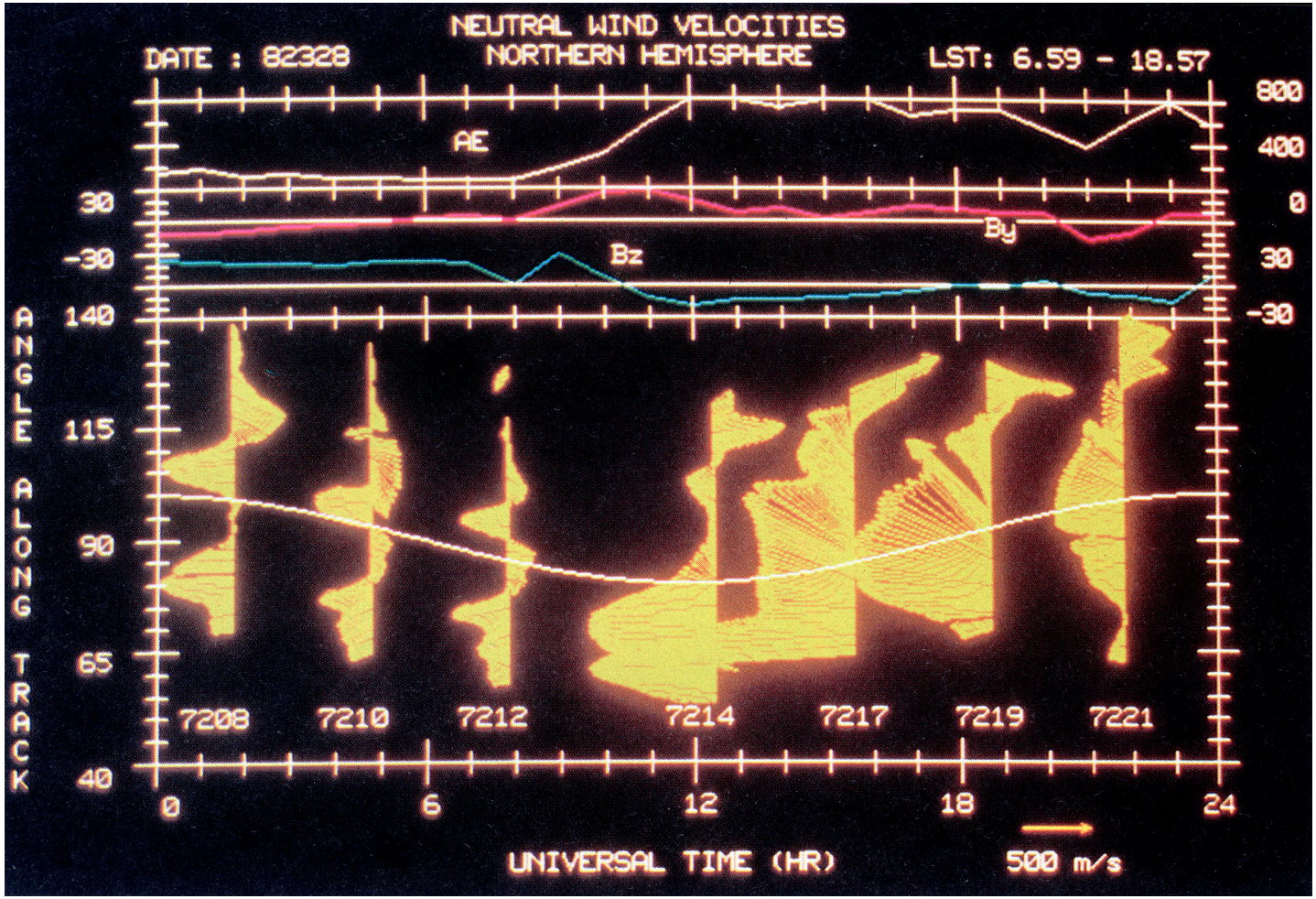
(See Talk by Antti Pulliken!)

When solar activity becomes strong…

→ Magnetic "Storms" result that profoundly effect the entire (global!) upper atmosphere and ionosphere in ways we do not understand

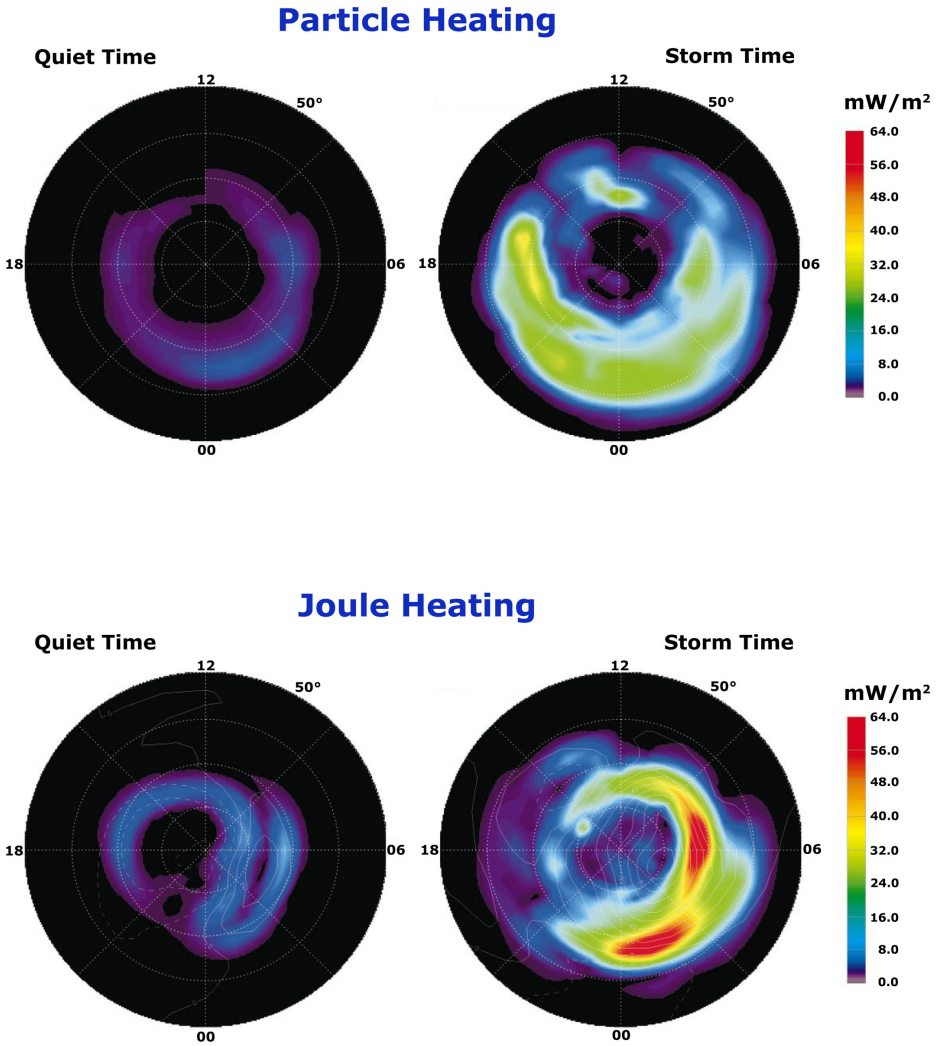
Earth's Upper Atmosphere is thrust into motion by the magnetosphere!

In particular, notice effects of Geomagnetic Storms!



[Killeen and Roble, 1988]

Heating due to particles, electric fields can be intense during storms

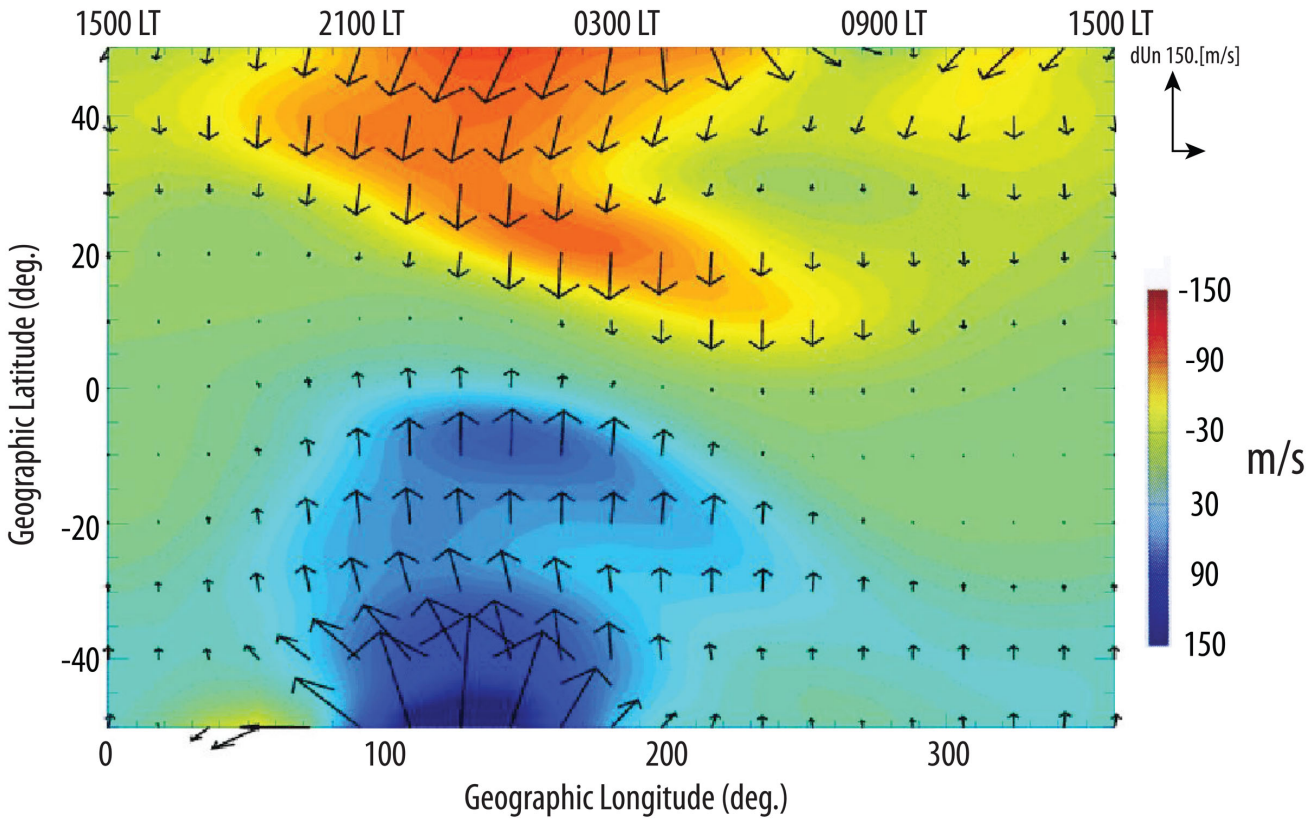


[Richmond and Lu, 2000]

Winds at high latitudes driven by magnetospheric electric fields keep going to middle and low latitudes!

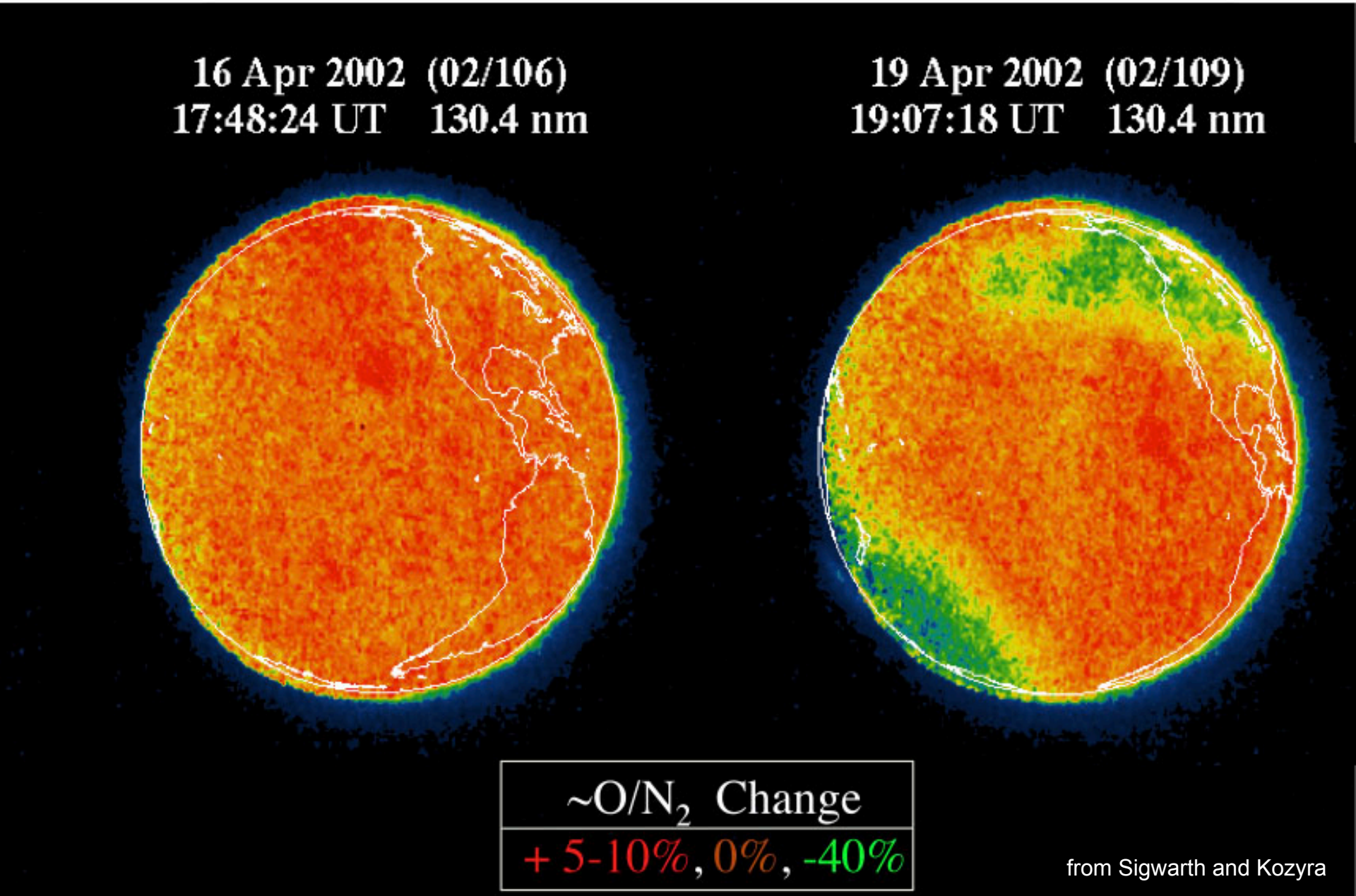
Model Wind Variations Driven by Auroral Heating

1500 U.T., 253km



Fuller-Rowell et al. [2008]

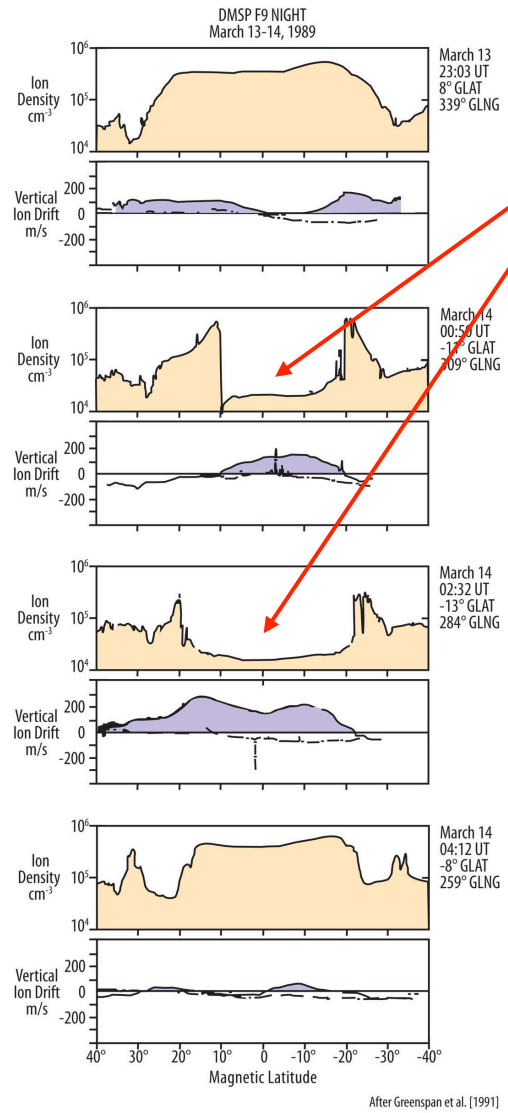
Upper atmosphere composition greatly altered during storms



from Sigwarth and Kozyra

Ionospheric plasma is greatly affected by magnetic storms

During magnetic storms, the low latitude ionosphere often rises above 840 km (as shown by DMSP satellites)



Ionosphere "disappears" at low latitudes

→ Why? Penetration Electric fields?

→ What happens at other local times?

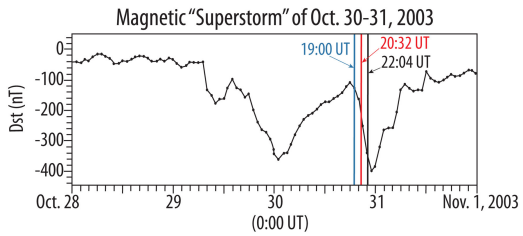
→ What about the upper atmosphere?

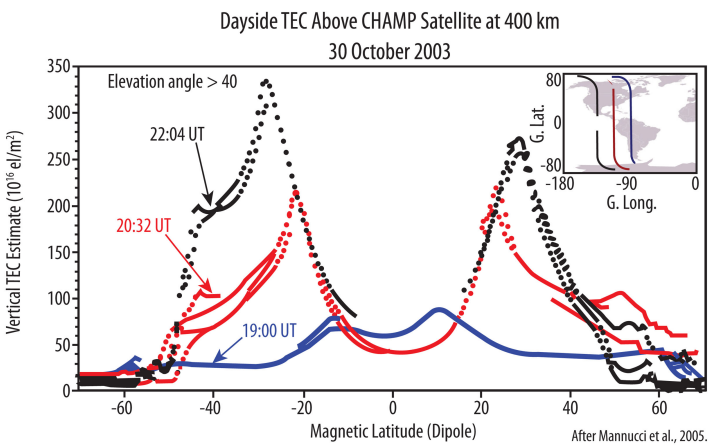
4 consecutive DMSP passes (100 minutes apart) near 21:30 L.T. show ionosphere rising above 840 km during magnetic storm

[Greenspan et al., 1991]

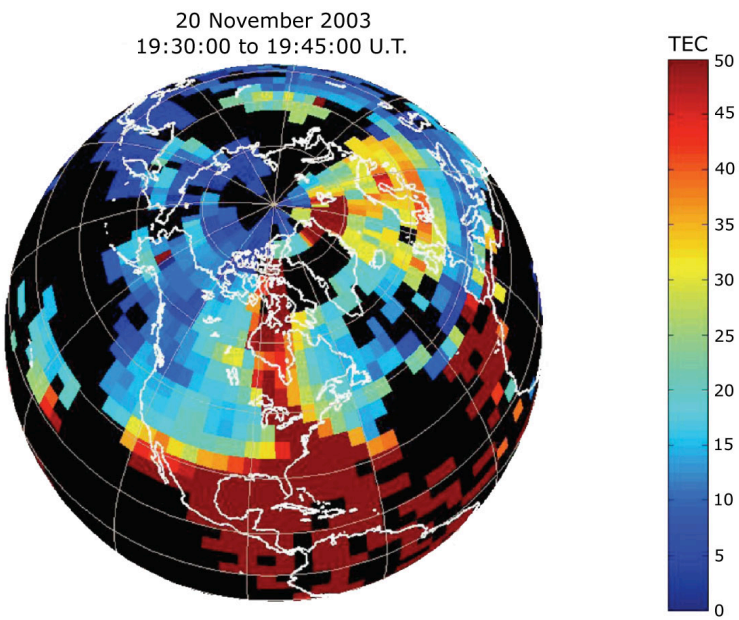
Ionospheric plasma is greatly affected by magnetic storms;

Here GPS shows strong increases in TEC, “structure”



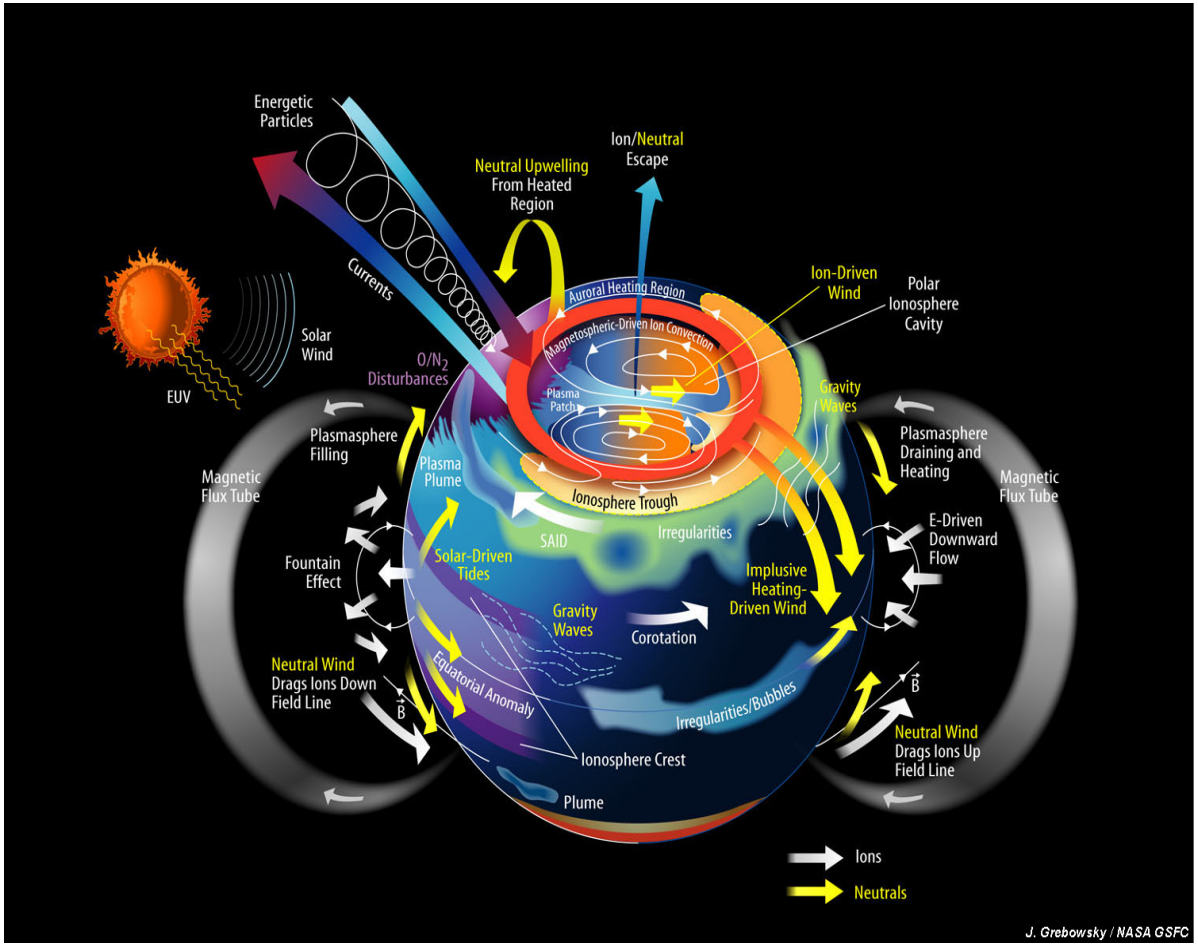


Mannucci et al., 2005



Courtesy, A. Coster

The ionosphere/upper atmosphere is highly complex, dynamic, and variable, and is strongly coupled the magnetosphere above and the troposphere below.



Studying this region, rich with fascinating physics and important, undiscovered processes, is among the most rewarding fields of space research

Ionosphere/Upper Atmosphere -- Key Space Weather Processes

1) Absorption of solar EUV radiation by the upper atmosphere — **protects life on Earth**

2) Ionospheric Density -- **affects radiowave propagation**

3) Ionospheric scintillations associated with ionospheric gradients and plasma depletions — **affects communications, navigation (e.g., GPS), radar, etc.**

4) Neutral density and its variations, gradients — **affects orbital drag and spacecraft attitude, affects meteoroids and other debris, "brakes" energetic particles**

5) Atomic oxygen in upper atmosphere — **erodes coatings, adversely effects satellites**

6) Energy inputs at high latitudes (electric fields, Joule heating, particle precipitation, etc.) — **moves plasma, drives winds that propagate to low latitudes affecting ionosphere, affects composition**

7) Upper atmosphere winds between 50 km to 600 km — **moves ionosphere, sets up electric fields, affects composition, distribution of aerosols, volcanic and other explosion material, exhaust…**

8) Geomagnetic induced currents (GIC) by high latitude magnetospheric coupling **—** **affects power grids**