Terrestrial Ionosphere(s)

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- PART I: Local Ionospheric processes, and terrestrial ionospheres
- PART II: global I/T system

Heliophysics Summer School XI: Boulder, Colorado 7 August, 2017

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Material adopted from the following authors.

- HSS lecture notes prepared by Professor Tim Fuller-Rowell (volume 1 HSS text book)
- HSS Chapter 13 volume 3 text book by Professor Stan Solomon.
- Robert Schunk and Andrew Nagy: their text "Ionospheres", a Cambridge press Atmospheric and Space Science Series book.

Thanks also to Dana Longcope upon whose presentation I will build.

The take-away message from this talk would be an appreciation of how important a narrow layer in our ionosphere is for various heliophysics processes.

This layer has various names:

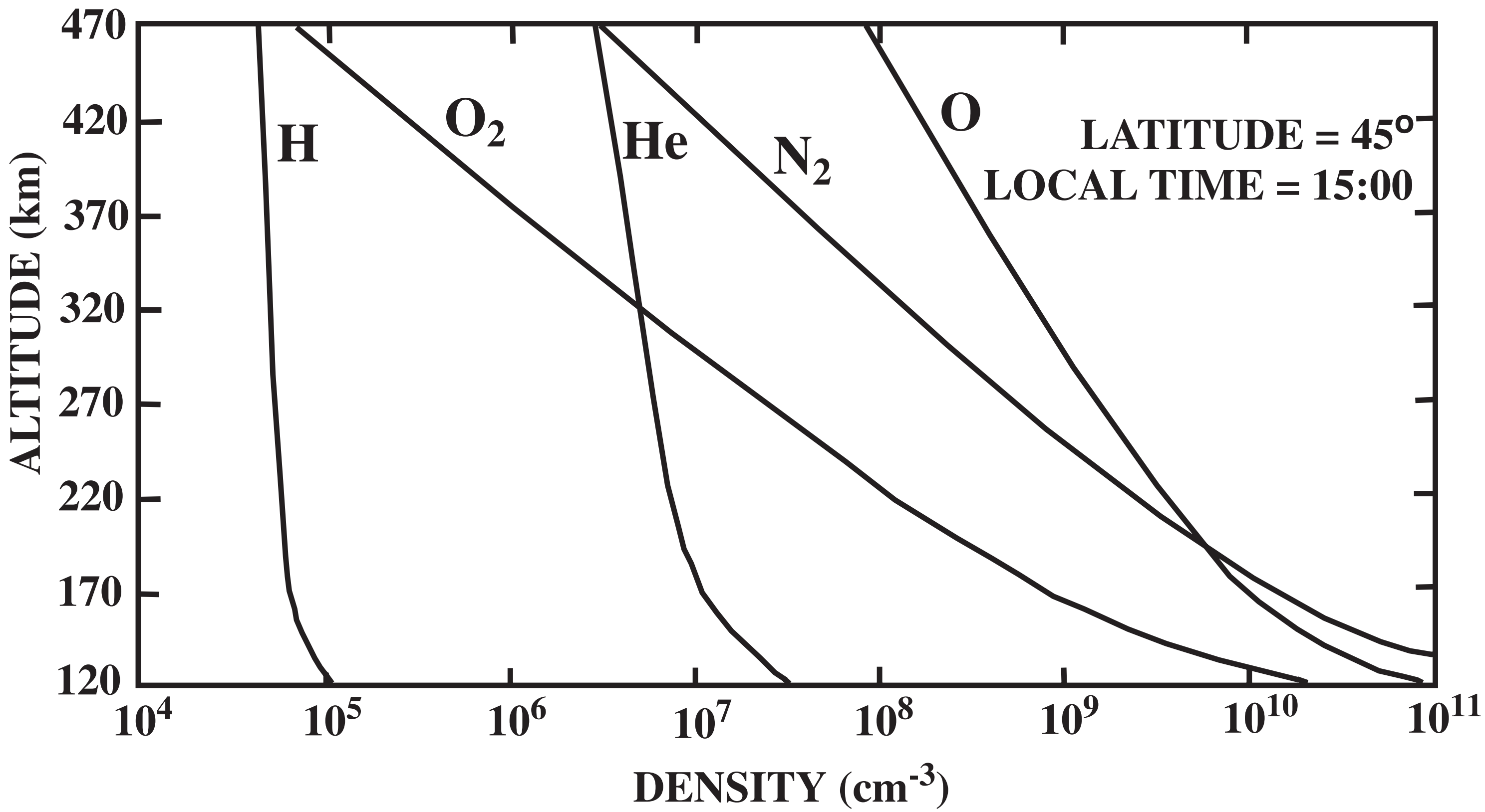
SAIR (definitions will come later)
E-layer
Turbopause
Pedersen and Hall conductivity layer
Altitudes from 100 to 120 km

Heck it even applies to the Sun!

Neutral Atmospheres

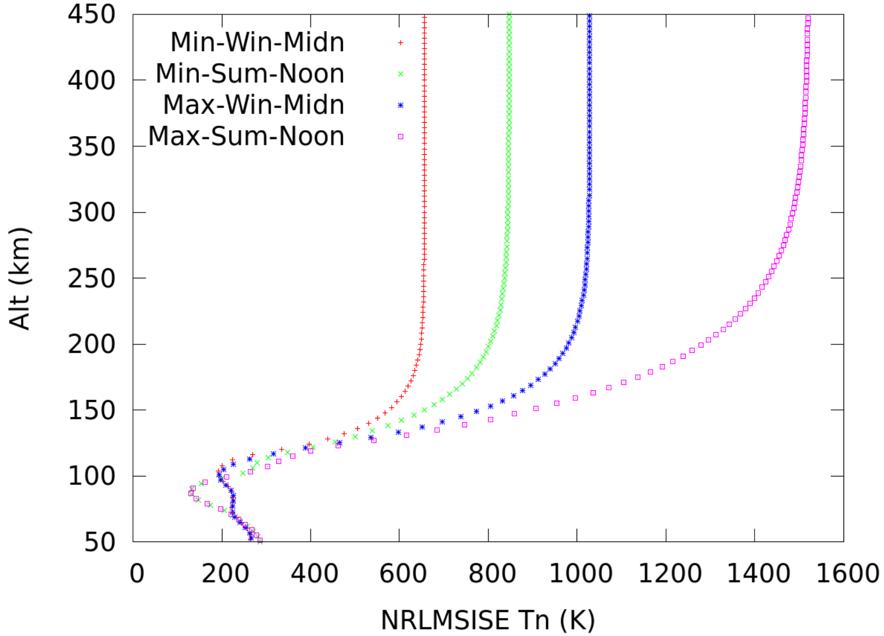
- All ionospheres exist in an atmosphere.
- The thermosphere-ionosphere forms the neutral to plasma interface between planets with atmospheres and space.
- The composition of the ionosphere is governed by the atmosphere, chemistry, and the ionizing radiation.
- The atmospheric dy ionosphere.

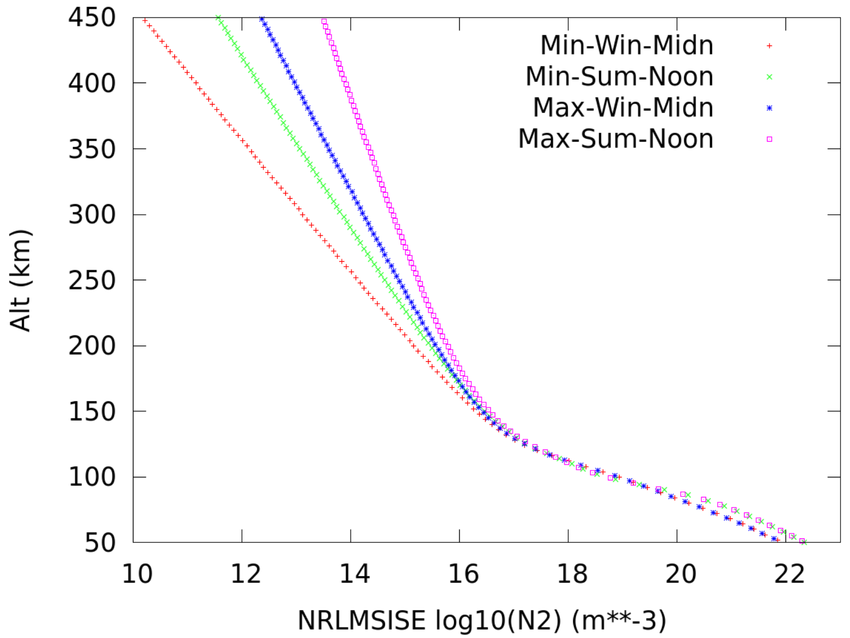
Apart from photons what other forms of ionizing radiation are there?



The Earth's thermospheric composition: the basis for the ionosphere

Earth' s Upper Atmosphere's dependence upon the Sun's solar cycle and our Seasonal and day-night cycles. [courtesy of NRLMSIS-00E]





The solar cycle is effective only above 100 to 120 km!

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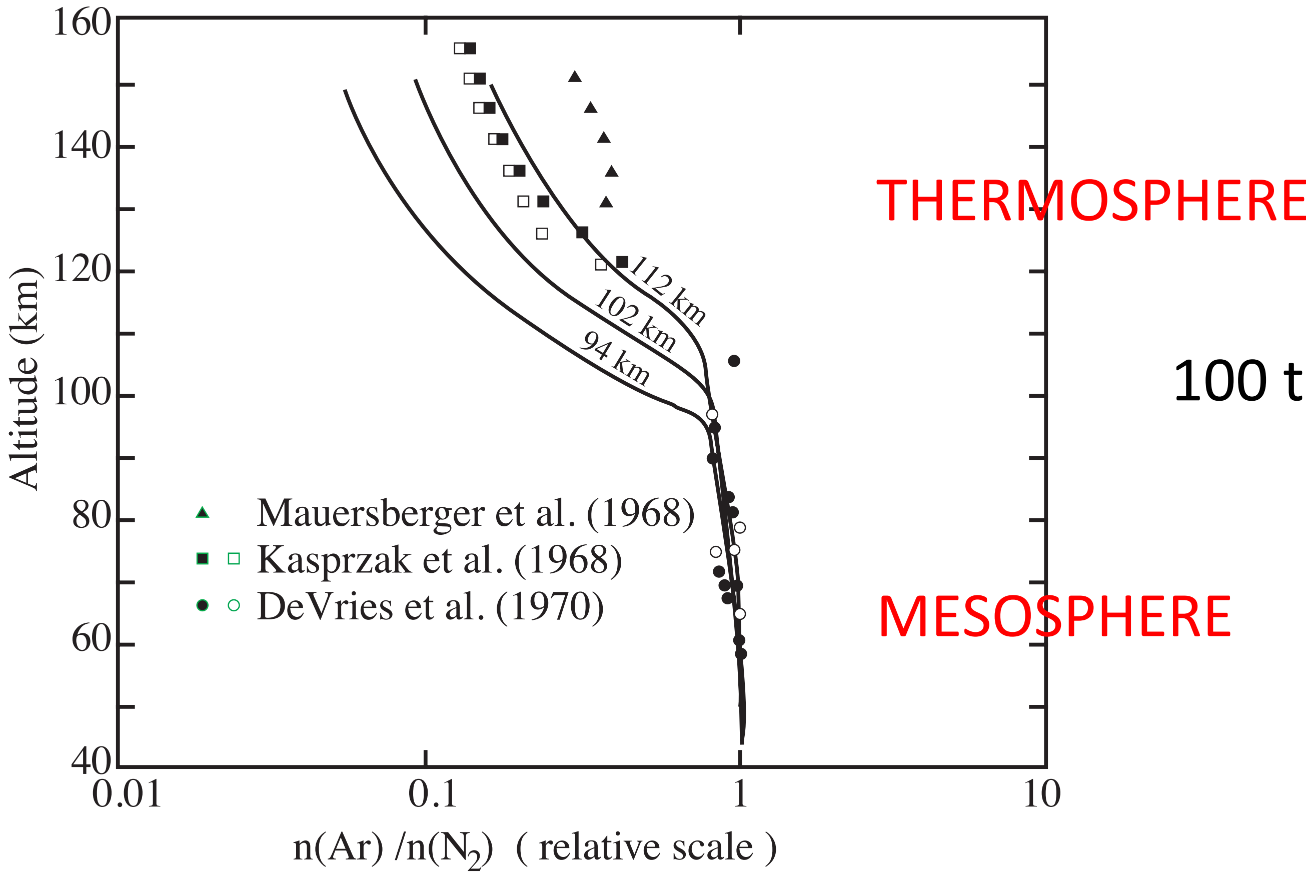
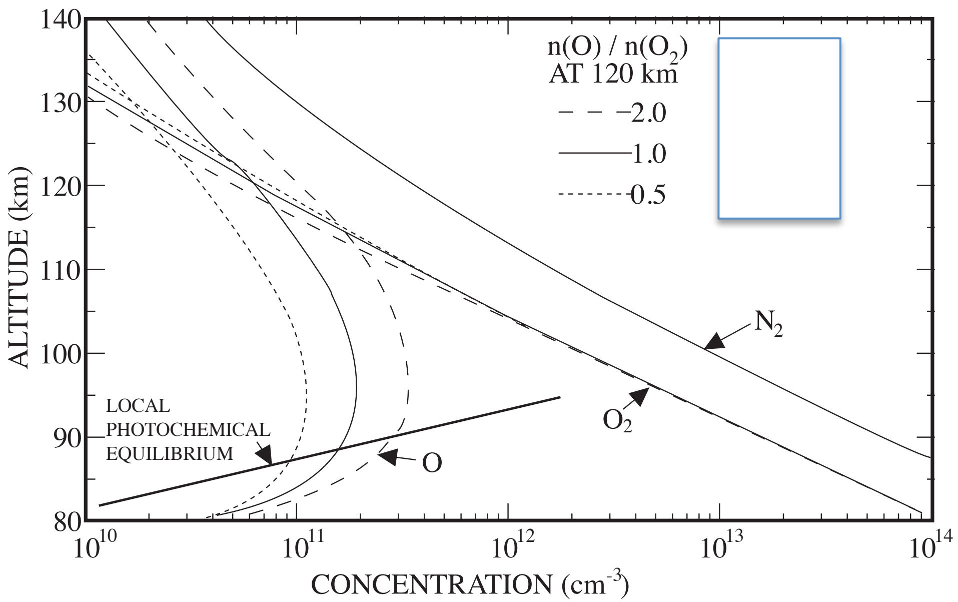


100 to 120 km

Lower atmosphere has turbulent mixing which leads to constant composition.

Above the turbopause the neutral species are in their own hydrostatic equilibrium.

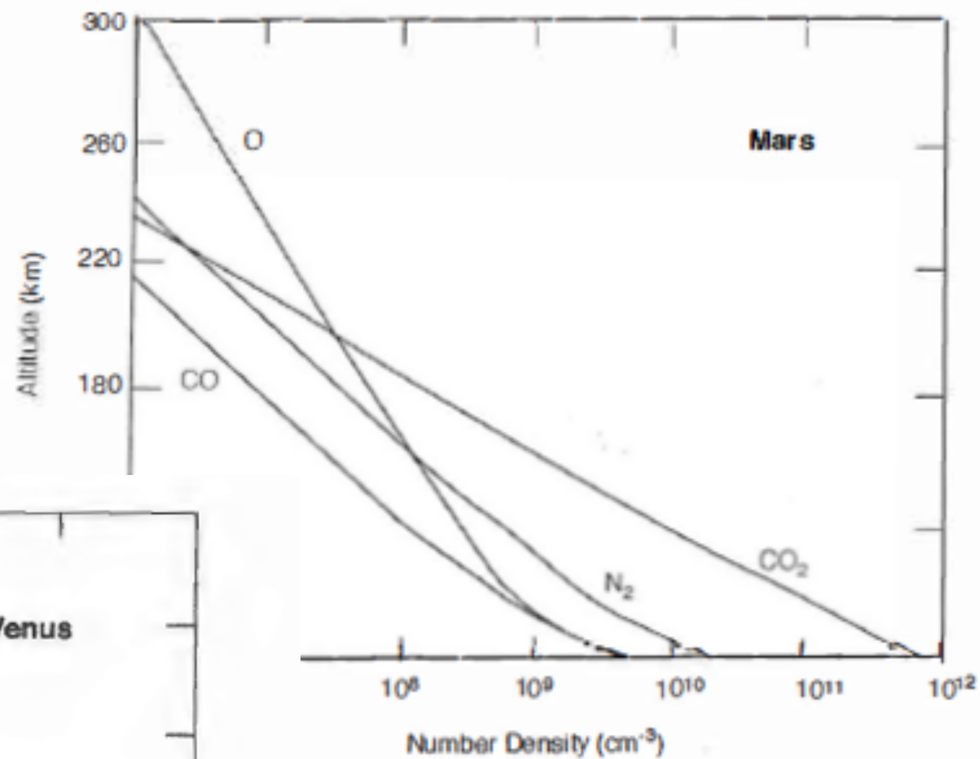
Neat fact about the upper atmosphere

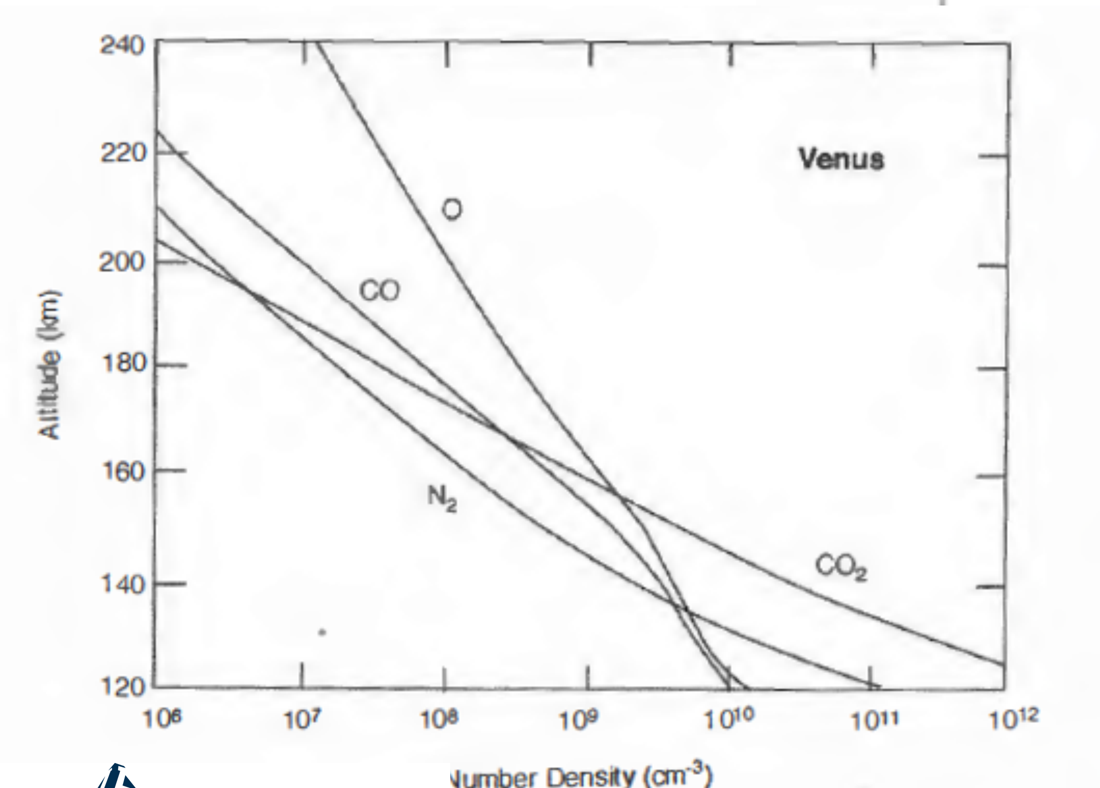


In the terrestrial upper atmosphere atomic oxygen is produced.

Atomic oxygen is associated with its own chemistry reactions.

Venus and Mars are viewed as having terrestrial ionospheres hence they need terrestrial atmospheres.





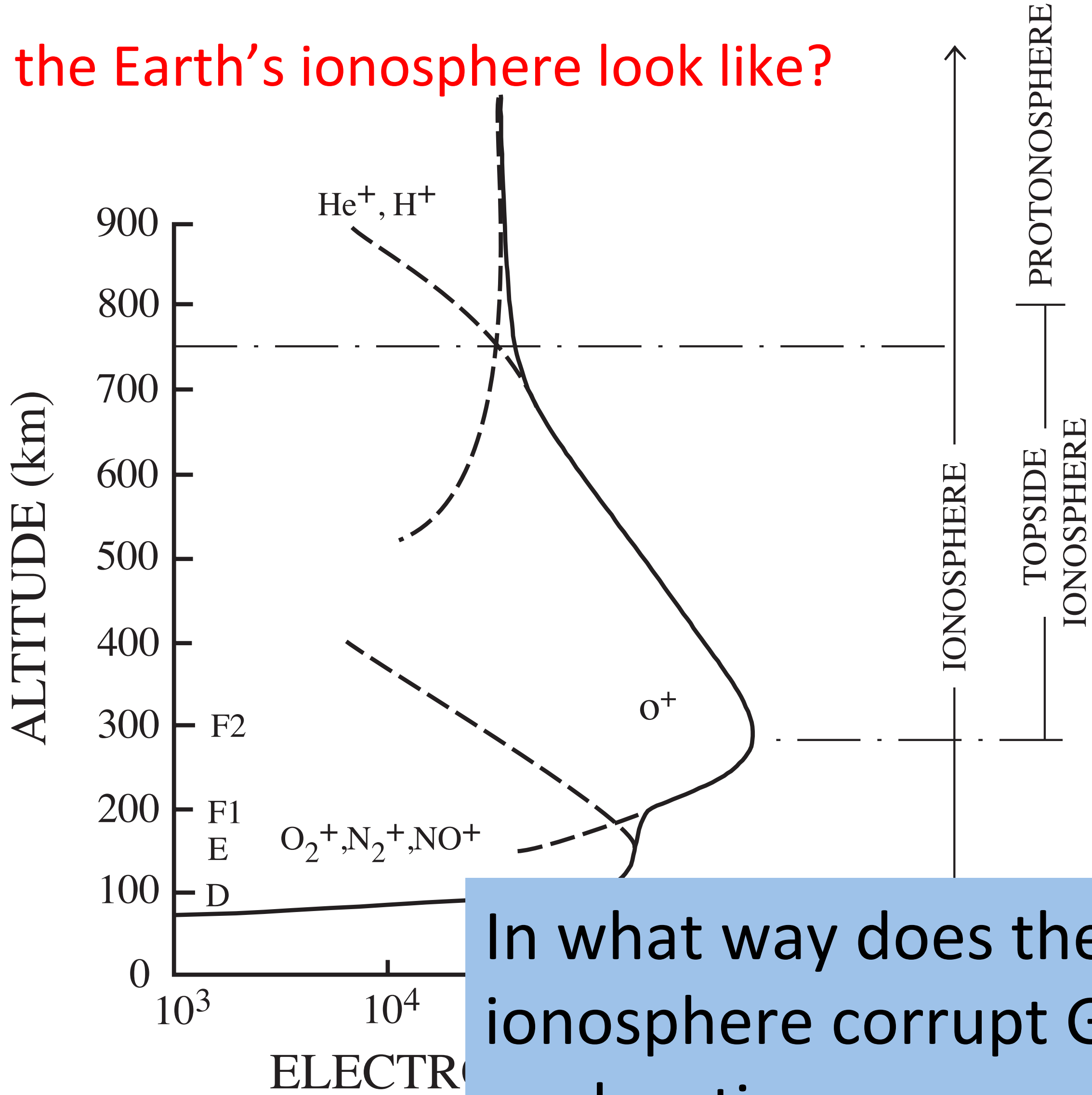
A lot of CO_2 and then a different chemistry produces atomic O.

Ionospheres

- Ionospheres exist in a neutral gas.
- The relative plasma to neutral density is variable, for terrestrial planets it is less than 1%.
- The daytime plasma is mainly produced by solar EUV and soft X-ray ionization.
- The night time plasma is created by resonantly scattered sun light, Star light, Cosmic Ray ionization.
- Auroral charged particles from the magnetosphere produce ionization, hence plasma.
- The ionosphere is e magnetosphere by ity channels.

If you had to guess at what altitudes are these conductivity channels?

What does the Earth's ionosphere look like?



In what way does the ionosphere corrupt GPS geolocation accuracy?

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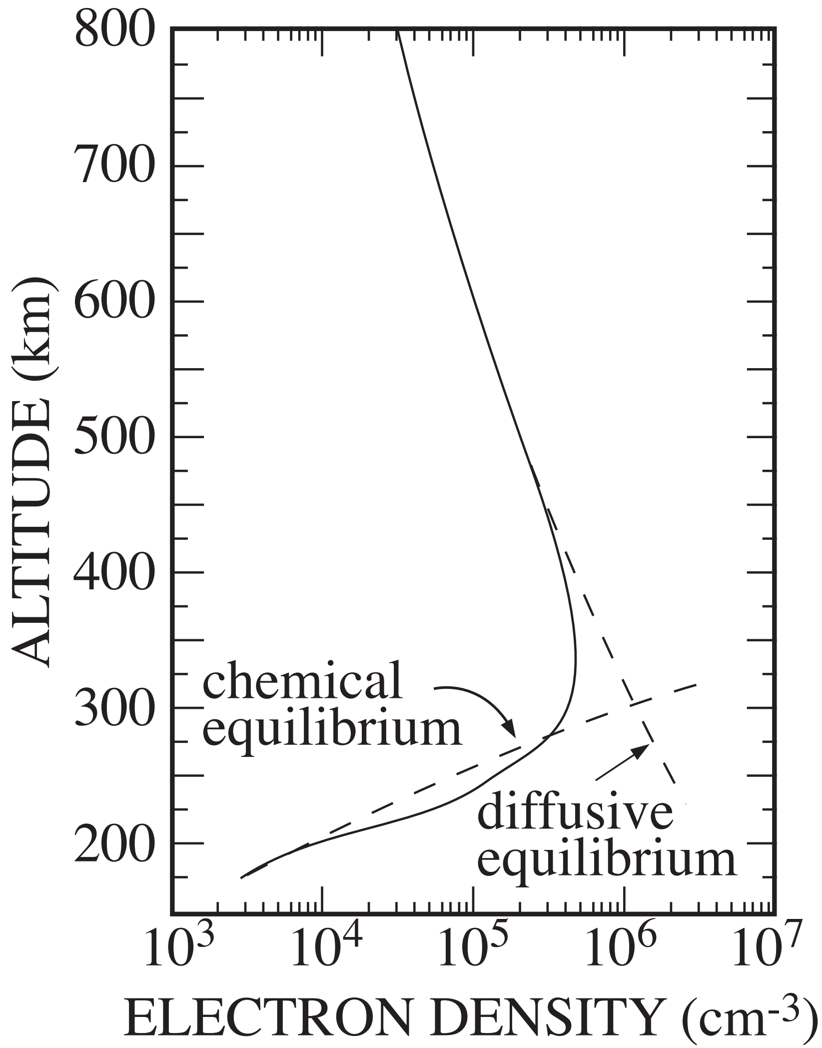
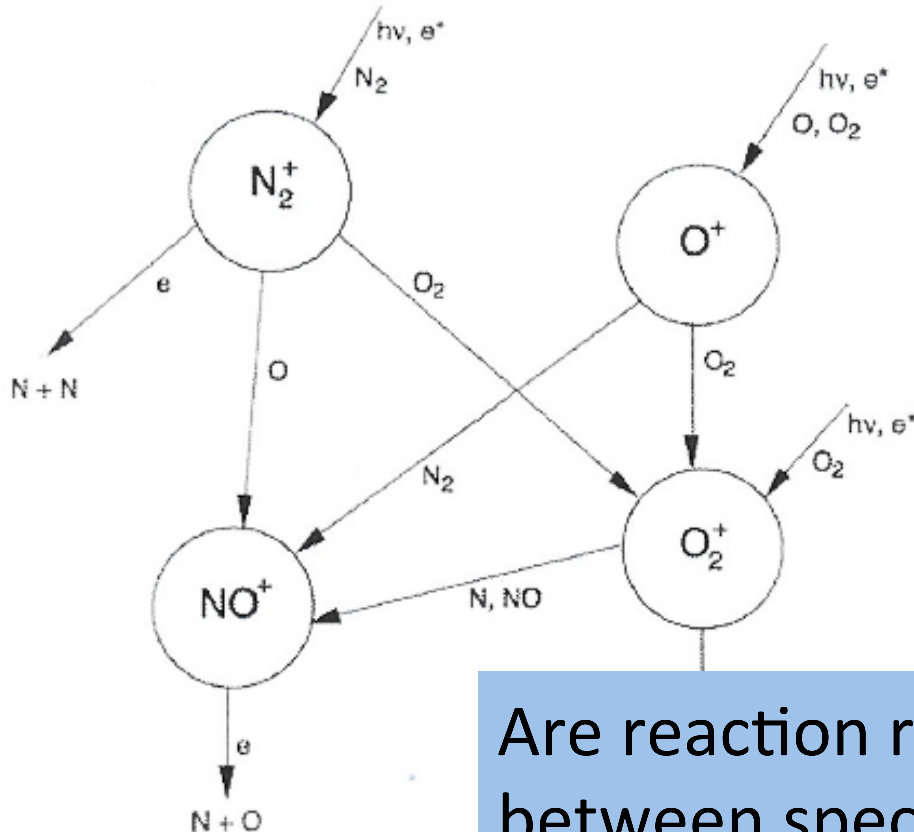
Atomic O+: F2-Layer is the main layer for Earth's Ionosphere.

Above the peak it is in diffusive equilibrium with its plasma scale height.

Below the peak chemistry dominates, but molecular composition creates a large range of chemical reactions and temperature dependencies.



Earth's ionosphere chemistry-simplified



Are reaction rates between specific species constant values?

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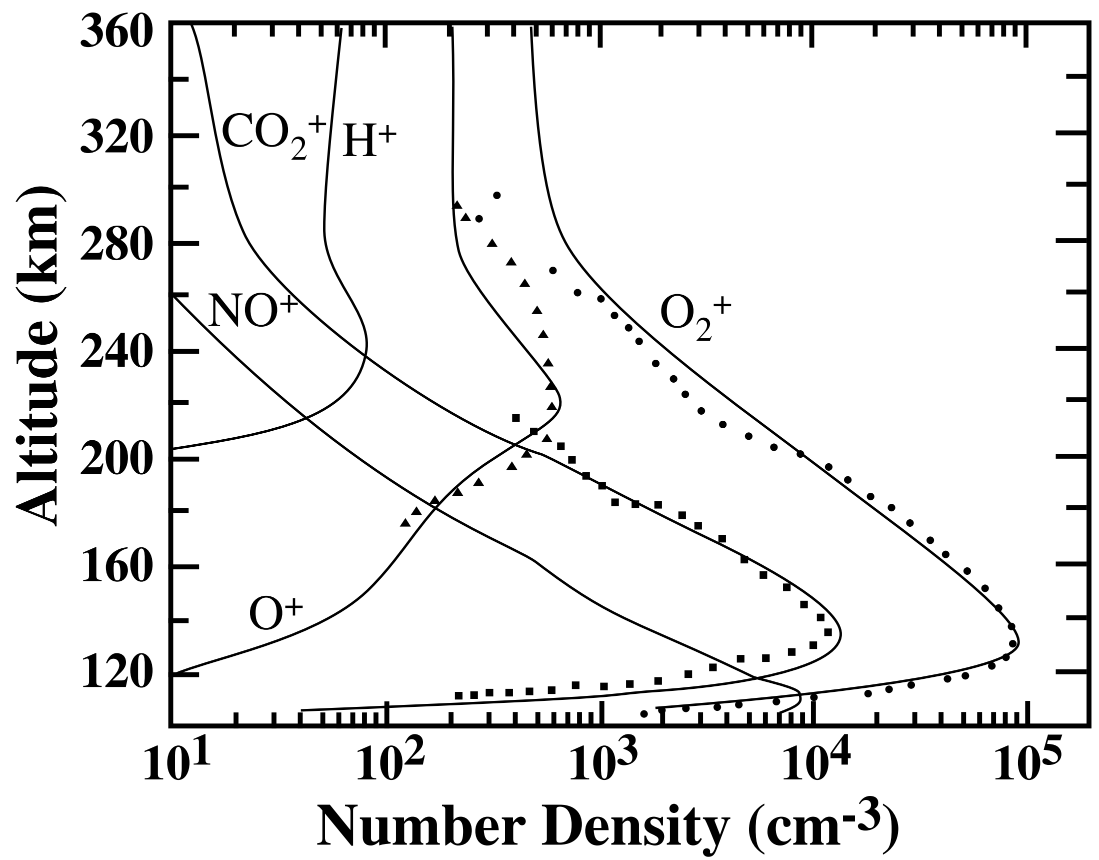
Mars has an Ionosphere!



The ionosphere is dominated by the molecular ion O2+. On the Earth the molecular ion peak is called the E-region.

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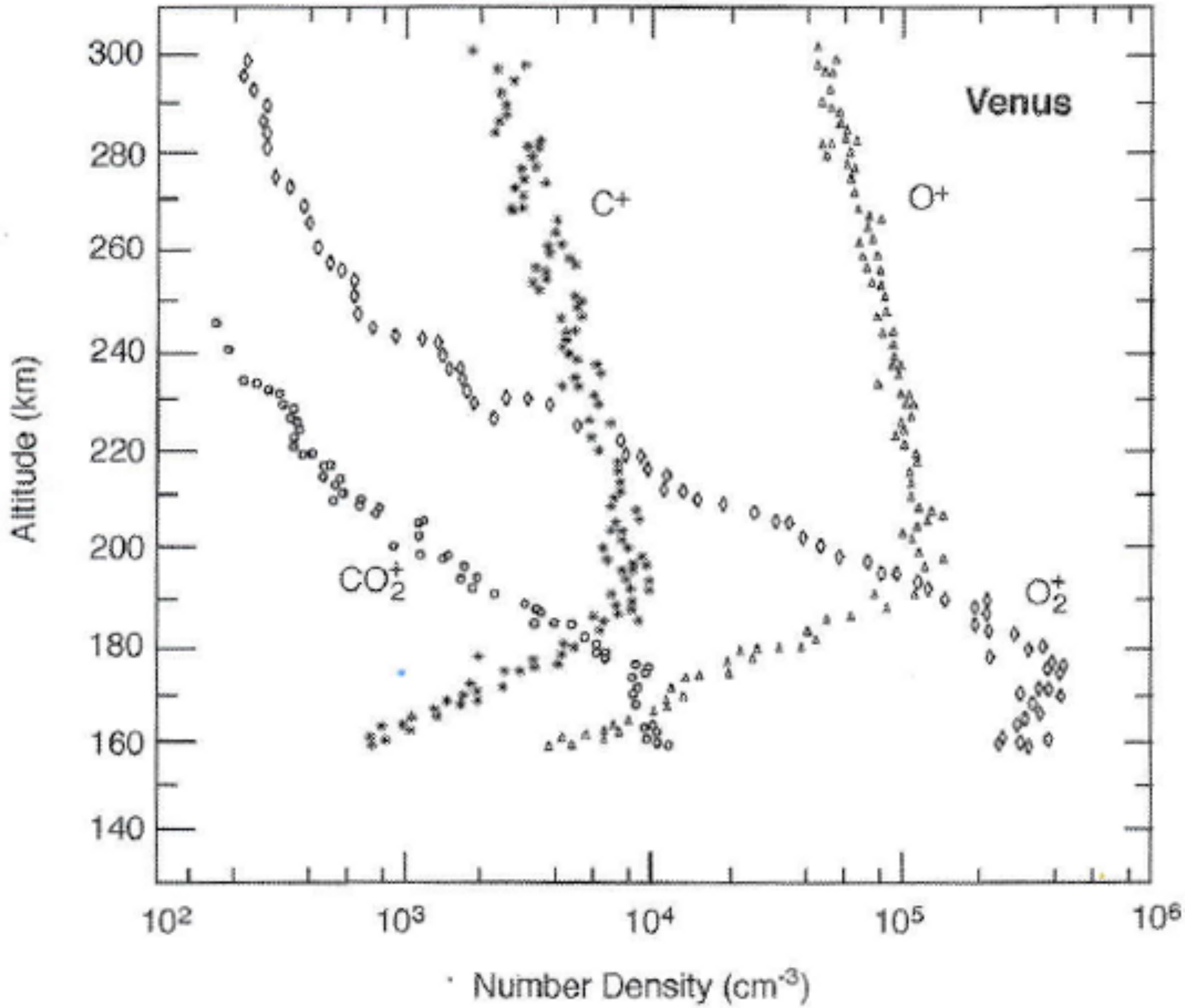
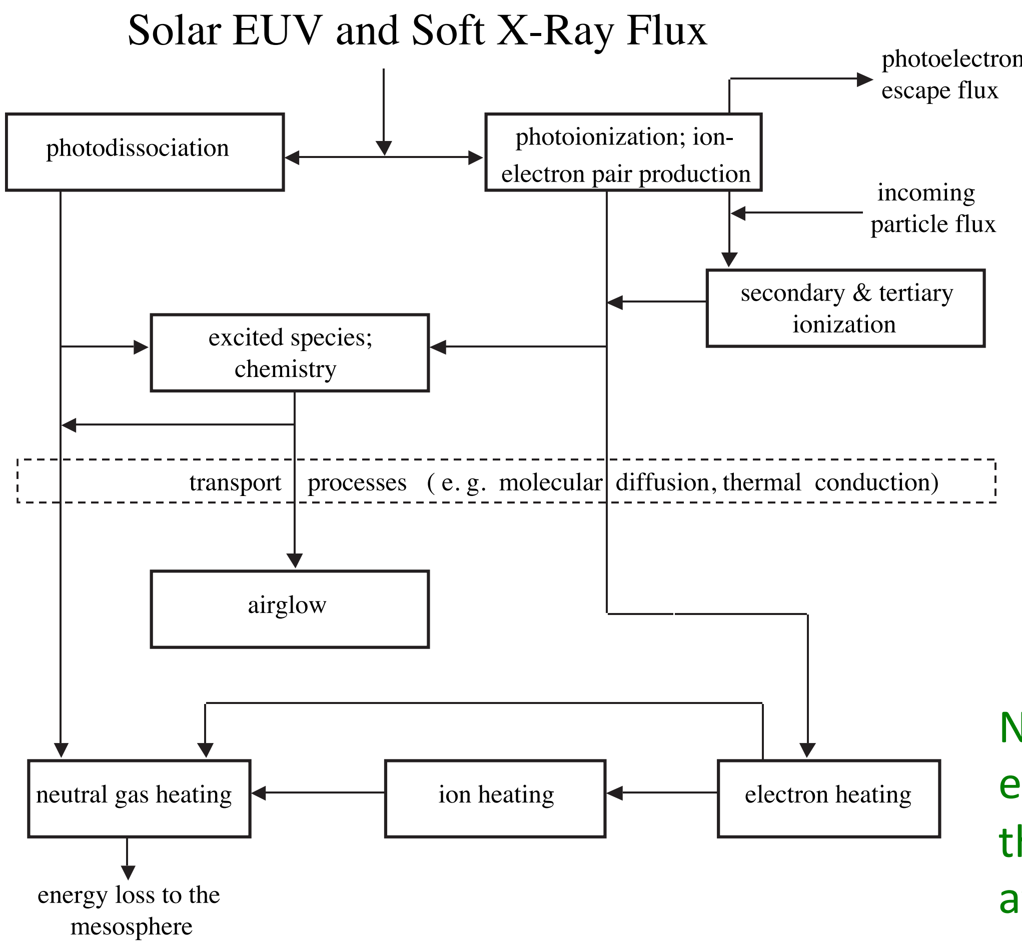
Venus also has an ionosphere.



Photoionization

- The Solar EUV irradiance is key.
- Only recently has the short wavelength component become routinely observable.
- Proxy indices are less than satisfactory!
- NASA: satellites TIMED(SEE) and SDO(EVE) have provided high resolution spectral and now temporal information about EUV irradiance variability.

EUV spectrum 10 nm to 120 nm

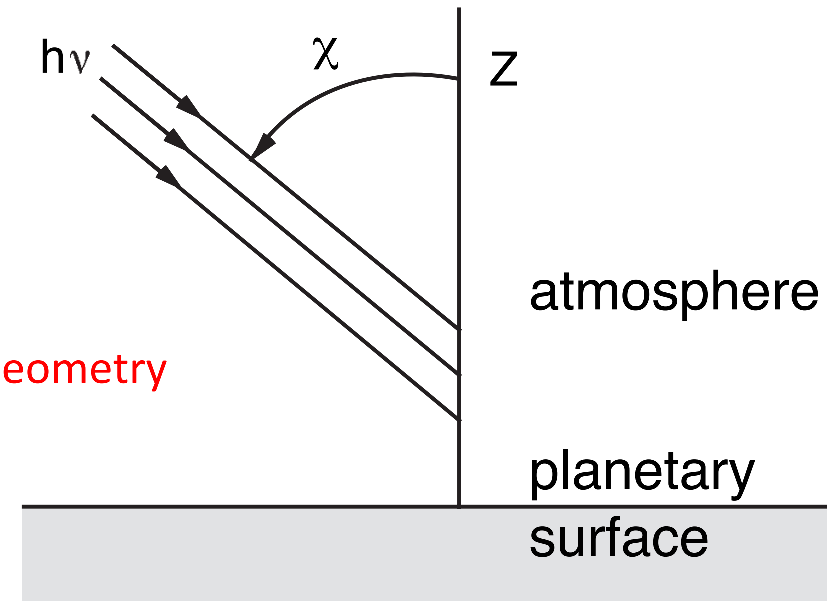


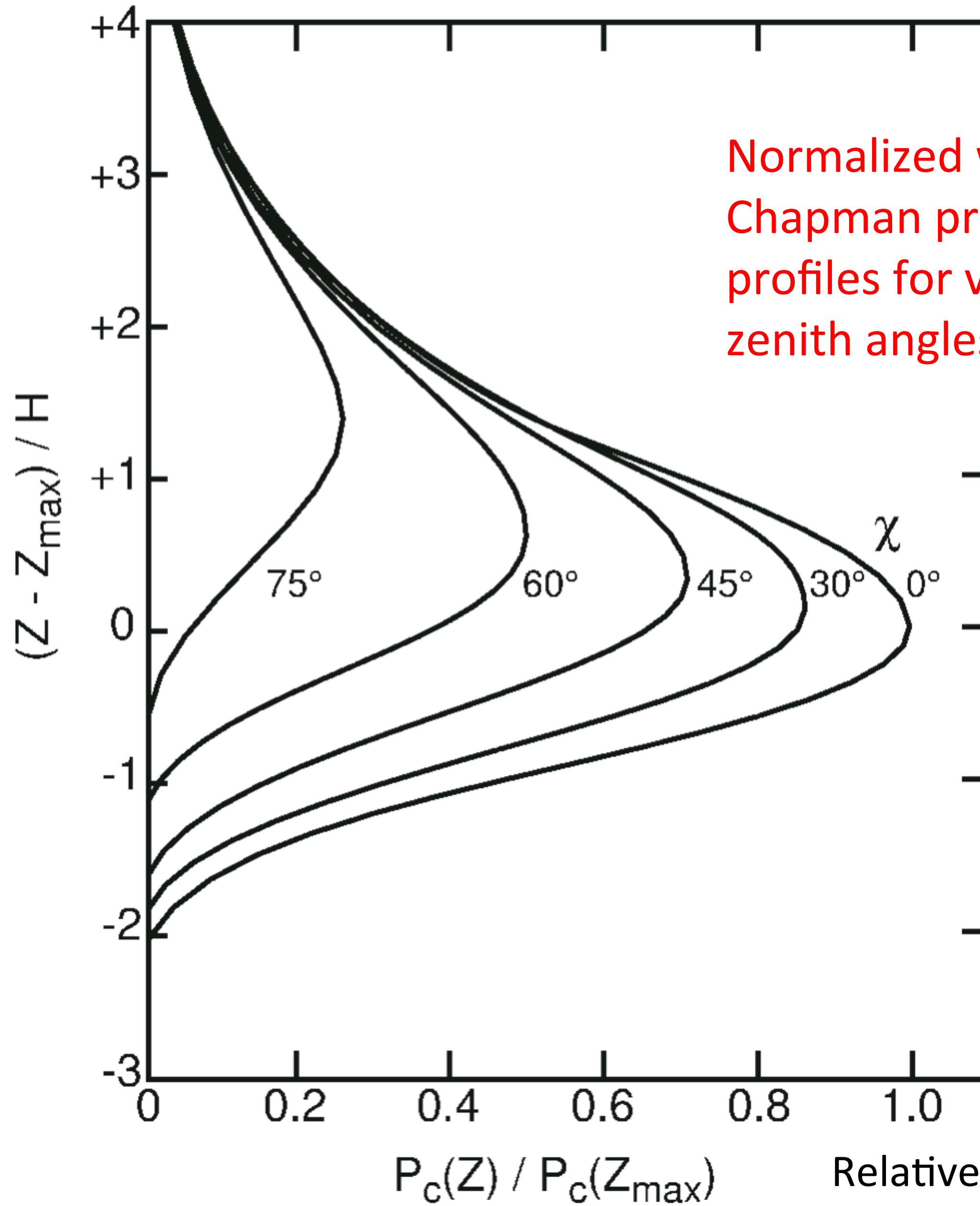
Soft X-rays 1 nm to 10nm

NO and CO_2 are very effective IR radiators that cool the upper-atmosphere.

Would someone like to describe the purpose of this slide?

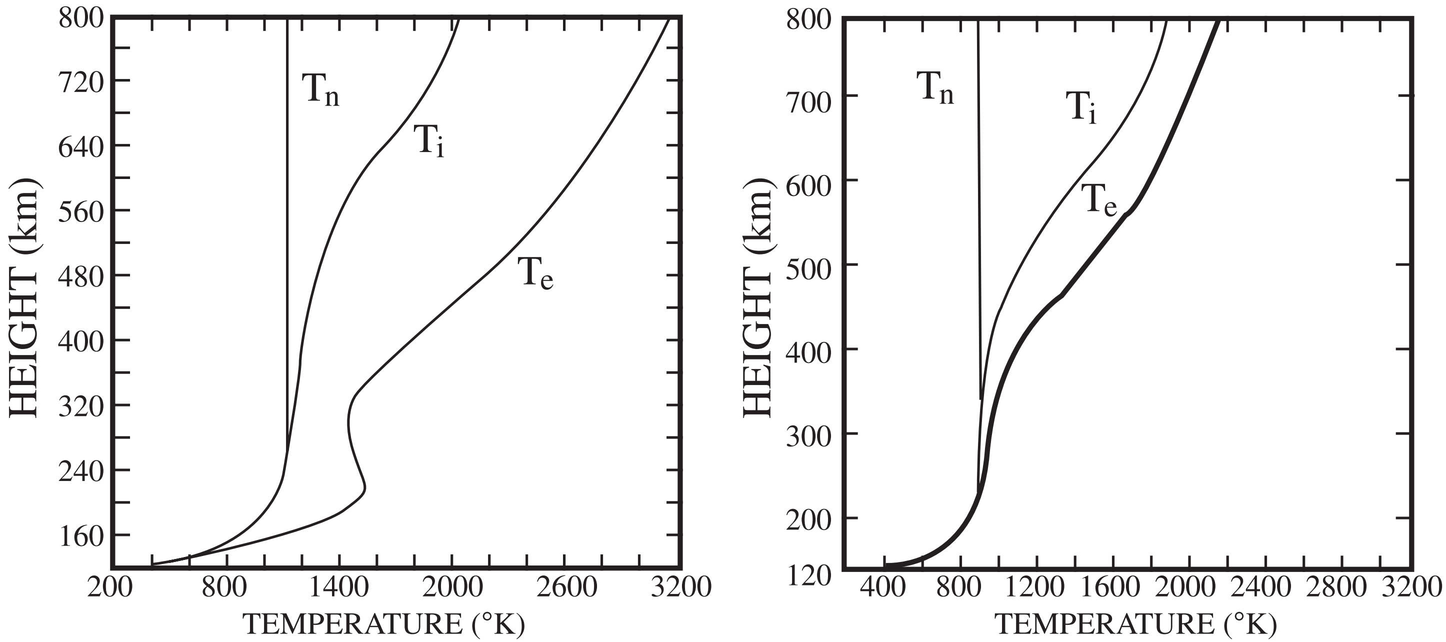
Solar Zenith angle geometry





Normalized wicked Chapman production rate profiles for various solar zenith angles.

Relative Production Rate



Daytime thermal profiles for the thermosphere and ionosphere at Millstone Hill, MA.

A midlatitude location: left pane

equinox in 1970.

What does Exospheric Temperature refer to?

If the planet has no significant magnetic field, hence devoid of a magnetosphere, the atmosphere with photoionization is the PHYSICS needed to generate the ionosphere.

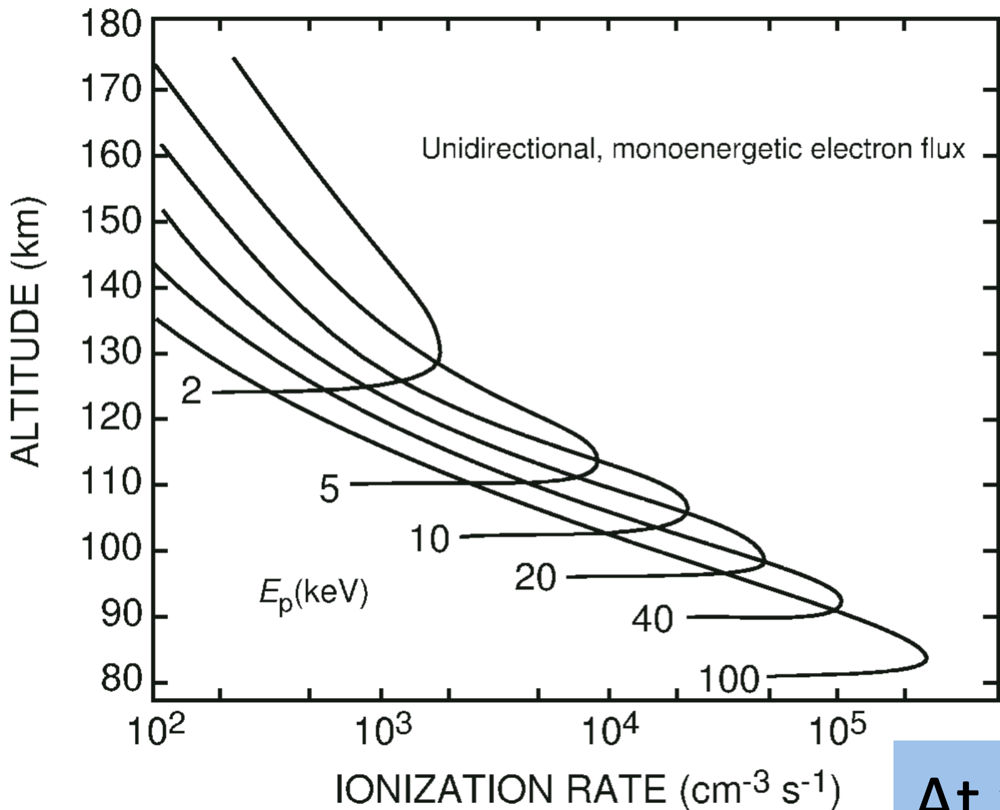
But we on Earth are lucky and have a magnetosphere hence we get even more PHYSICS to complicate our ionosphere!!!

Lets take a break

Auroral Ionization

- The magnetosphere generates ionization via energetic particles, usually electrons.
- These particles are energized in the magnetosphere and create ionization and heating in the thermosphere-ionosphere.
- Auroral displays are the manifestation of this process.
- Ionospheric conductivity is a dynamic "resistor" in the M-I electro-dynamics (MHD).

6 different auroral electron populations and their deposition altitudes

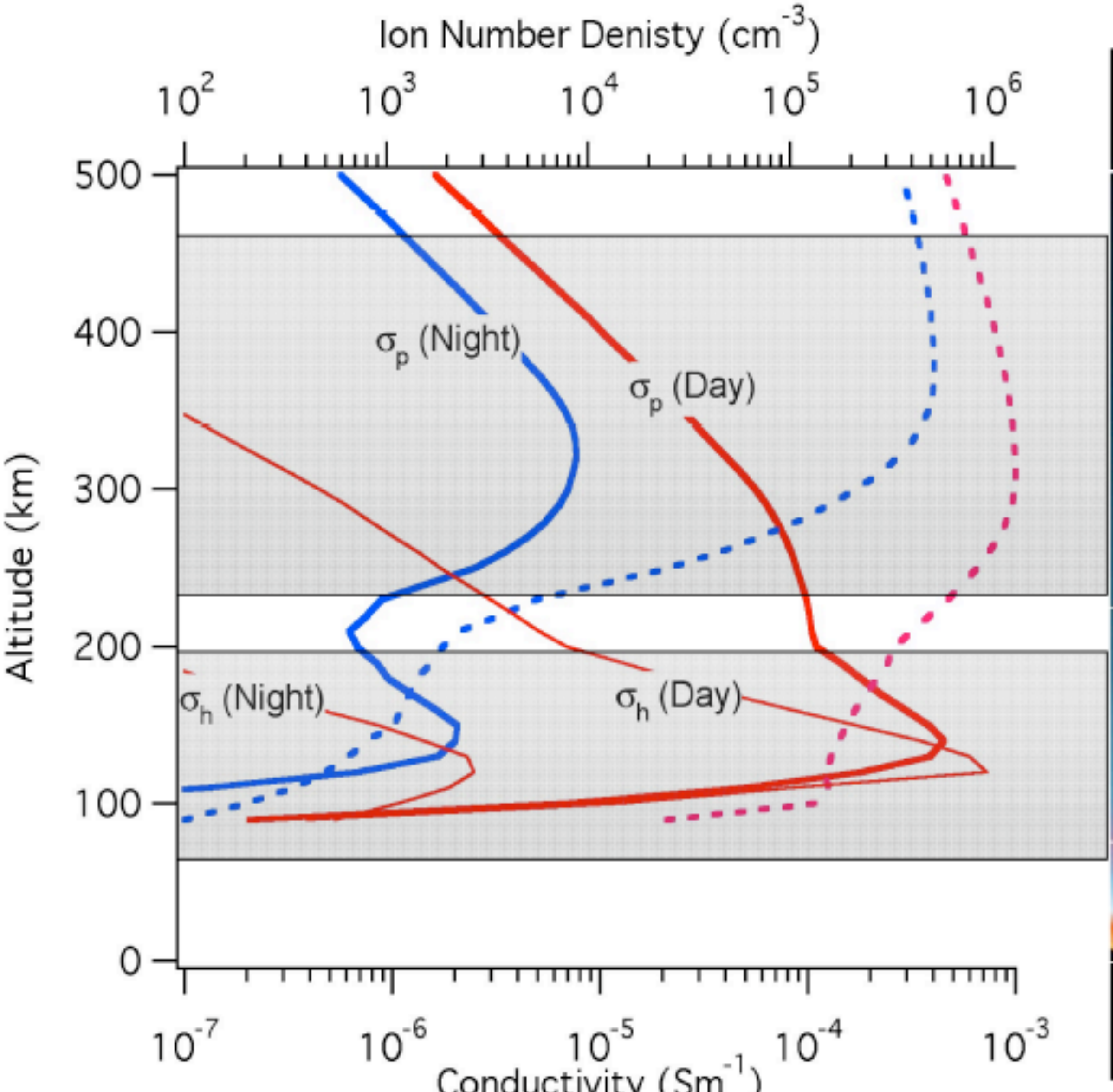


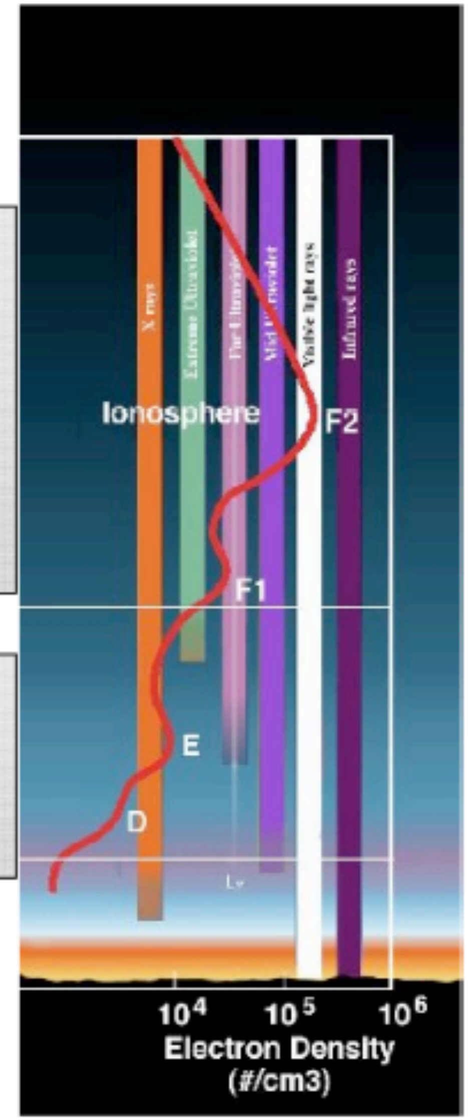
Standard auroral displays have characteristic energies between 3 and 8 keV.

The altitude of ionization depends upon th

At what altitudes do the 3 to 8 keV auroral electrons produce most of their ionization?

Pedersen and Hall Conductivity



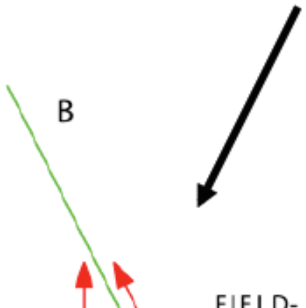


Electric Fields and Winds

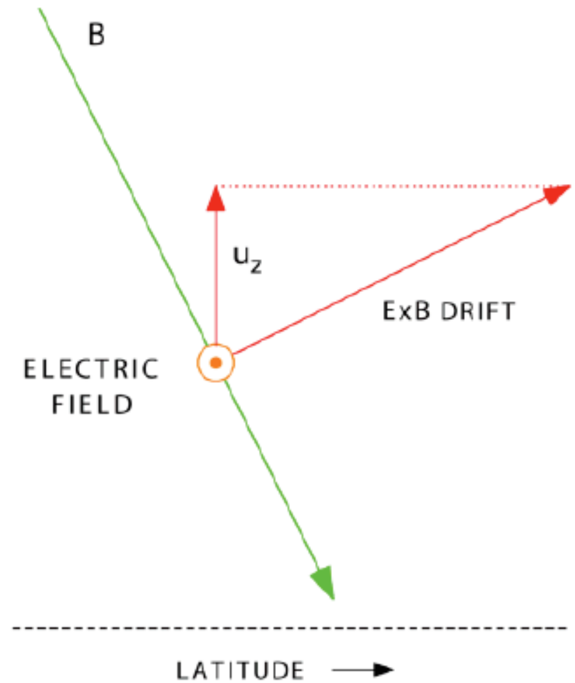
- In the F-region the electric field (and neutral winds) can induce plasma drifts to raise and lower the F-Layer.
- This modifies the plasma diffusion balance and hence density and profile shape.
- Joule heating of the atmosphere depends on the Pedersen conductivity and the square of the electric field.
- At all latitudes E X B can transp
perpendicular to the magnetic

At what altitudes would Joule Heating be maximized?

Equatorward wind at mid latitudes with inclined magnetic field pushes plasma upward along the magnetic field direction to regions of different neutral composition

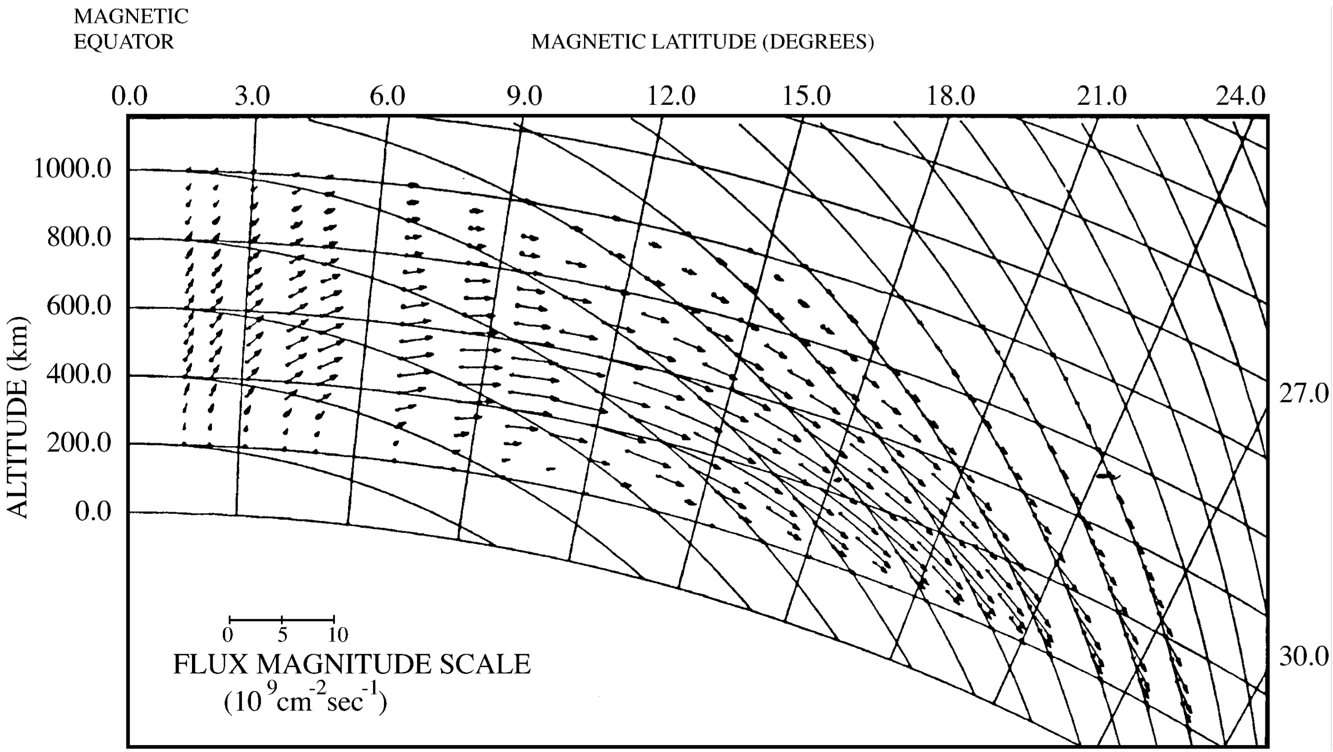


What process are charged particles obeying that prevents them following the wind or electric field?



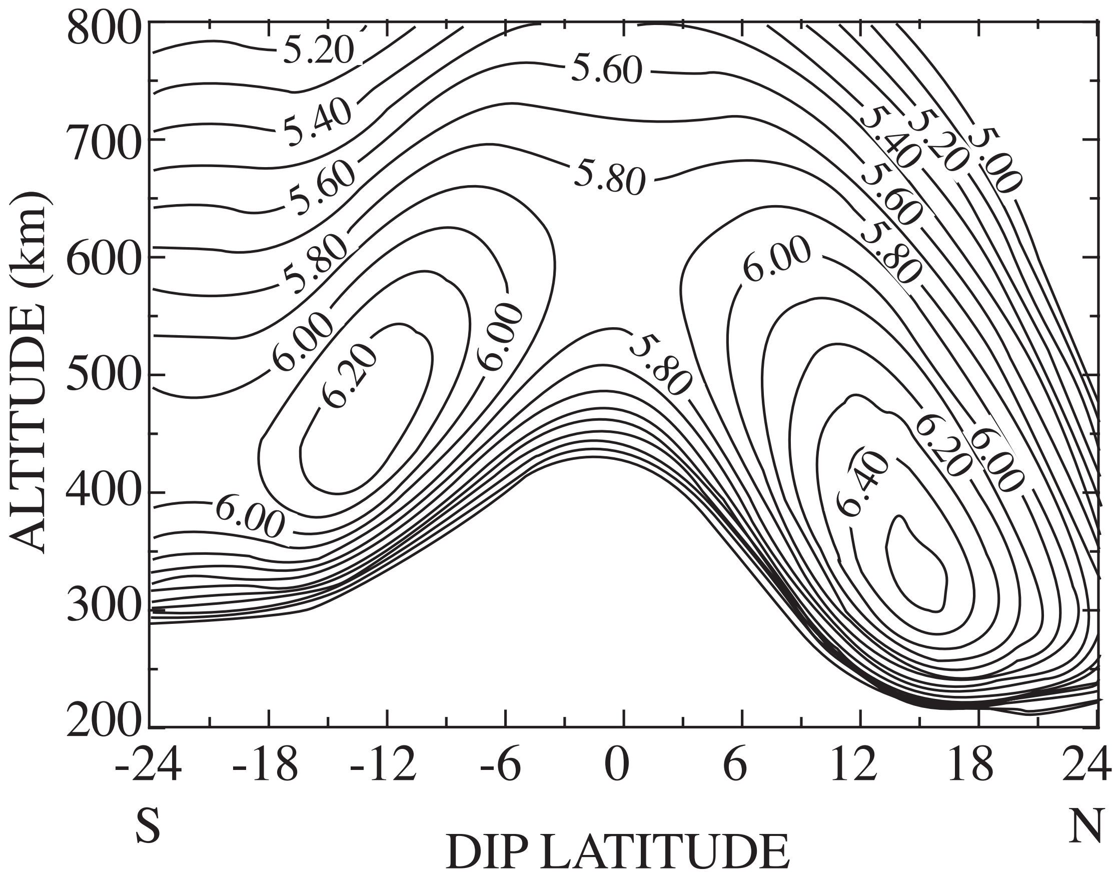
An Eastward Electric field together with the magnetic field creates an upward plasma drift.

EQUATOR



The low latitude day time ionosphere is dominated by transport caused by the Eastward electric field. This results in plasma redistribution and the formation of the Appleton Anomaly (equatorial anomaly).

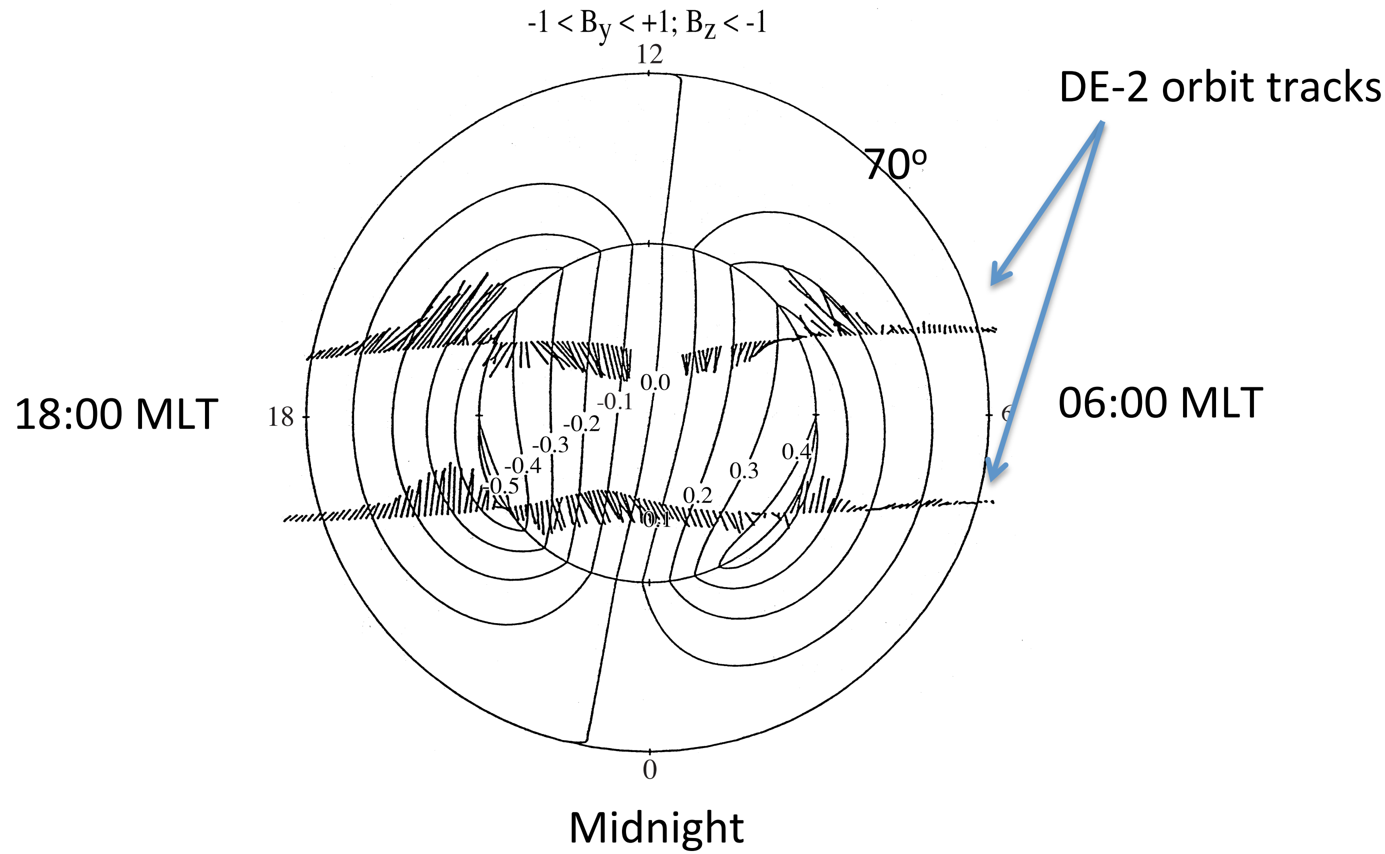
EQUATOR



The Appleton anomalies also known as the Equatorial anomalies.

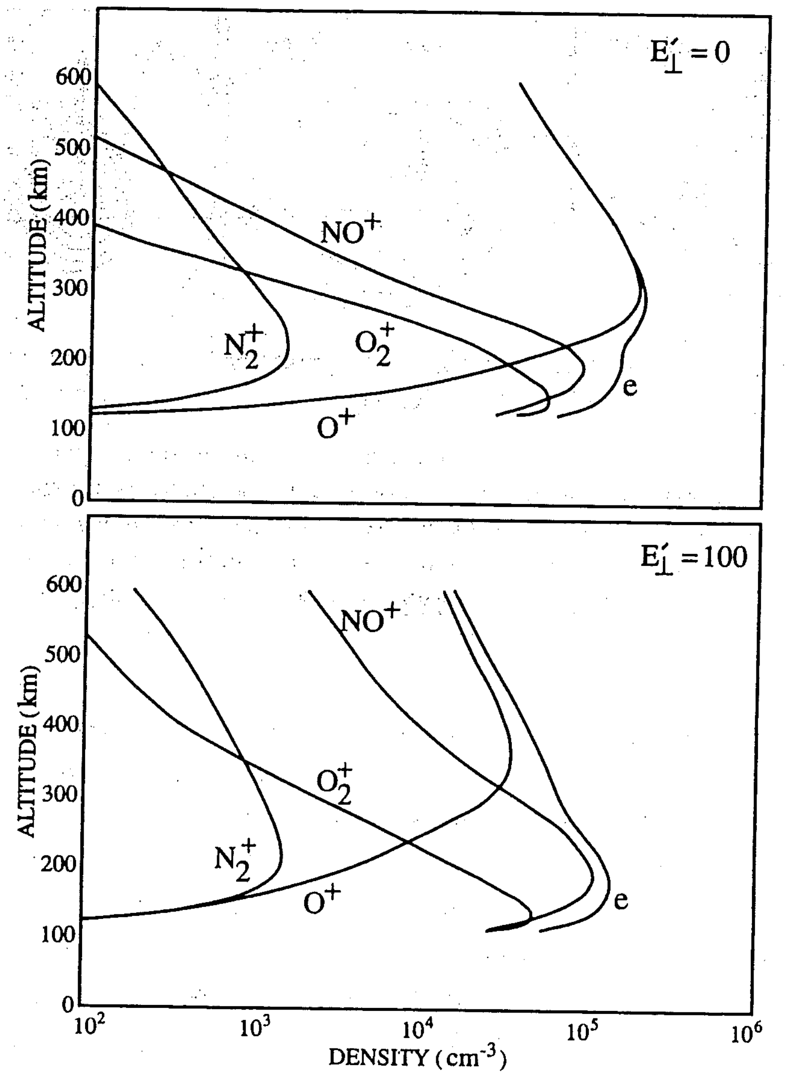
The F-region densities are shown as Log10 Ne (cm**-3)

POLARCAP-AURORAL LATITUDES



Observed ionospheric plasma drift velocities measured from DE-2 over-layed with a corresponding 2-cell electric field pattern

POLARCAP-AURORAL LATITUDES

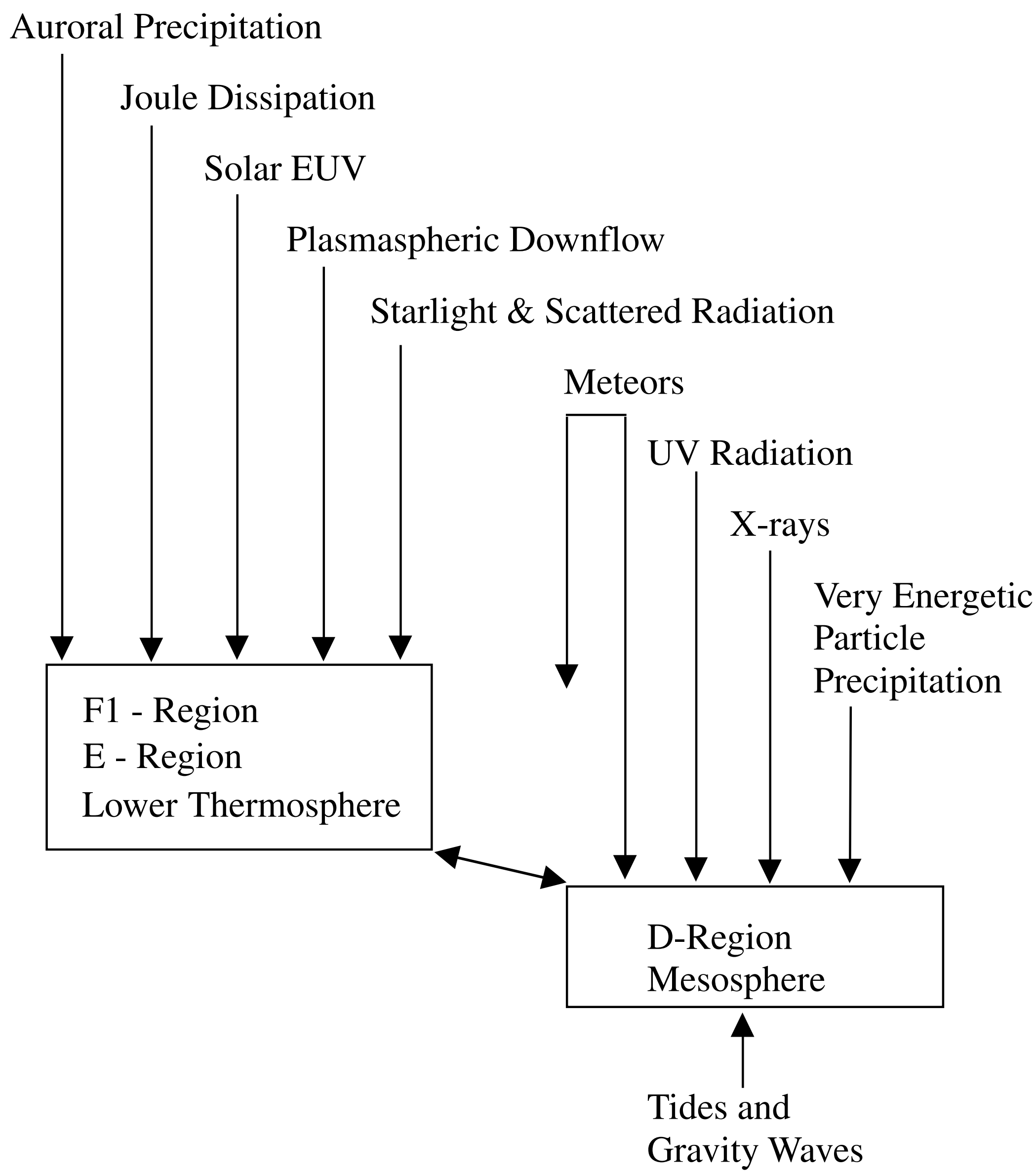


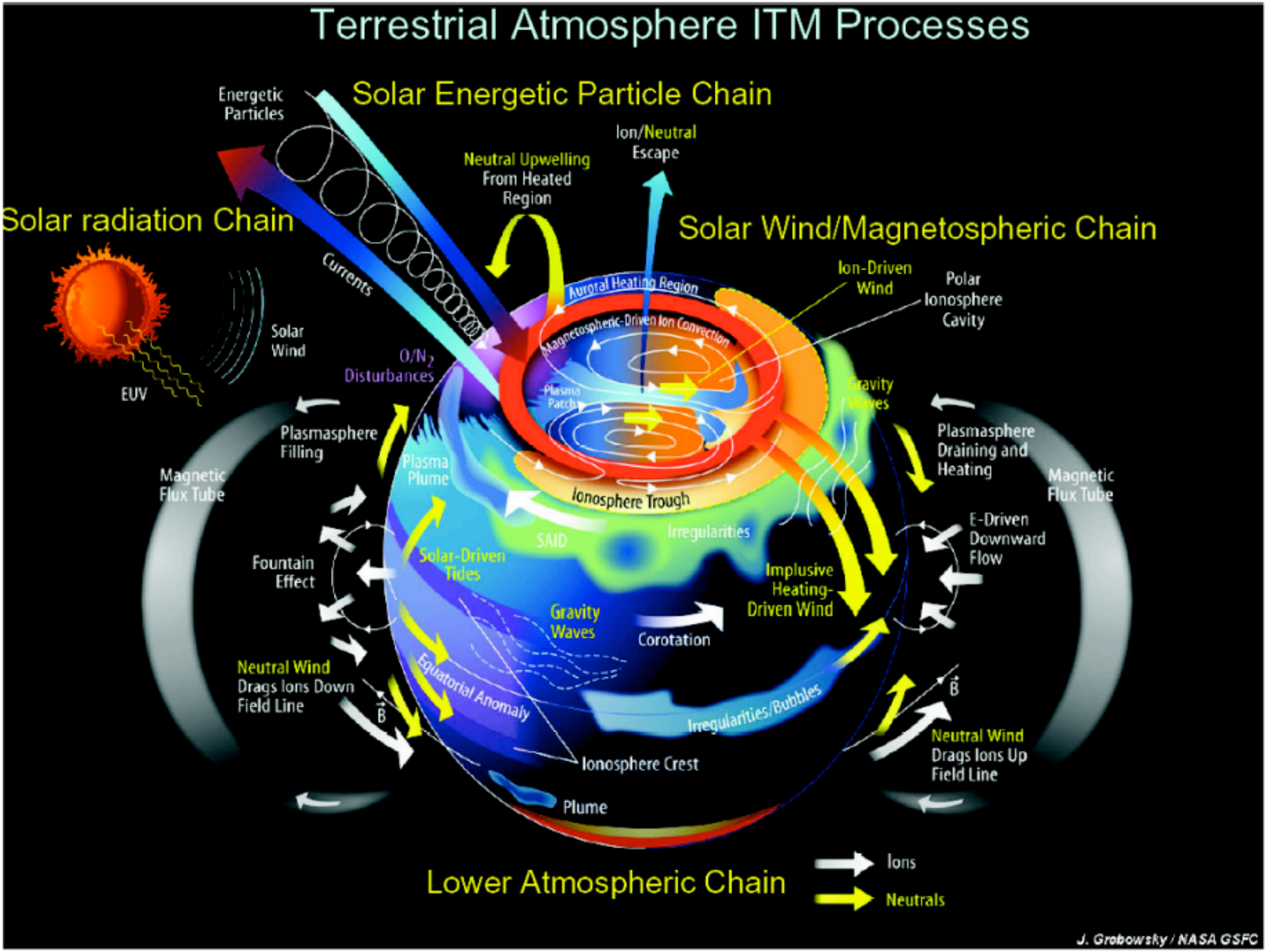
O+ F2-layer is the dominant ionospheric layer under quiet geomagnetic conditions. The height is about 300 km.

100 mV/m electric field, large!

However, during very disturbed geomagnetic conditions the rapid conversion of O+ into NO+ leads to a E/F1 layer becoming dominant. The peak height drops to 150 km!

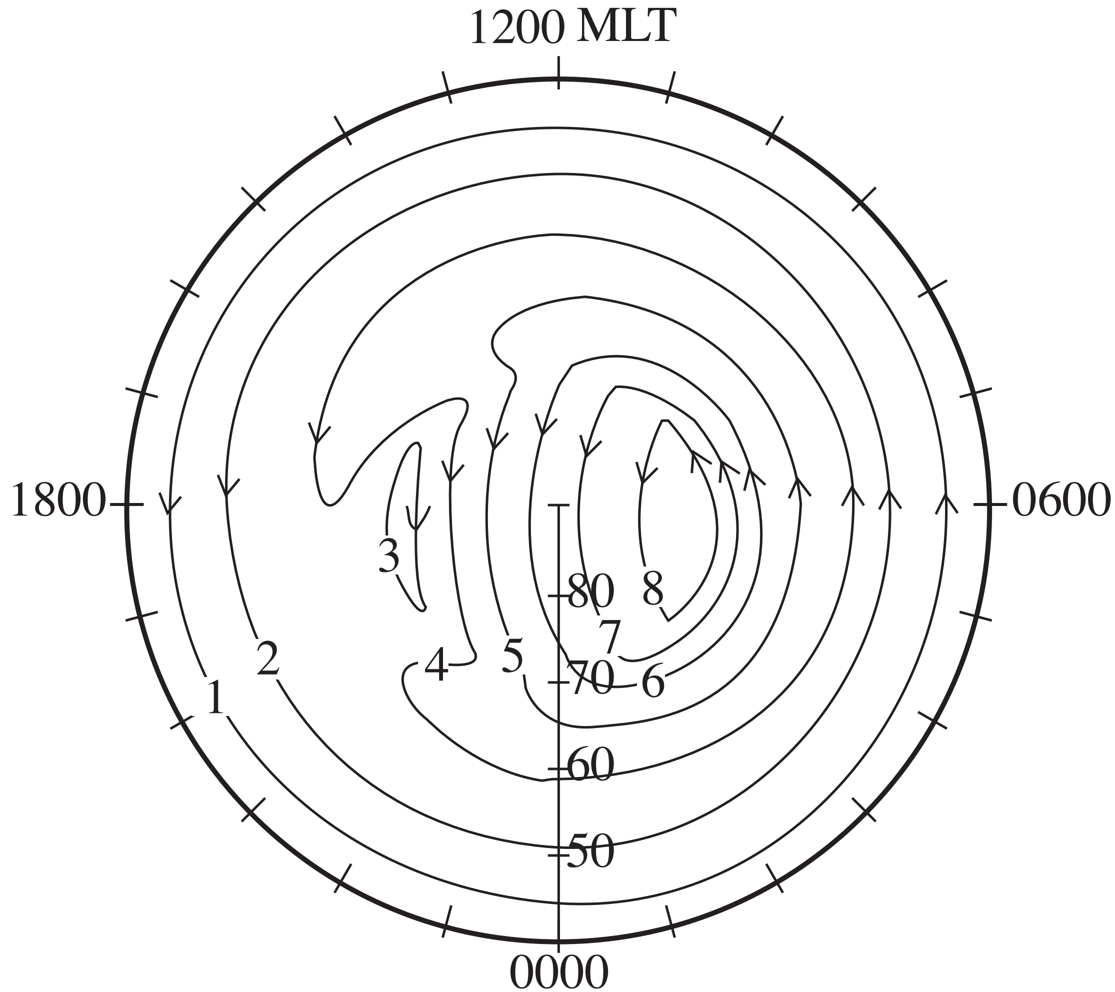
- Morphology of the global ionosphere is a systems level problem.
- Many physics processes operate together as a system but in different latitude regions.
- Historically studies attempted to understand these processes individually and then "assimilate" their net effects……. NOT A GOOD APPROACH not a linear superposition problem!


Auroral Precipitation
Joule Dissipation
Solar EUV
Plasmaspheric Downflow
Starlight & Scattered Radiation
Meteors
UV Radiation
X-rays
Very Energetic Particle Precipitation
F1 - Region
E - Region
Lower Thermosphere
D-Region
Mesosphere
Tides and Gravity Waves


Terrestrial Atmosphere ITM Processes
Solar Energetic Particle Chain
Energetic Particles
Ion/Neutral Escape
Neutral Upwelling From Heated Region
Solar radiation Chain
Solar Wind/Magnetospheric Chain
Currents
Solar Wind
EUV
O/N2 Disturbances
Auroral Heating Region
Magnetospheric-Driven Ion Convection
Ion-Driven Wind
Polar Ionosphere Cavity
Plasma Patch
Gravity Waves
Plasmasphere Filling
Plasmasphere Draining and Heating
Magnetic Flux Tube
Plasma Plume
Ionosphere Trough
SAID
Irregularities
Magnetic Flux Tube
E-Driven Downward Flow
Fountain Effect
Solar-Driven Tides
Implusive Heating-Driven Wind
Gravity Waves
Corotation
Neutral Wind Drags Ions Down Field Line
B
Equatorial Anomaly
Irregularities/Bubbles
B
Neutral Wind Drags Ions Up Field Line
Ionosphere Crest
Plume
Lower Atmospheric Chain
Ions
Neutrals
J. Grobowsky / NASA GSFC

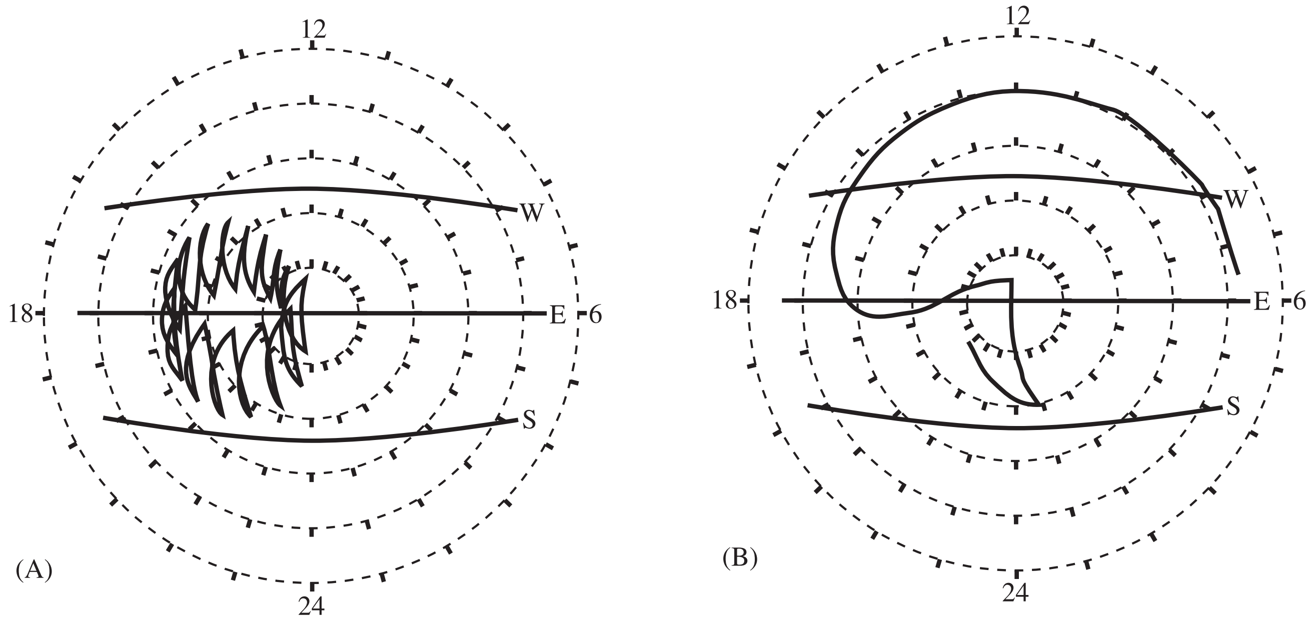
Even simple E X B is complex because there are two separate sources of E

The ionosphere co-rotates, implying an E field, and then the magnetosphere's E field maps into the ionosphere and an atmospheric dynamo generated yet Another E field.



LABEL	1	2	3	4	5	6	7	8
CIRCULATION PERIOD (day)	1.00	1.01	0.10	1.34	0.50	0.31	0.18	0.11

GEOGRAPHIC LOCAL TIME COORDINATES



The F-region plasma as seen in a geographic local time from executes very complicated trajectories!

This means that a ground based observatory at high latitudes is not monitoring the same plasma flux tube continually, and hence the observer is not seeing the plasma evolution!

Energy Flow

magnetospheric energy
500 - 1000 GW

particle precipitation <20%

heat, ionization, airglow e.g. auroral illumination

electromagnetic energy >80%

Joule heating
$\mathbf{J}\ .\ (\ \mathbf{E} + \mathbf{UxB}\ )$
>80%

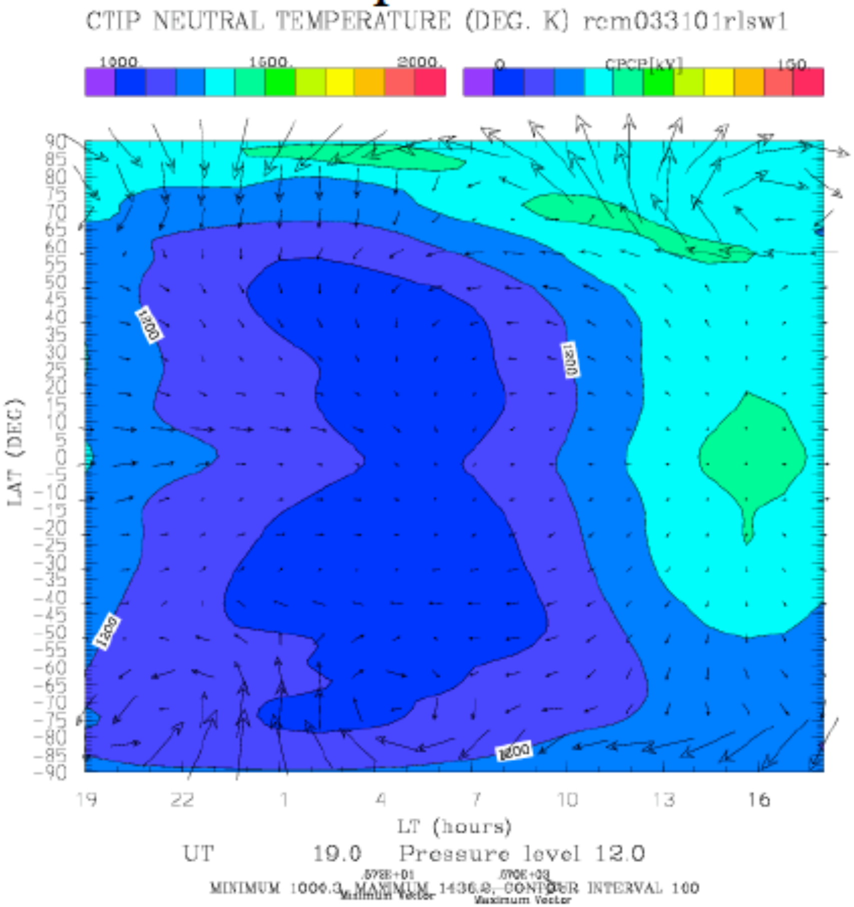
heat, pressure gradients, winds, etc.

kinetic energy
$\mathbf{U}\ .\ (\ \mathbf{JxB}\ )$
<20%

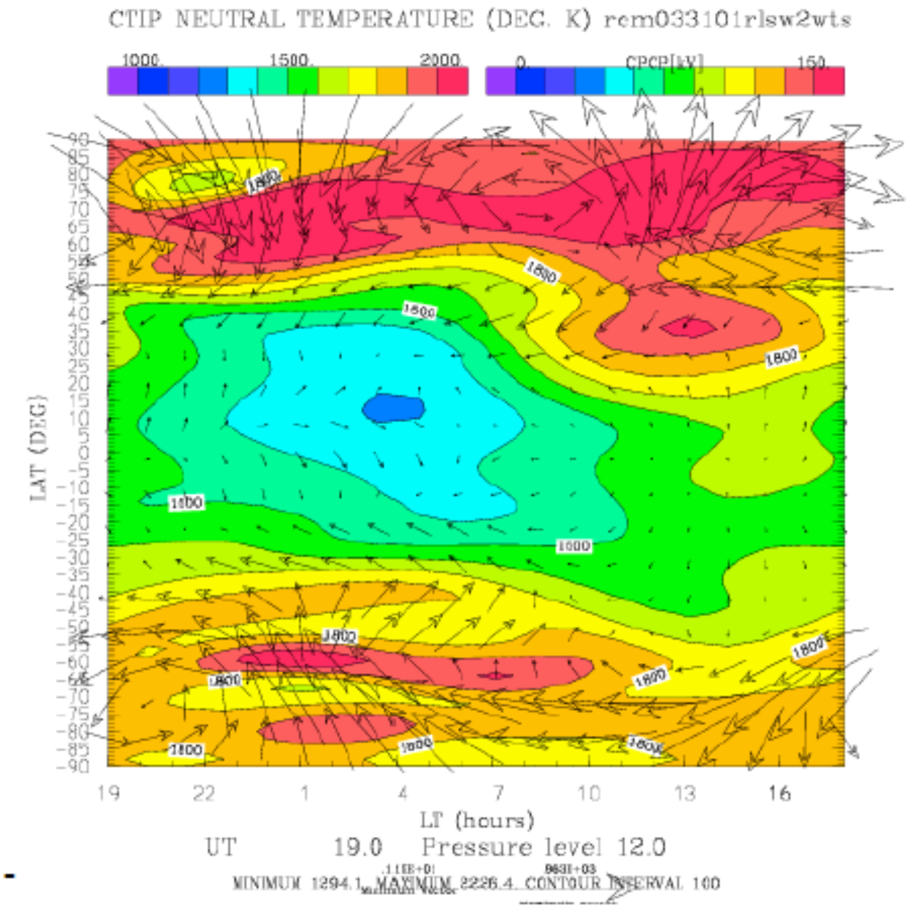
Ion drag drives neutral winds

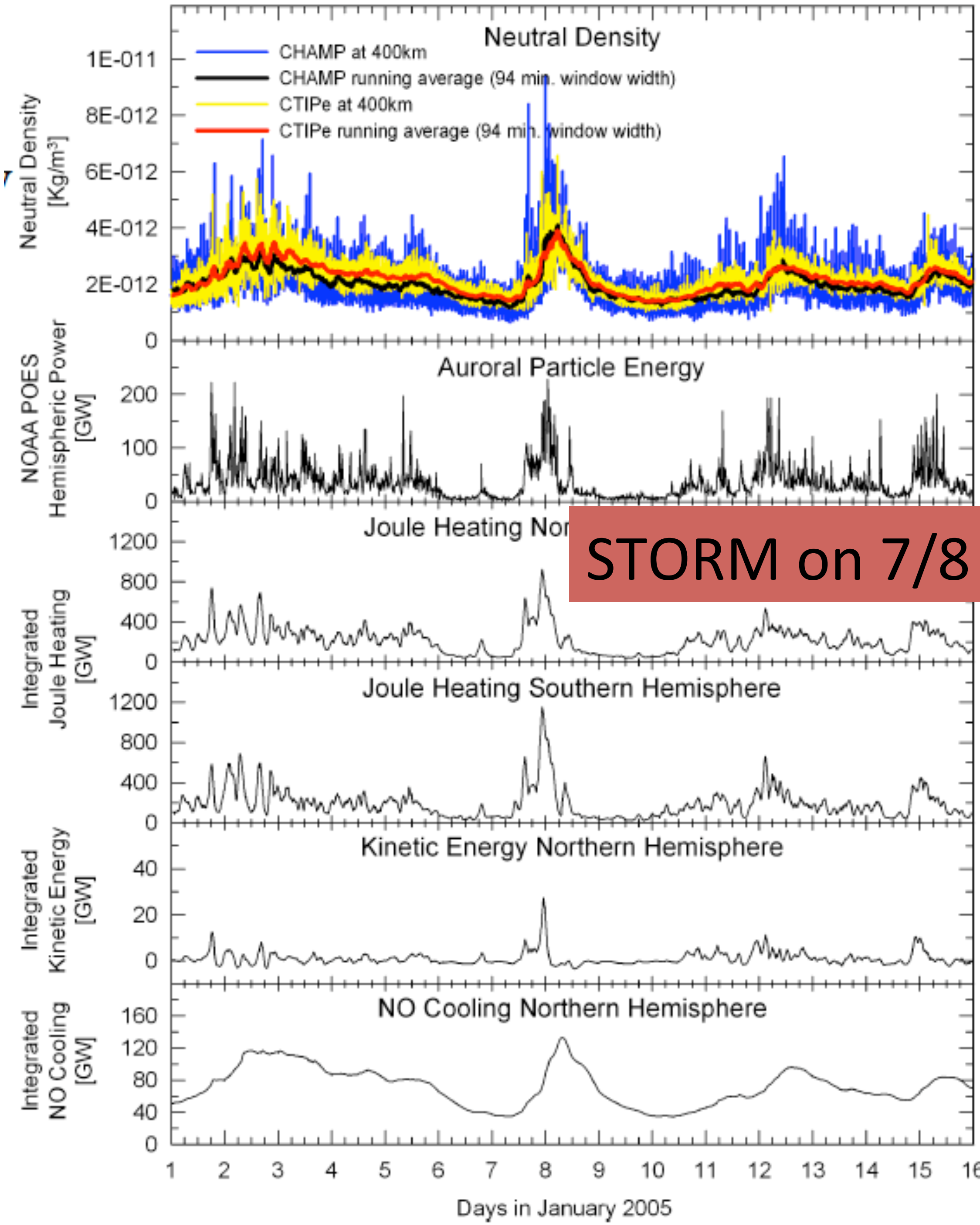
Joule heating: J . (E + V x B)
Large temperature and circulation changes in the upper thermosphere

quiet



disturbed



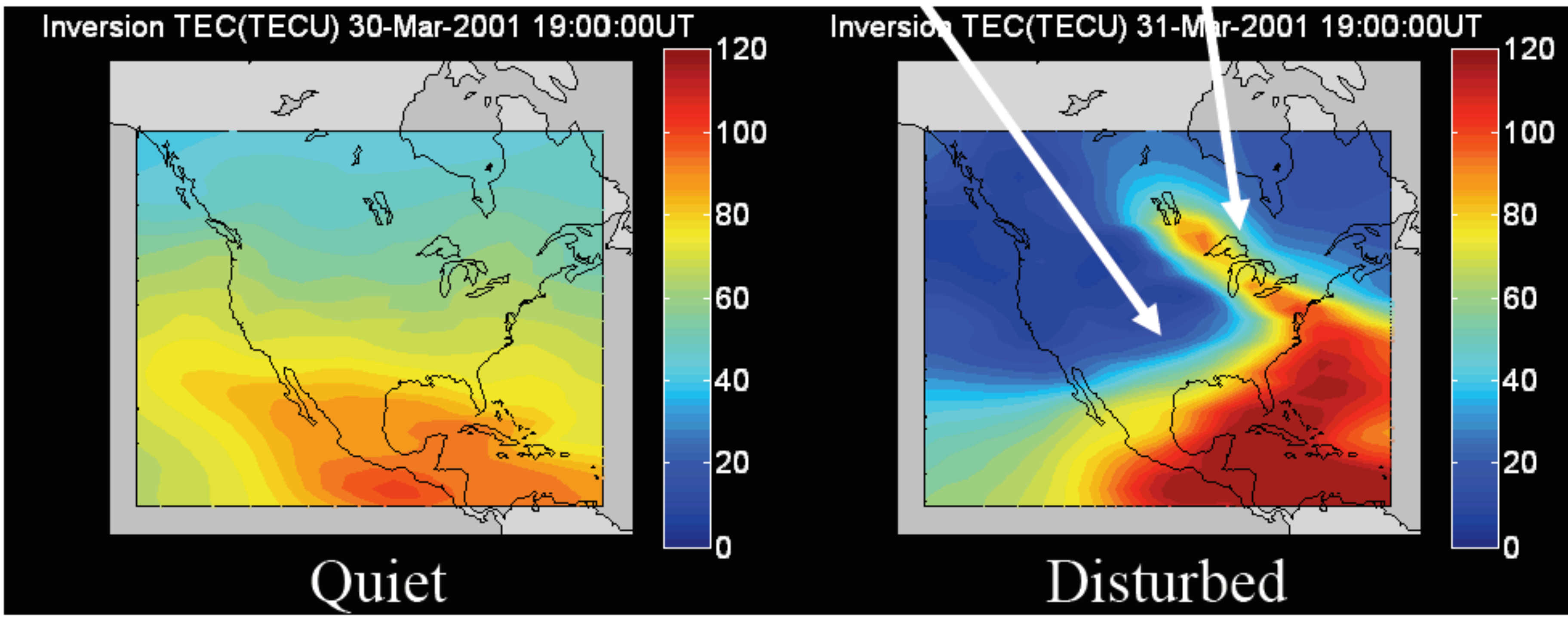


STORM on 7/8 January 2005

US-TEC – SWPC
IRI plus data

"positive phase"
and tongue of ionization

"negative phase"



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Can you list important properties of the Earth's ionosphere between 100 and 120 km?

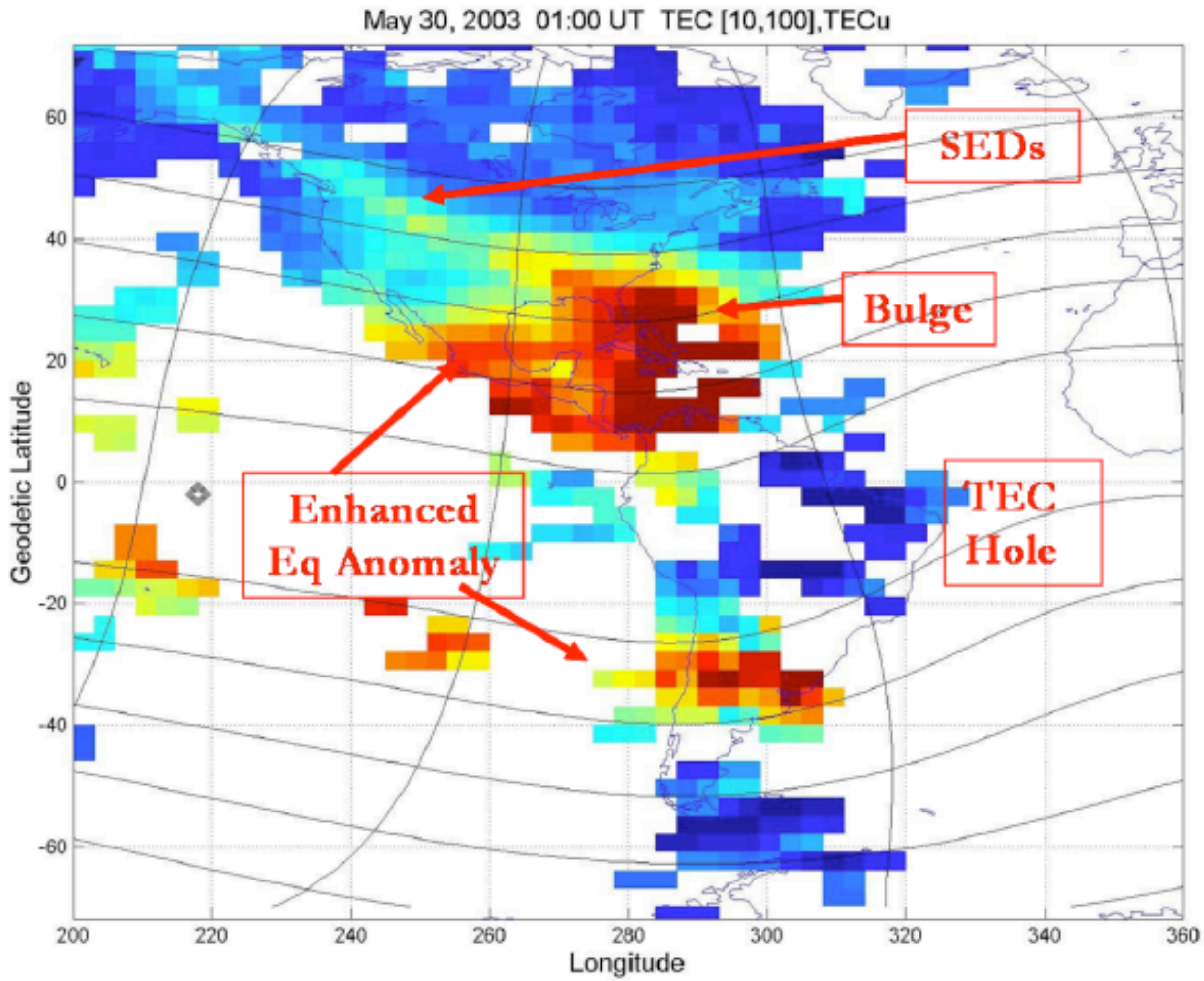
SAIR : Sun Atmosphere Interaction Region

But also

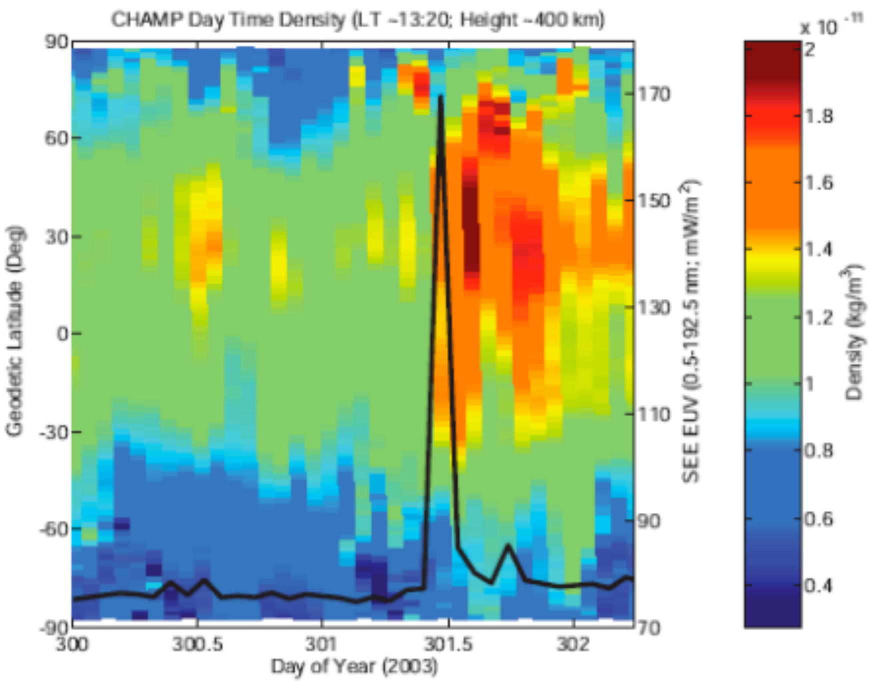
SAIR: Space Atmosphere Interaction Region

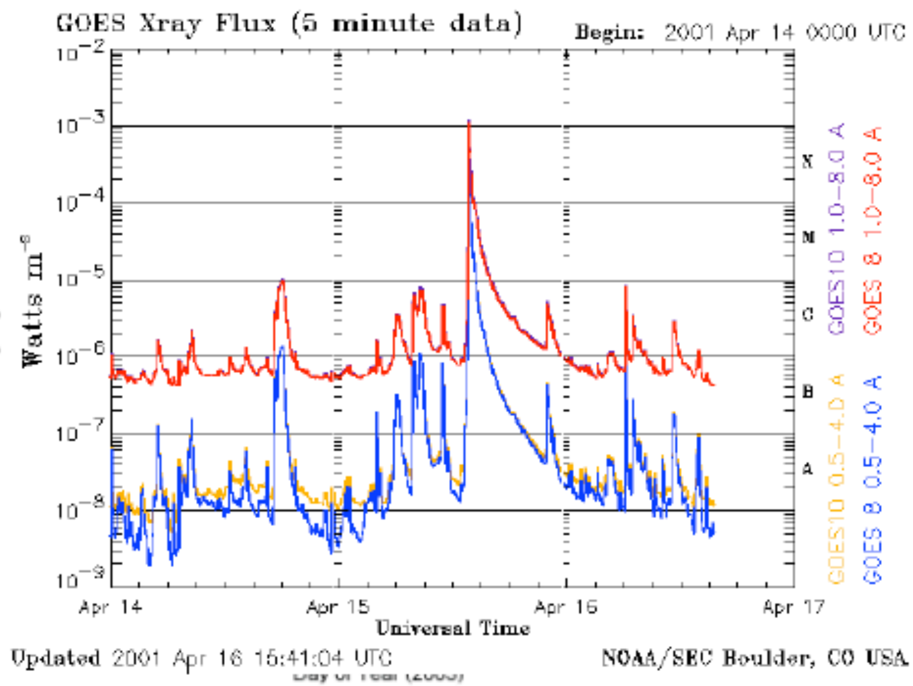
And there is lots more!

Plasma "bulge" and Storm Enhanced Density

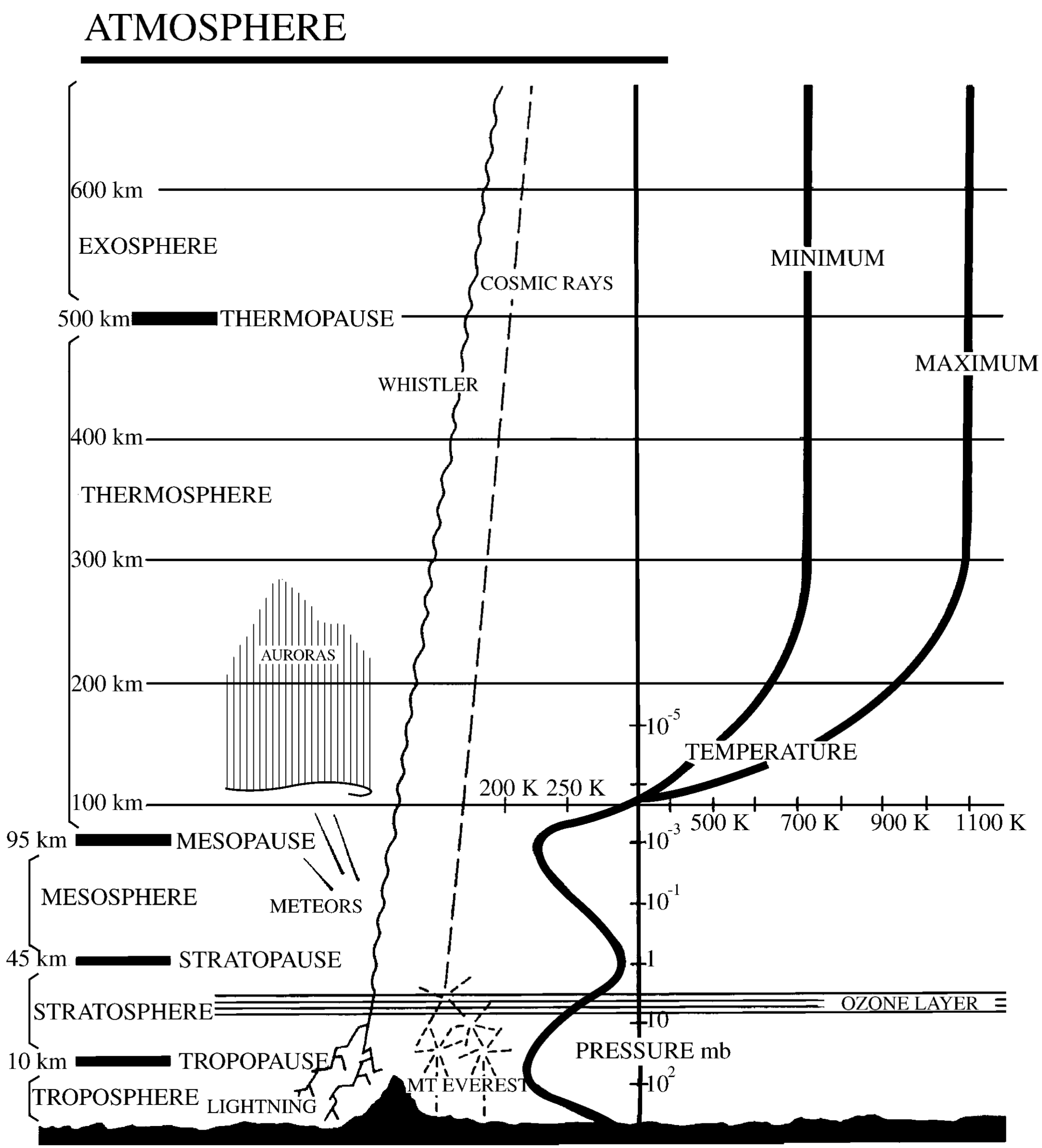


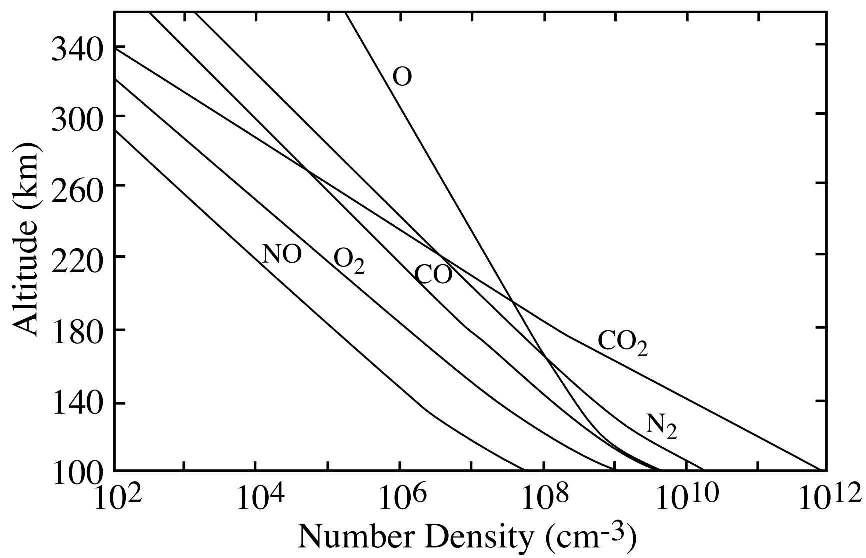
Neutral density response to flares
(Sutton and Forbes)





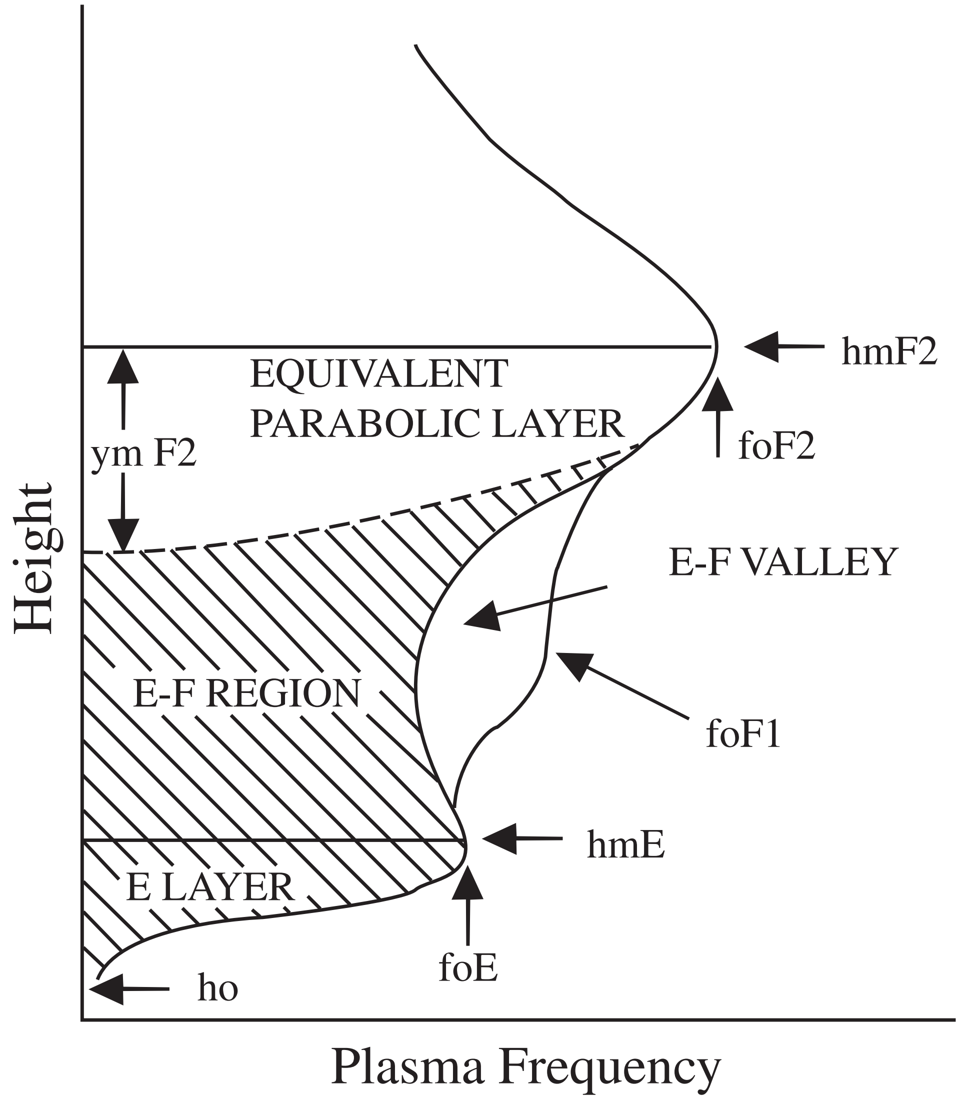
CHAMP satellite data


ATMOSPHERE
600 km
EXOSPHERE
500 km
THERMOPAUSE
400 km
THERMOSPHERE
300 km
200 km
100 km
95 km
MESOPAUSE
MESOSPHERE
45 km
STRATOPAUSE
STRATOSPHERE
10 km
TROPOPAUSE
TROPOSPHERE
COSMIC RAYS
WHISTLER
MINIMUM
MAXIMUM
AURORAS
TEMPERATURE
200 K 250 K
500 K
700 K
900 K
1100 K
10^{-5}
10^{-3}
10^{-1}
1
10
10^{2}
METEORS
OZONE LAYER
PRESSURE mb
MT EVEREST
LIGHTNING



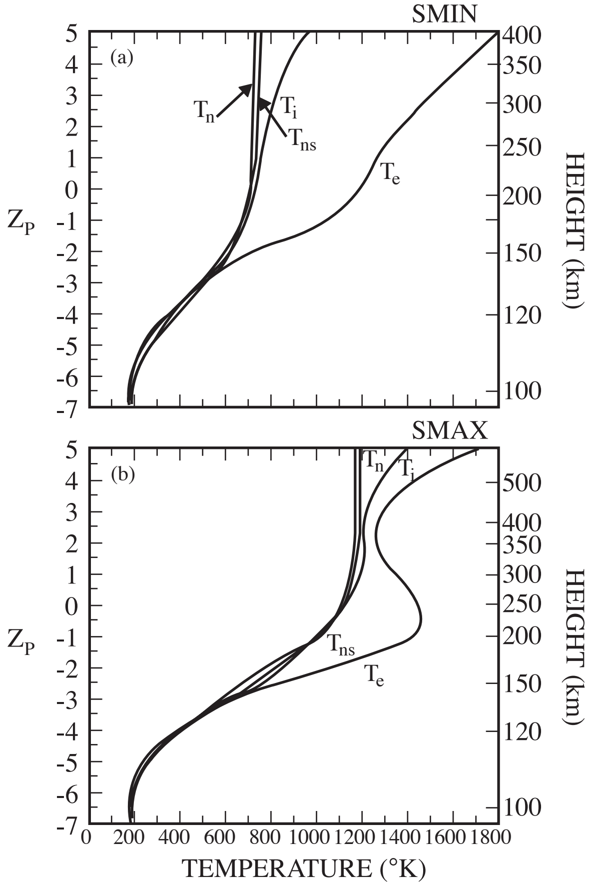
MARS, it also has an atmosphere!

Atomic oxygen is also present, as is a lot of carbon dioxide.



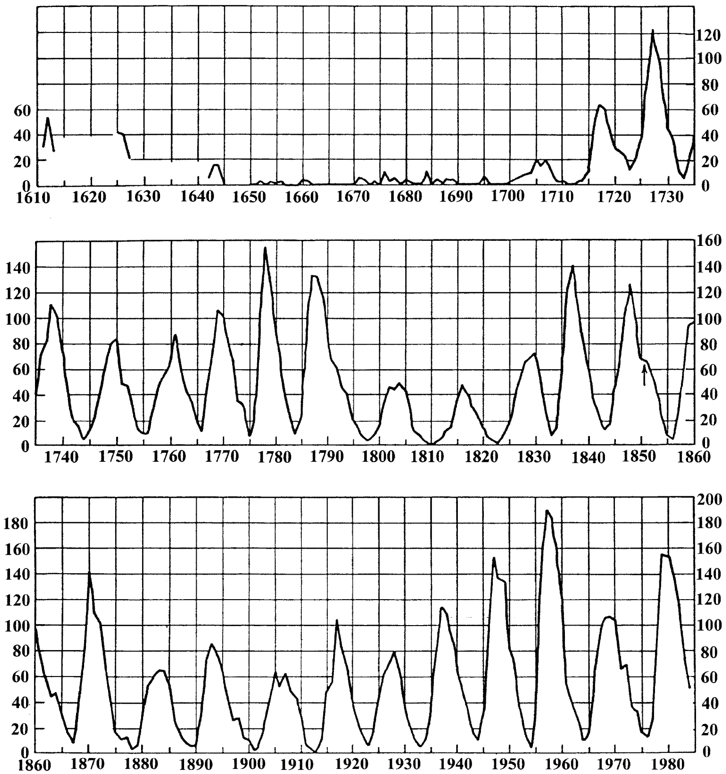
Nomenclature and simple mathematical functions for the ionosphere.

Neat fact about the ionospheres vertical profile



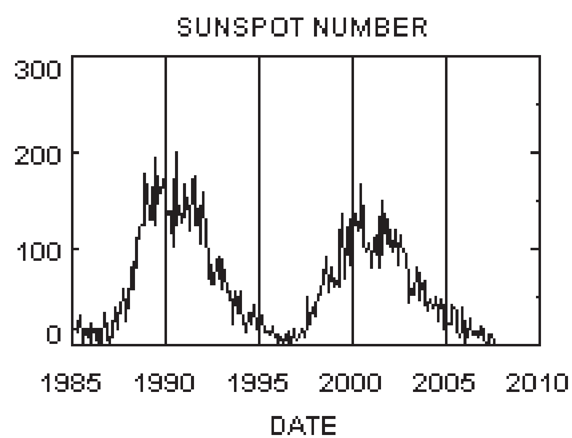
A natural coordinate for the atmosphere is the pressure level!

(a)



0
20
40
60
80
100
120
140
160
180
200
1610 1620 1630 1640 1650 1660 1670 1680 1690 1700 1710 1720 1730
1740 1750 1760 1770 1780 1790 1800 1810 1820 1830 1840 1850 1860
1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980

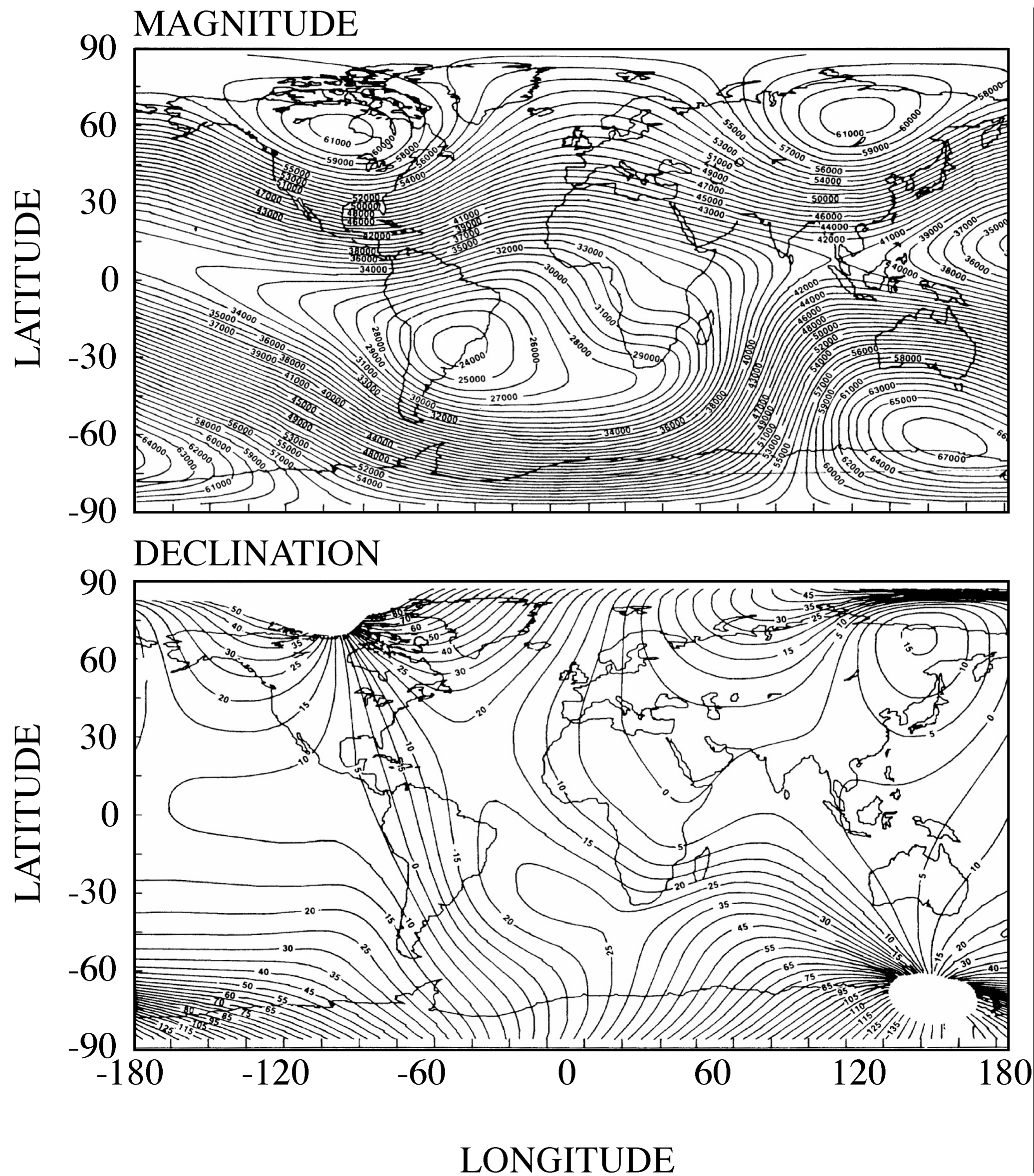
(b)

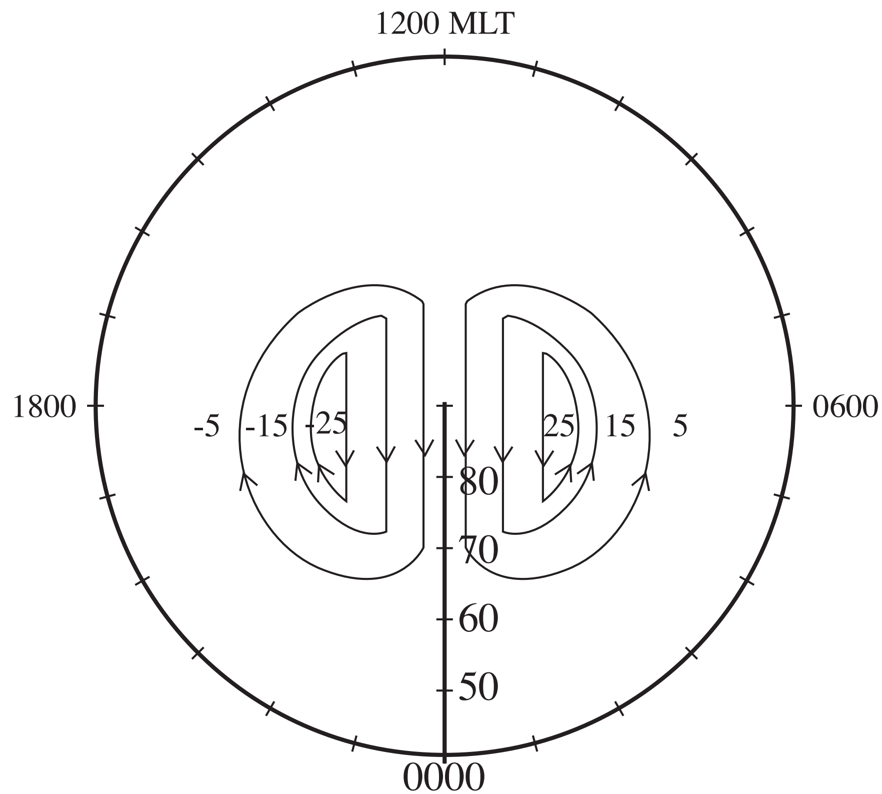


SUNSPOT NUMBER
300
200
100
0
1985 1990 1995 2000 2005 2010
DATE

The Earths magnetic field is a poor dipole!

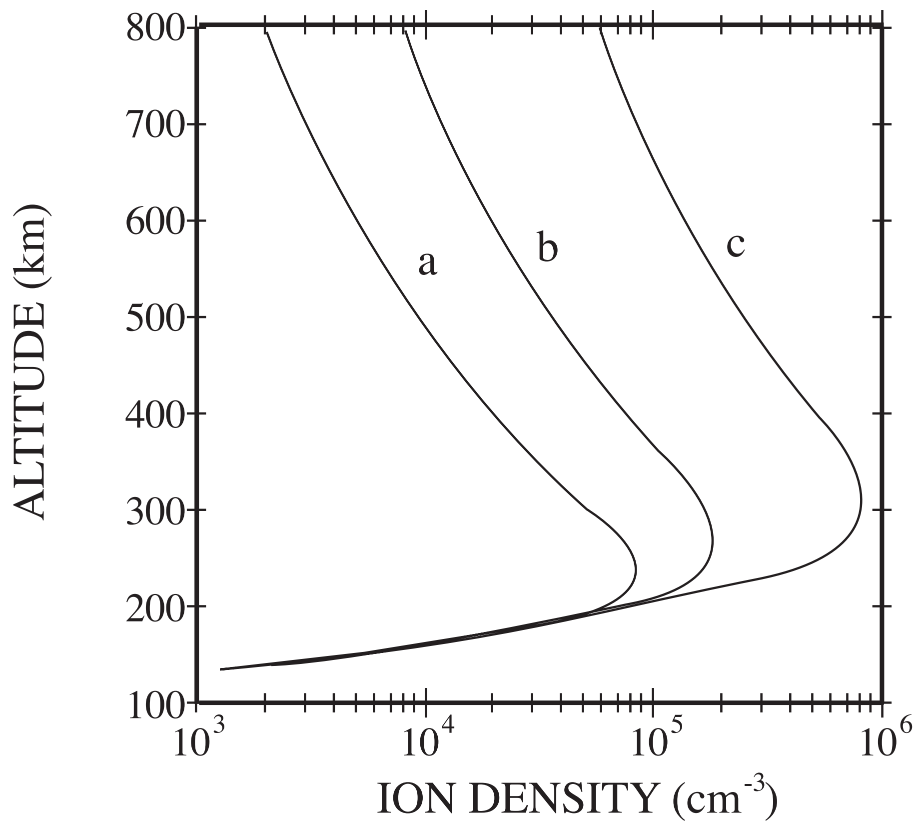
But many models still use a dipole representation!



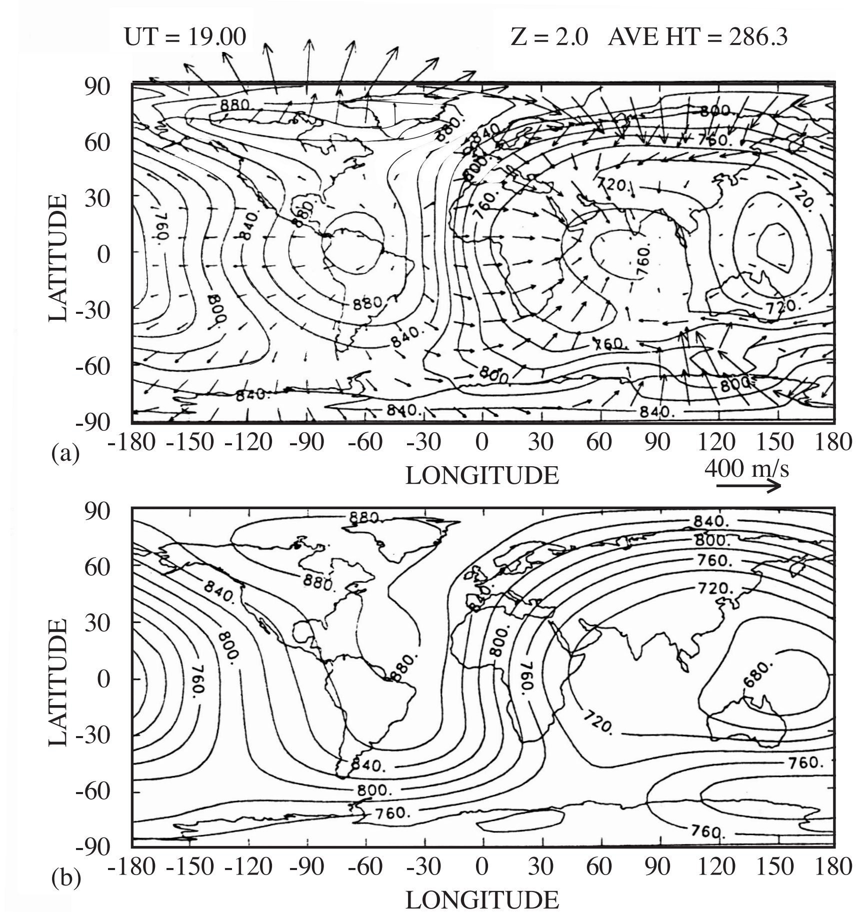


Schematic polar plot of the electric field called a 2-cell pattern.

The F-region plasma E X B drift trajectory directions are shown by the arrows.



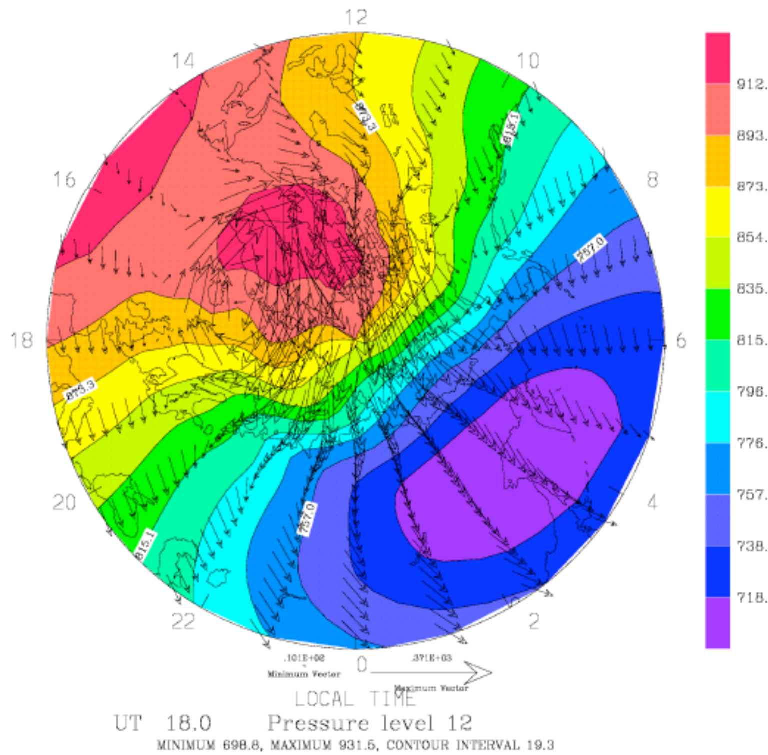
The effect of the E X B induced electric field (or wind) on the ionospheric density and profile.



Thermospheric wind field are altitude dependent and responsive to Changes in magnetospheric energy input, STORMS.

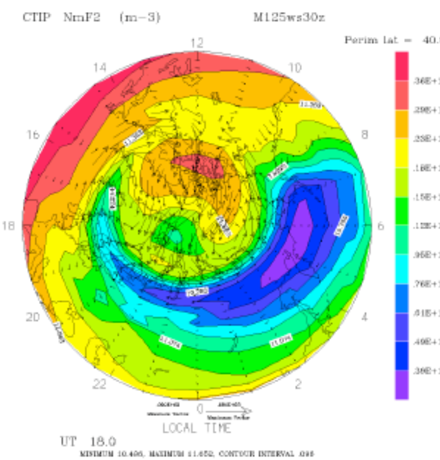
Ion-neutral collisions in upper thermosphere frequent enough to drive high velocity neutral wind

Neutral Winds and Temperature: 300 km altitude



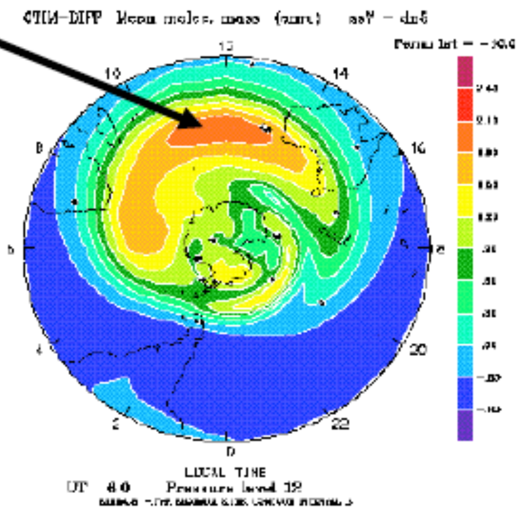
Maximum wind speed observed by DE-2 ~ 1400 m/s

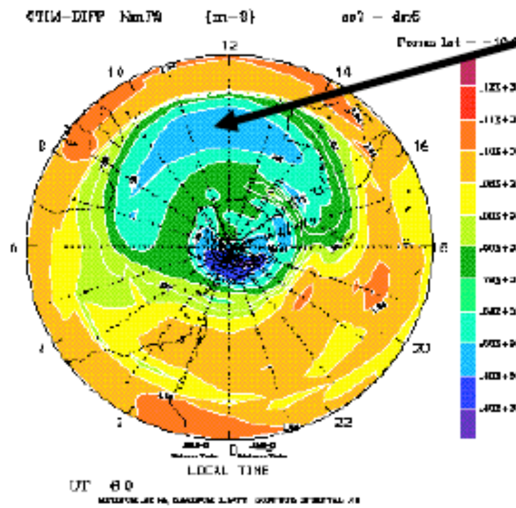
ExB ion drift and NmF2



At mid-latitudes: can be high correlation between composition changes and ion density

Increase in N_2

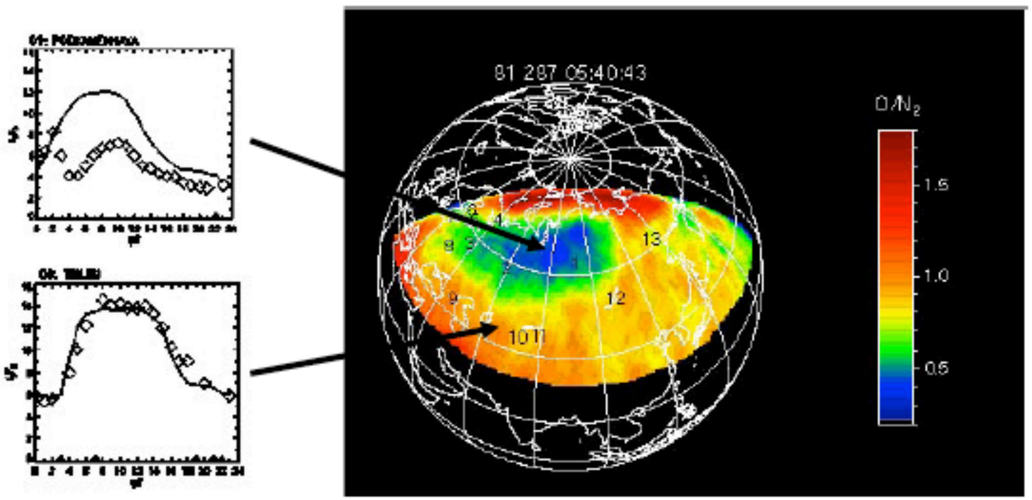


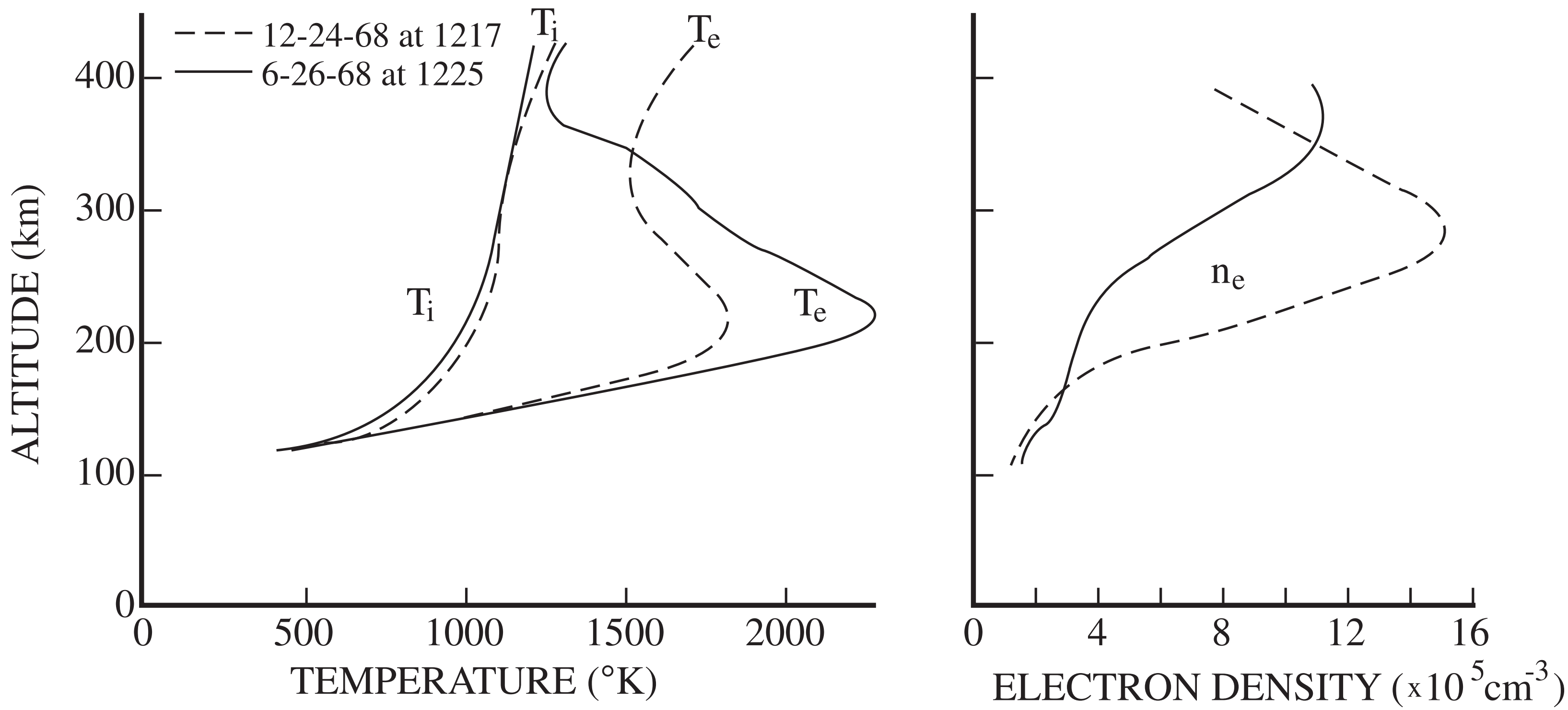


Ionospheric depletion

Modeling

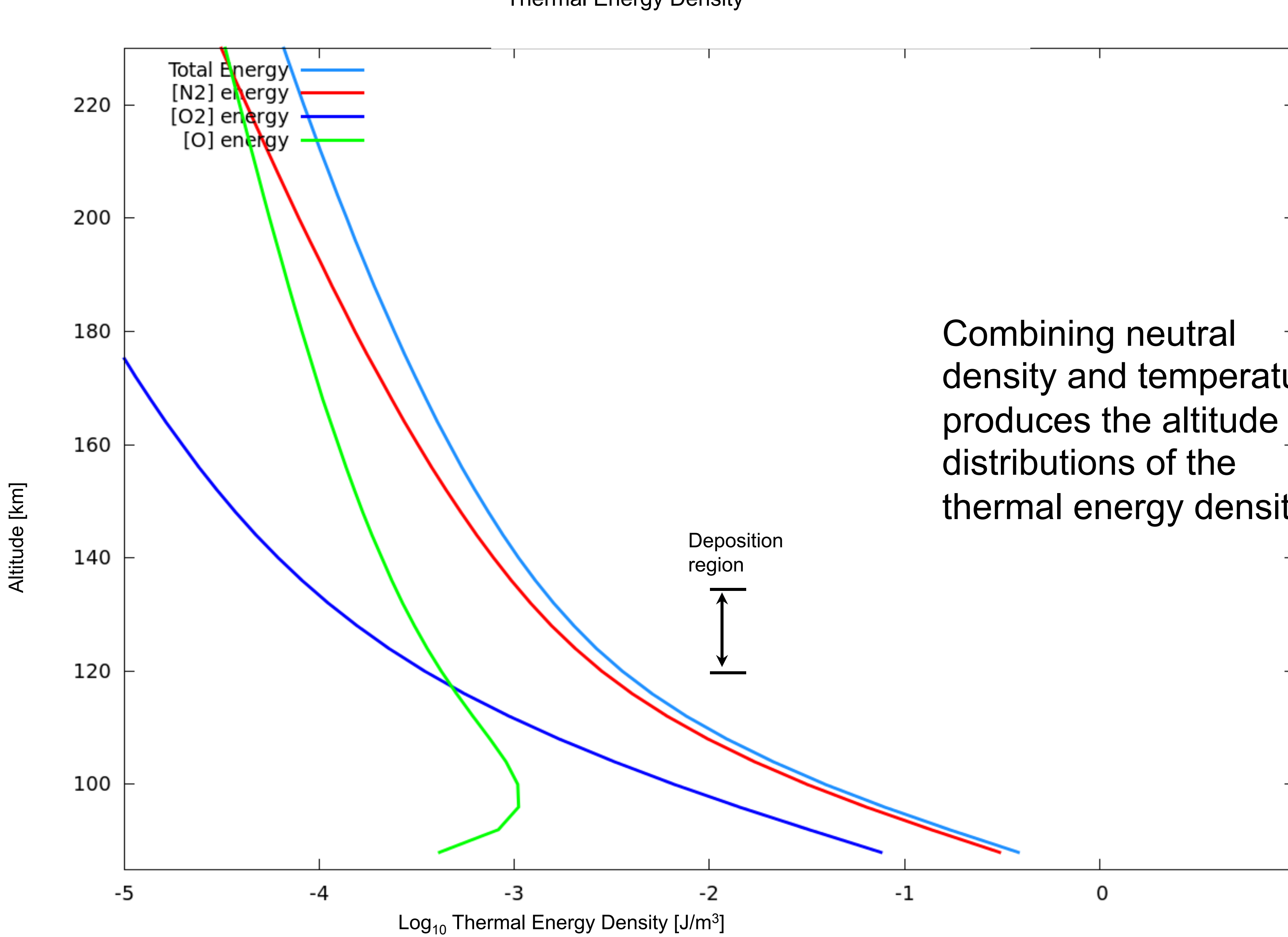
Observations





The auroral electrons precipitation leads to heating and density increases/decreases in the ionosphere

Back of envelope calculation!



Combining neutral density and temperature produces the altitude distributions of the thermal energy density.