Ionosphere-Thermosphere

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- PART I: Local I/T processes (relevance for Homework Assignments)
- PART II: Terrestrial I/T system (relevance for Laboratory Tasks)

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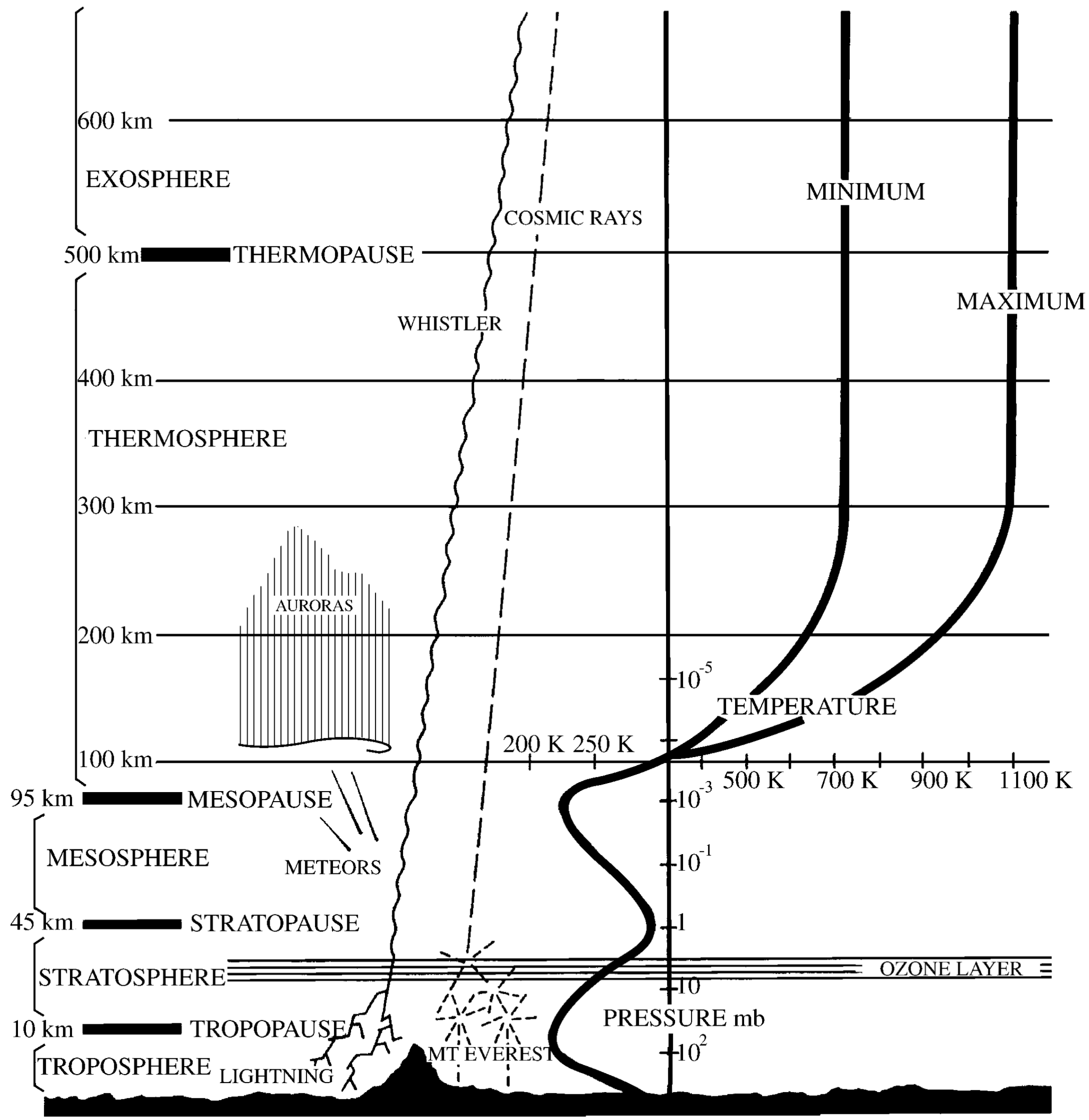
Material adopted from the following authors.

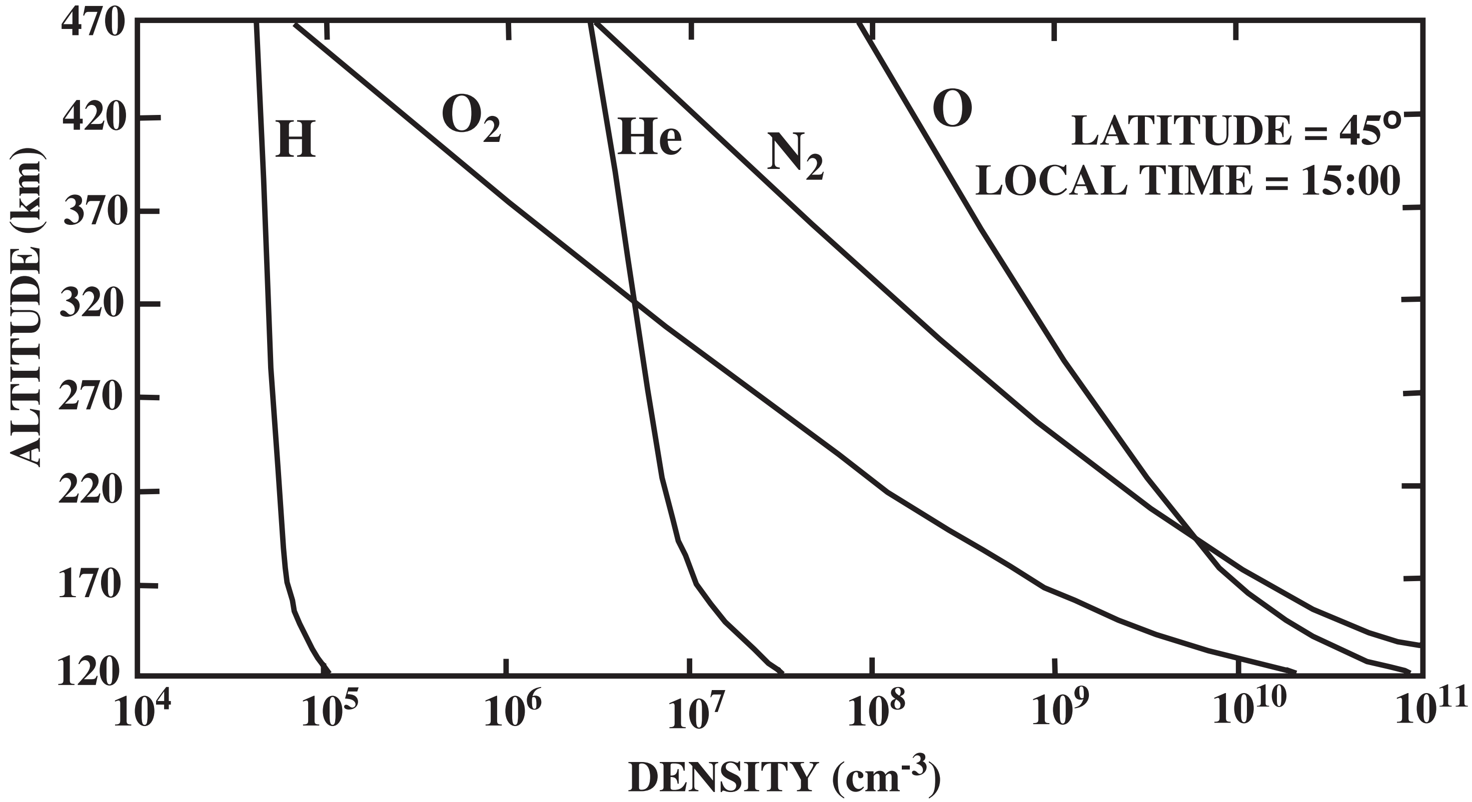
- HSS lecture notes prepared by Professor Tim Fuller-Rowell (volume 1 HSS text book)
- Robert Schunk and Andrew Nagy: their text “Ionospheres”, a Cambridge press Atmospheric and Space Science Series book.

Neutral Atmospheres

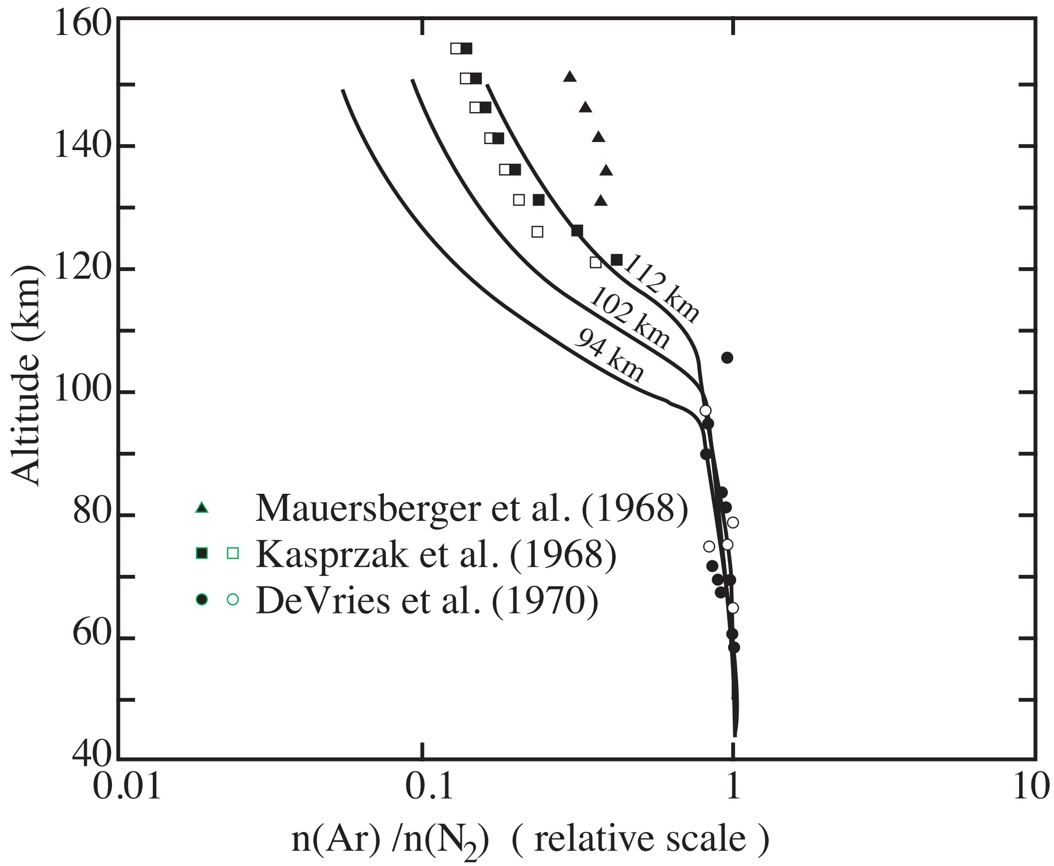
- All ionospheres exist in an atmosphere.
- The thermosphere-ionosphere forms the neutral to plasma interface between planets with atmospheres and space.
- The composition of the ionosphere is governed by the atmosphere and the ionizing radiation.
- The atmospheric dynamics influences the ionosphere.

ATMOSPHERE


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

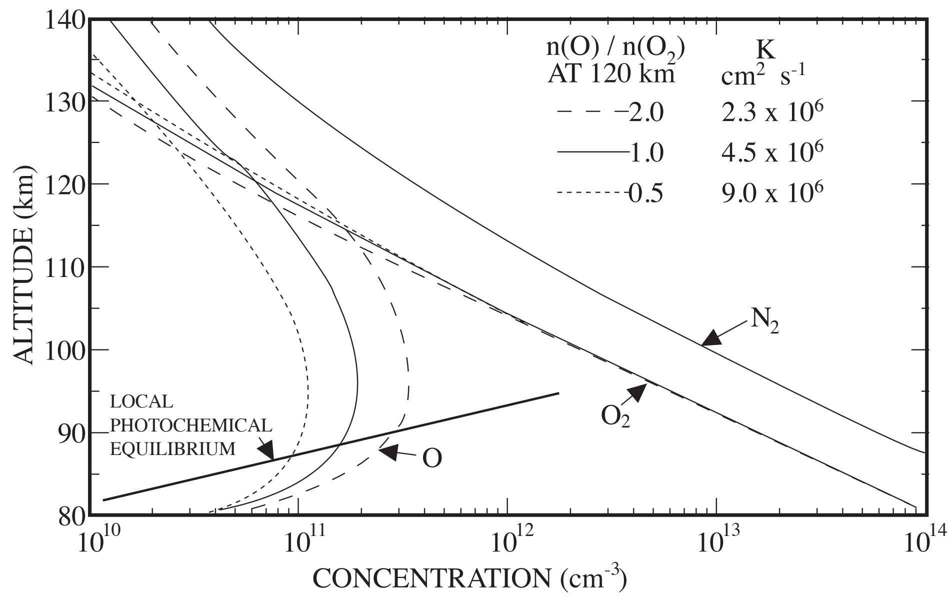


The Terrestrial Thermospheric composition: the basis for the ionosphere



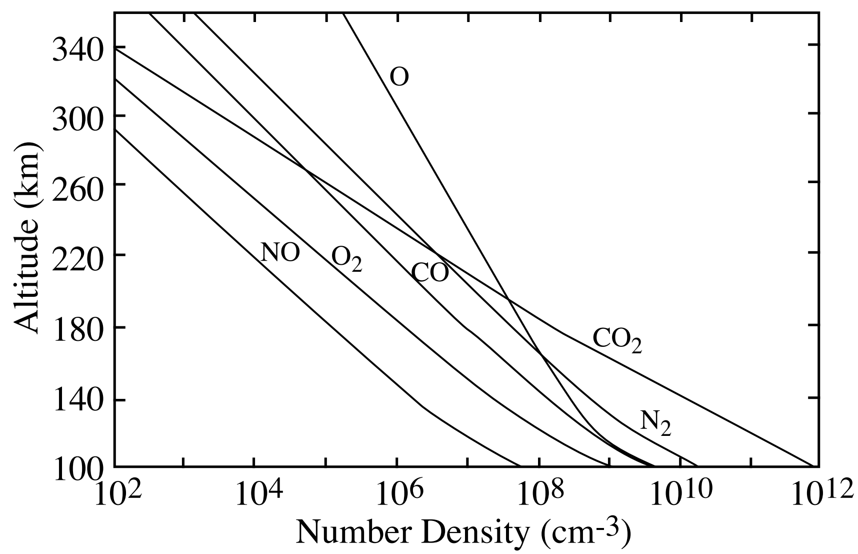
Lower atmosphere has turbulent mixing which leads to constant composition.

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



In the terrestrial upper atmosphere atomic oxygen is produced.

Atomic oxygen is associated with its own chemistry reactions.

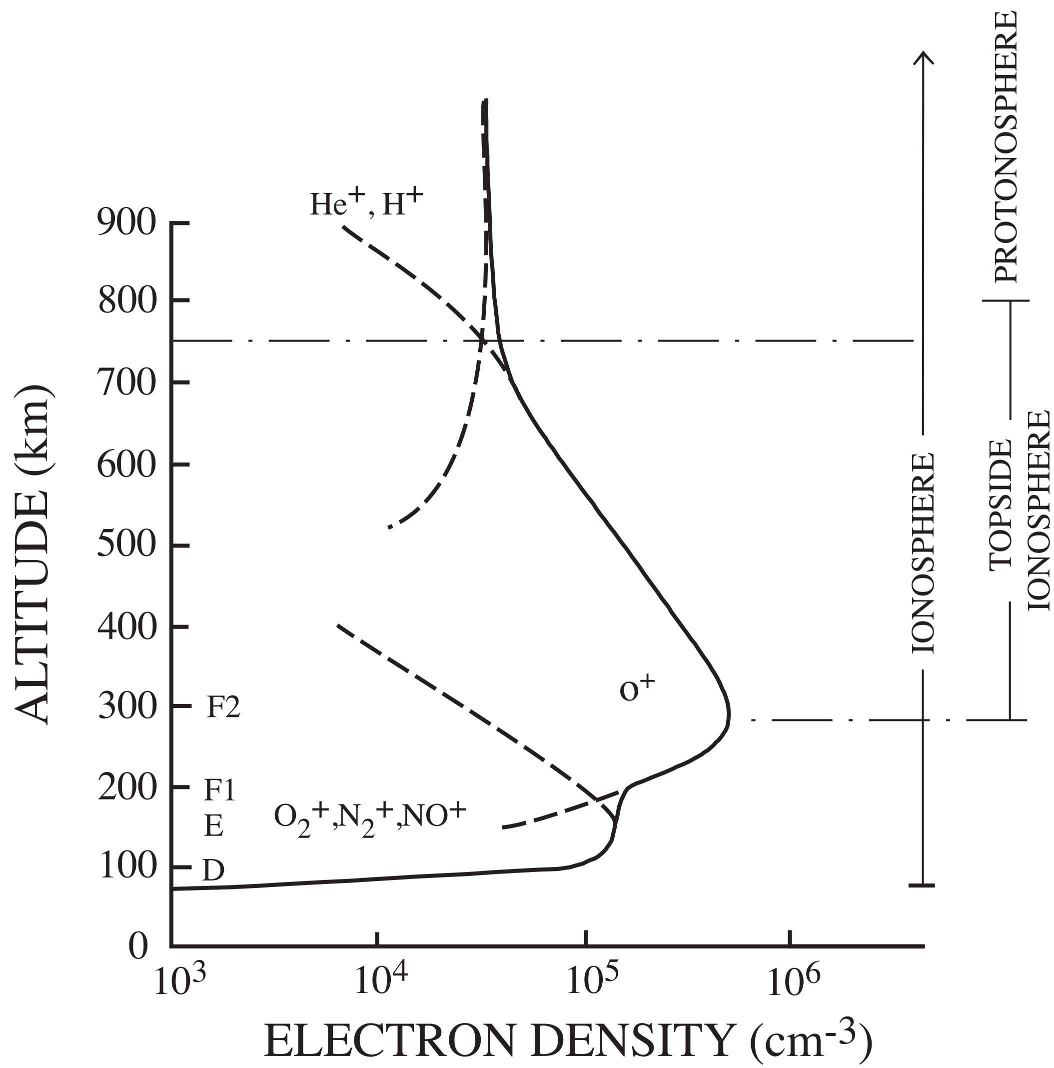


MARS, it also has an atmosphere!

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

Ionospheres

- Ionospheres exist in a neutral gas.
- The relative plasma to neutral density is variable.
- The daytime plasma is produced by solar EUV soft X-ray ionization.
- The ionosphere is electrically coupled to the magnetosphere.
- The terrestrial ionospheres natural coordinate system is the Earths magnetic field.

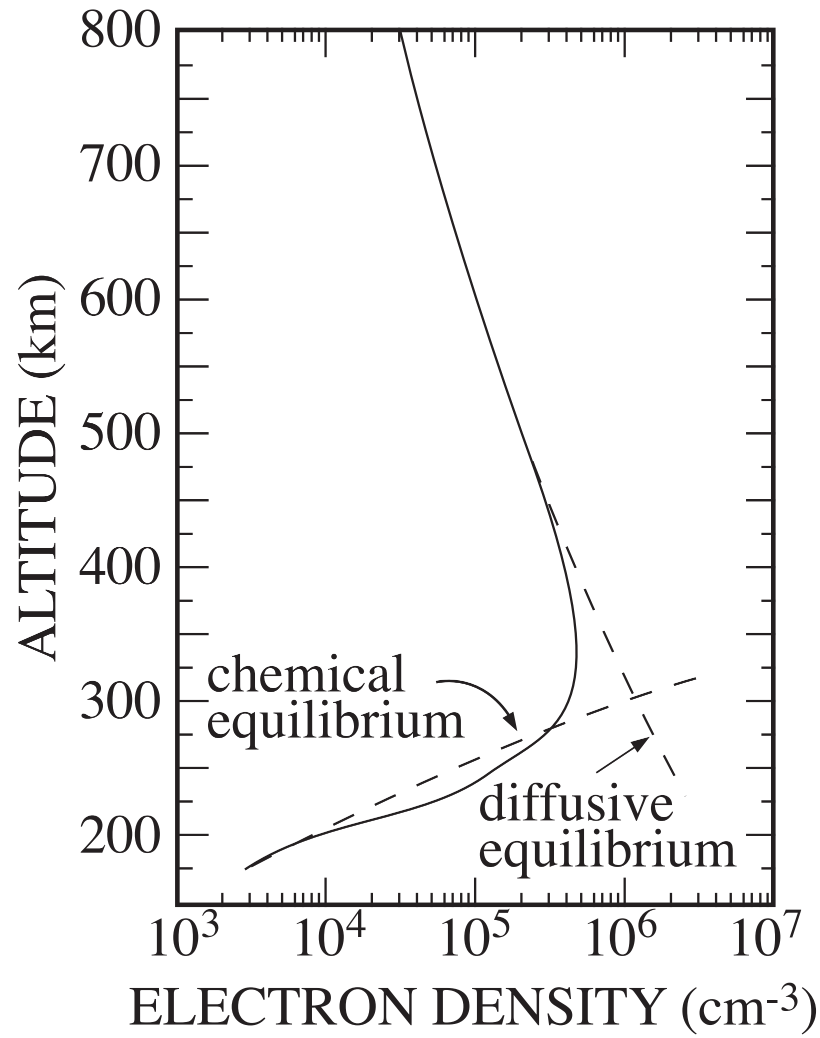


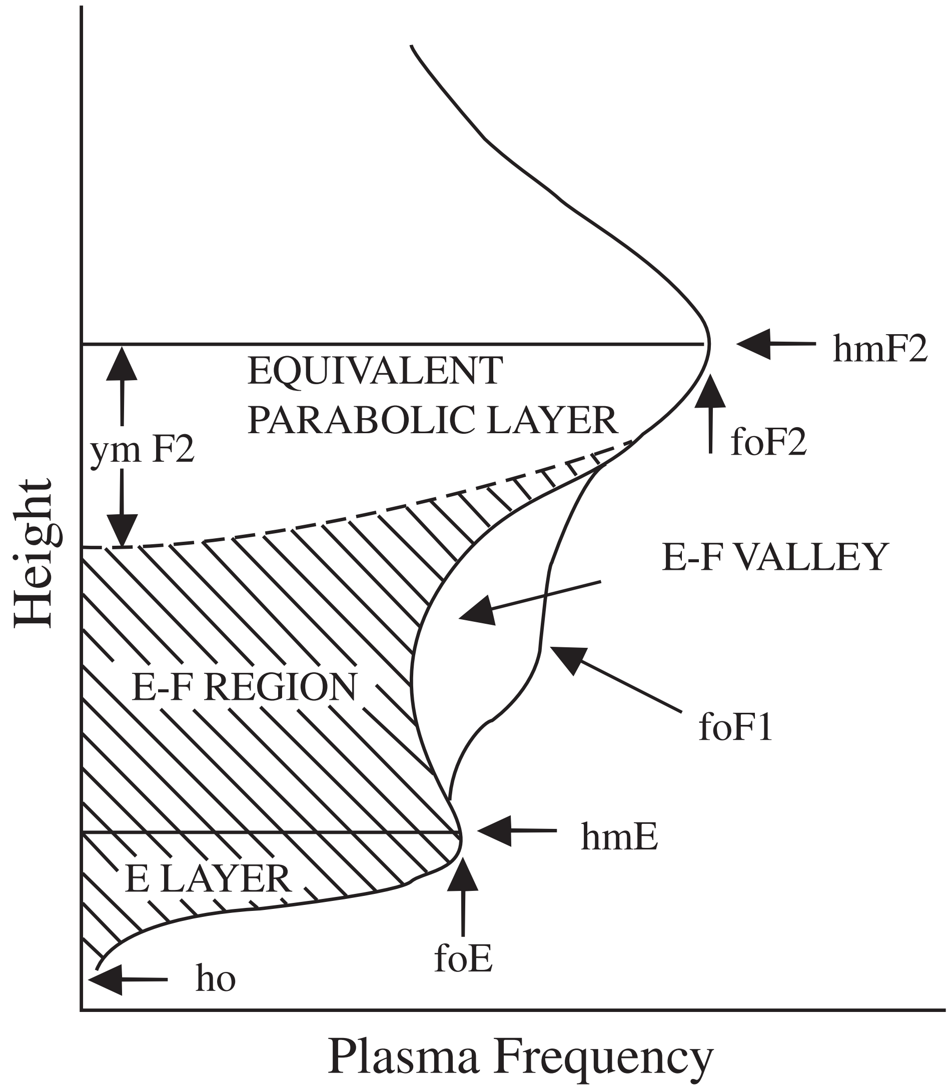
ALTITUDE (km)
900
800
700
600
500
400
300
200
100
0
10^3
10^4
10^5
10^6
ELECTRON DENSITY (cm^{-3})
He^+, H^+
O^+
O_2^+,N_2^+,NO^+
F2
F1
E
D
PROTONOSPHERE
IONOSPHERE
TOPSIDE IONOSPHERE

O+ F2 Layer

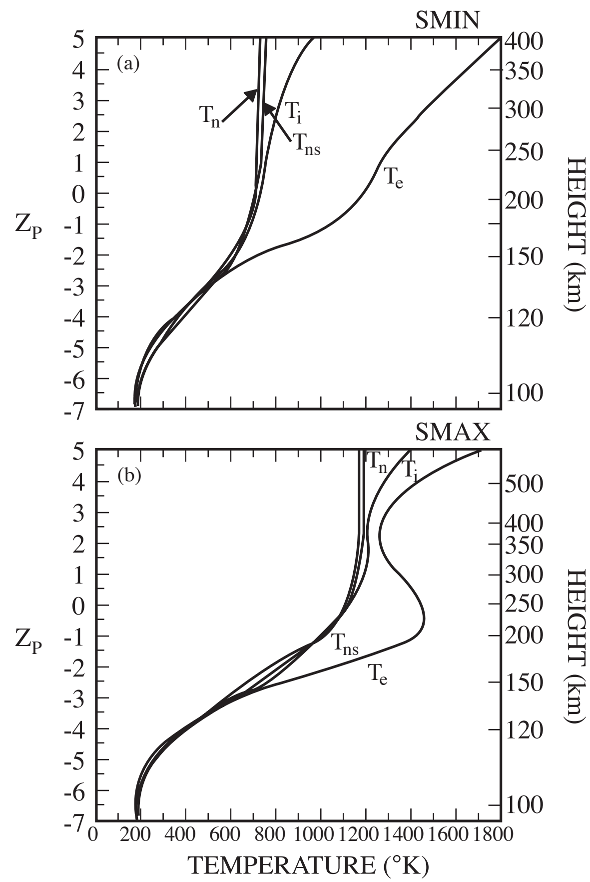
Above the peak it is in diffusive equilibrium with its plasma scale height.

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

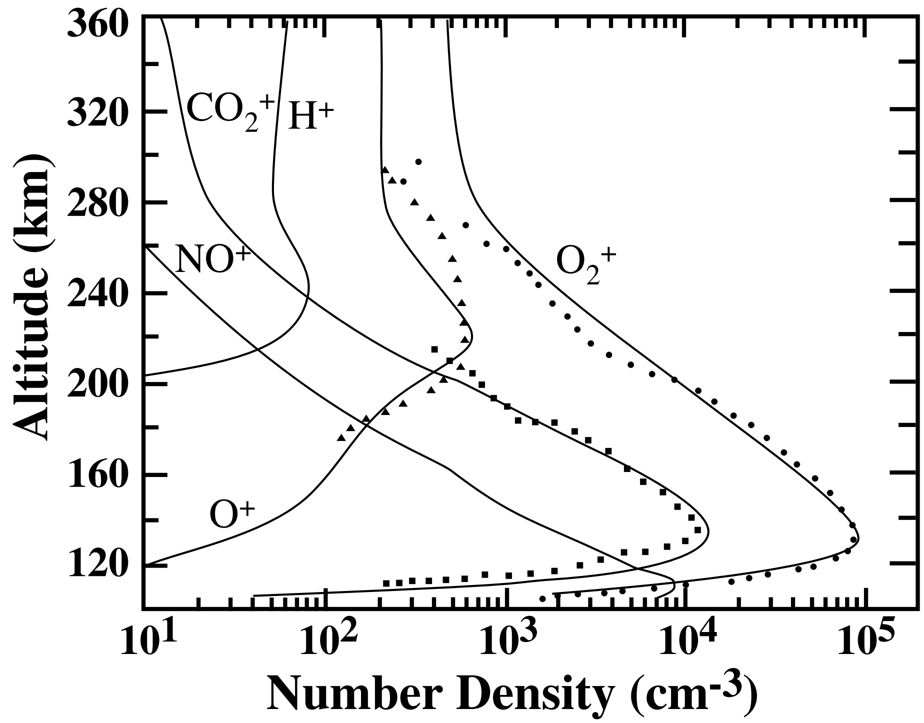




Nomenclature and simple mathematical functions for the ionosphere.



A natural coordinate for the atmosphere is the pressure level!



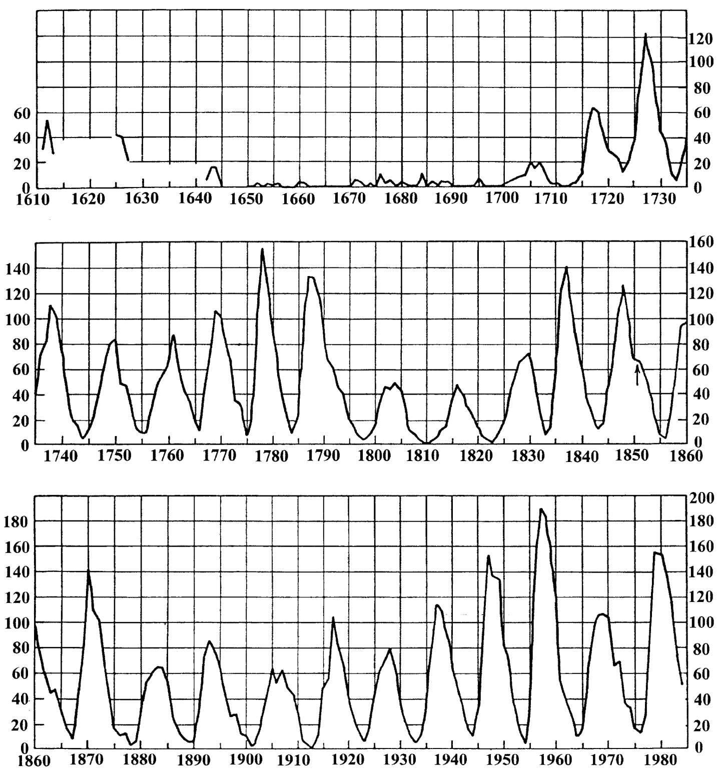
MARS has an ionosphere!

The ionosphere is dominated by the molecular ion O2+, that on the Earth would be called the E-region.

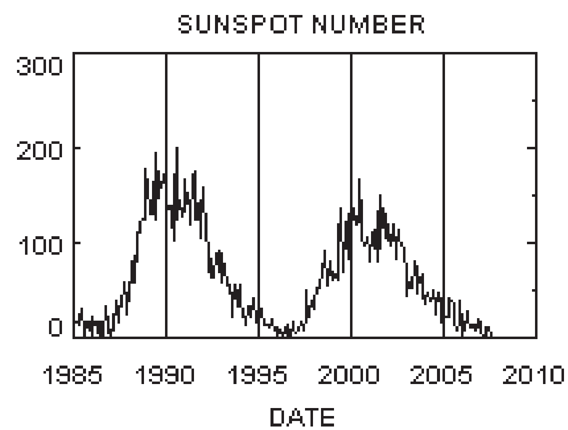
Photoionization

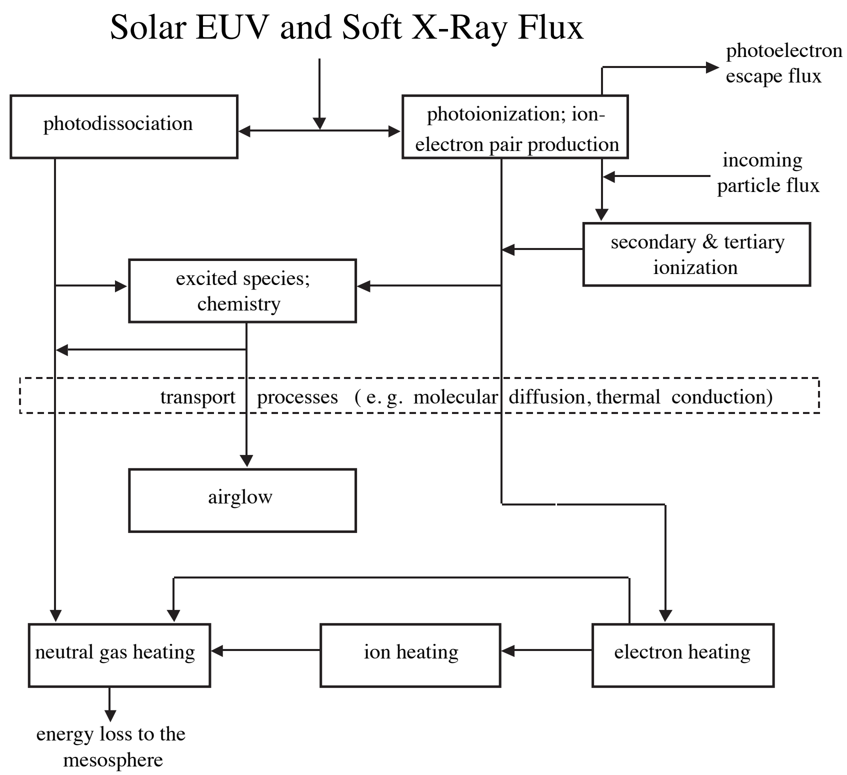
- The Solar EUV irradiance is key.
- Only recently has the short wavelength component become routinely observable.
- Proxy indices are less than satisfactory!
- NASA: satellites TIMED(SEE) and SDO(EVE) have provided high resolution spectral and now temporal information about EUV irradiance variability.

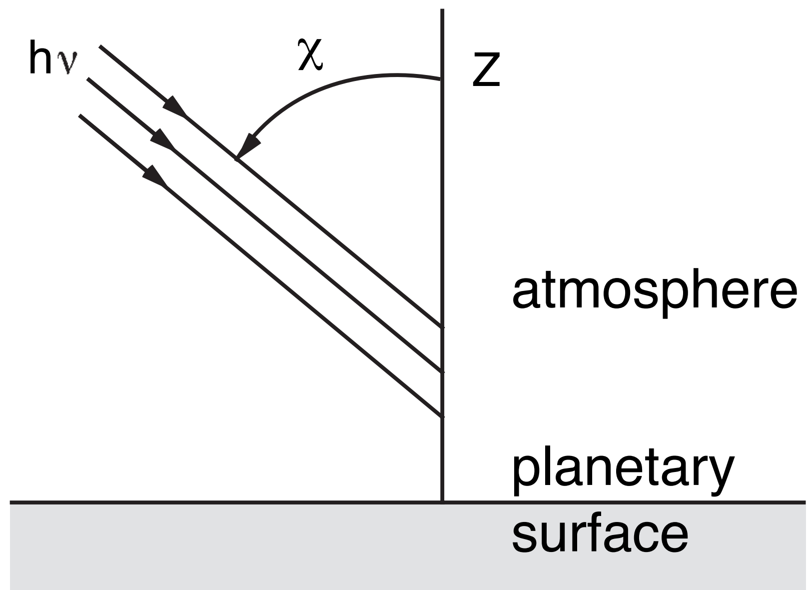
(a)


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

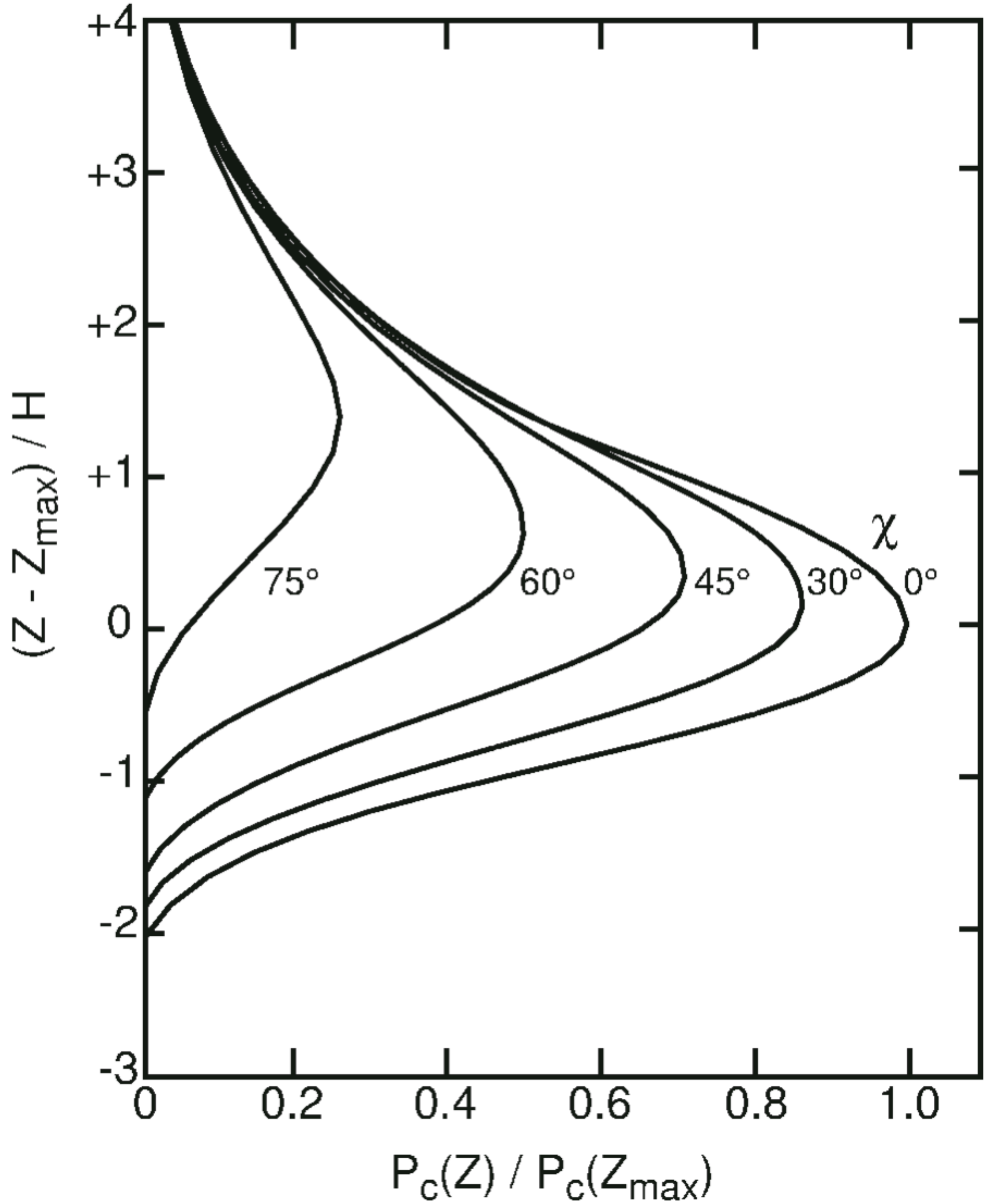
(b)


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

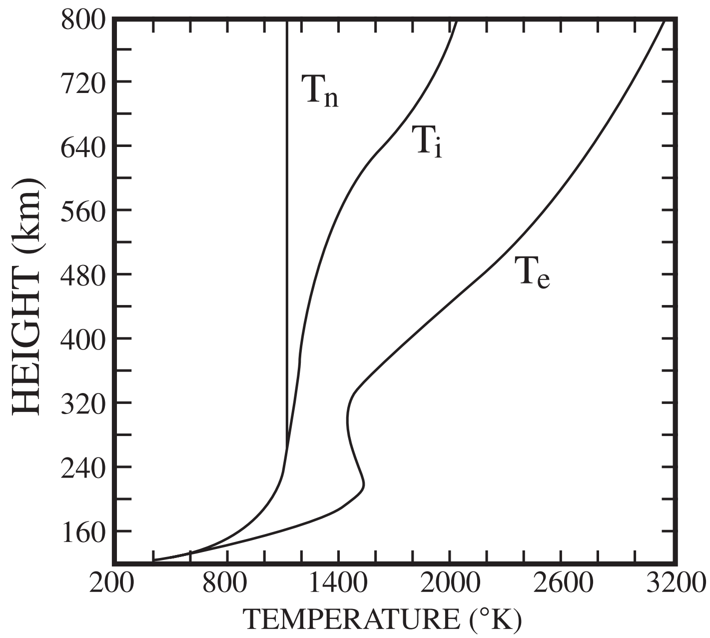

Solar EUV and Soft X-Ray Flux
photoelectron escape flux
photodissociation
photoionization; ion-electron pair production
incoming particle flux
secondary & tertiary ionization
excited species; chemistry
transport processes (e. g. molecular diffusion, thermal conduction)
airglow
neutral gas heating
ion heating
electron heating
energy loss to the mesosphere

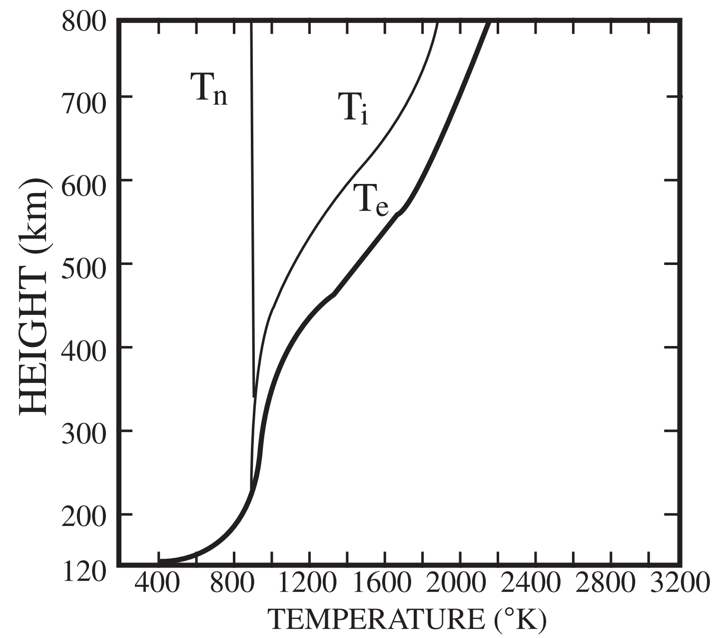


Solar Zenith angle geometry



+4
+3
+2
+1
0
-1
-2
-3
(Z - Z$_{max}$) / H
75°
60°
45°
30°
0°
χ
0
0.2
0.4
0.6
0.8
1.0
P$_c$(Z) / P$_c$(Z$_{max}$)

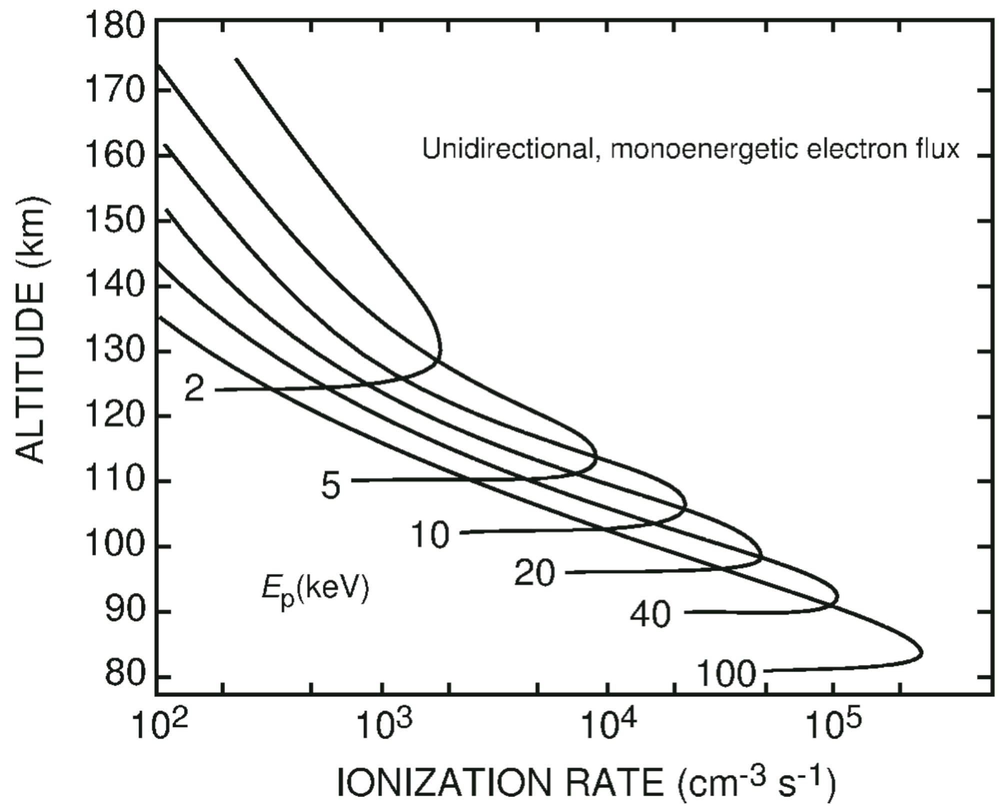




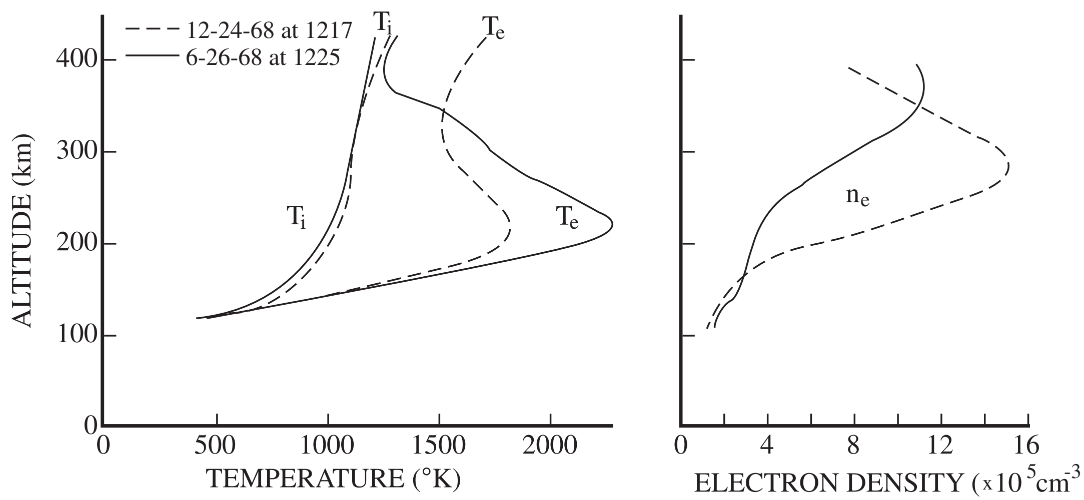
Daytime thermal profiles for the thermosphere and ionosphere at Millstone Hill, MA.
A midlatitude location: left panel 14:22 LT, right panel 02:22 LT at equinox in 1970.

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).



The altitude of ionization depends upon the energy of the auroral particles



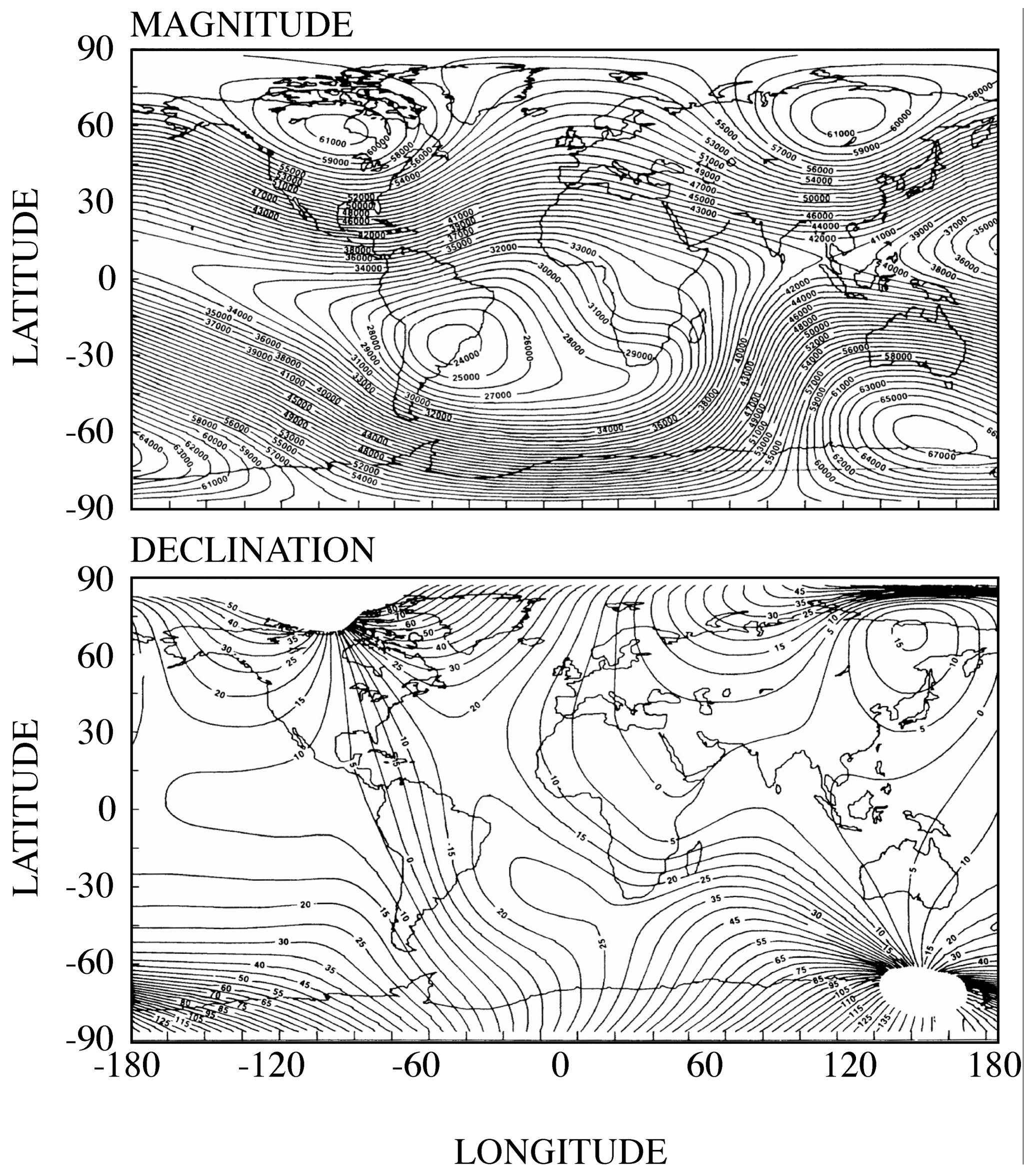
The auroral electrons precipitation leads to heating and density increases in the ionosphere

Electric Fields and Winds

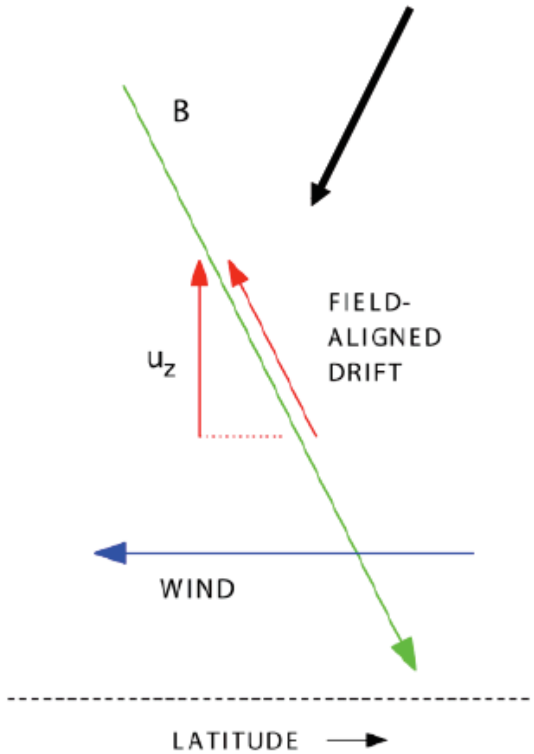
- In the F-region the electric field and neutral winds can induce plasma drifts to raise and lower the F-Layer.
- This modifies the plasma diffusion balance and hence density and profile shape.
- The ionosphere also corotates.
- At all latitude E X B can transport plasma perpendicular to the magnetic field line.

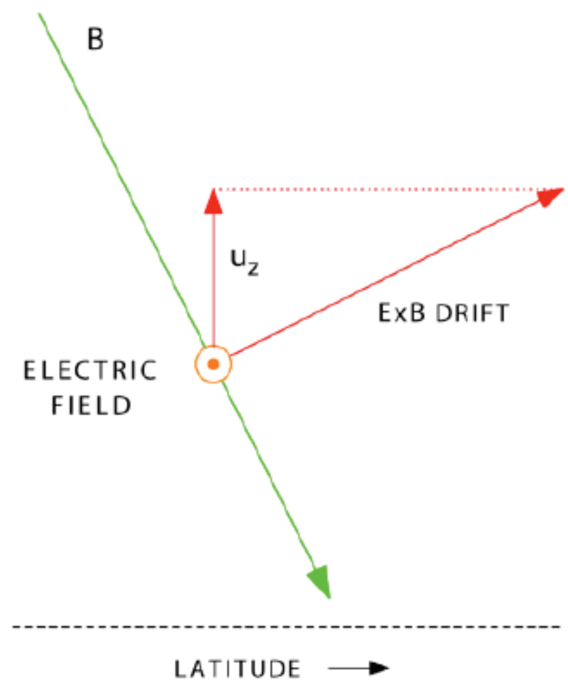
The Earths magnetic field is a poor dipole!

But many models still use a dipole representation!

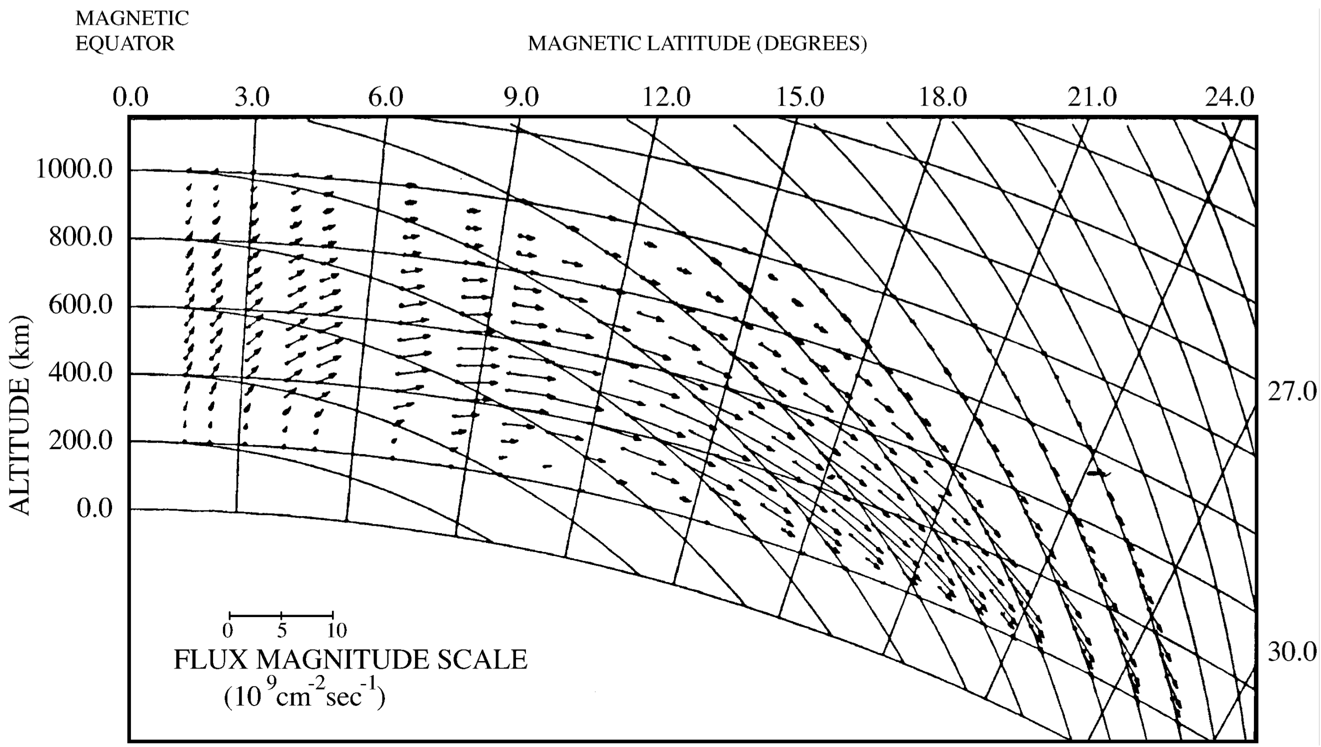


Equatorward wind at mid latitudes with inclined magnetic field pushes plasma upward along the magnetic field direction to regions of different neutral composition

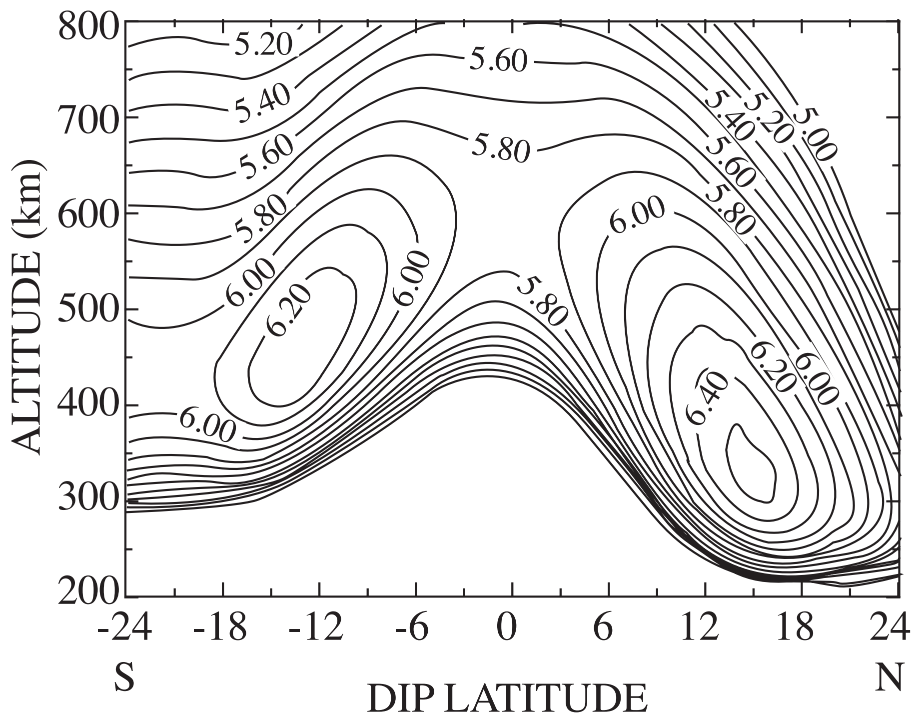




An Eastward Electric field together with the magnetic field creates an upward plasma drift.

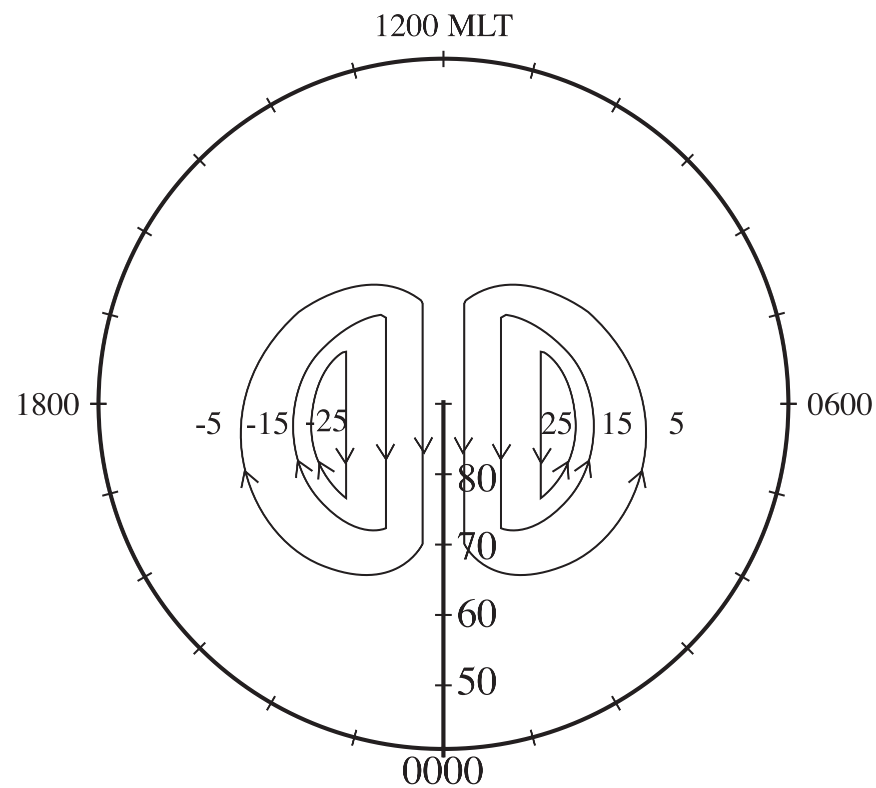


The low latitude day time ionosphere is dominated by transport caused by the Eastward electric field. This results in plasma redistribution and the formation of the Appleton Anomaly (equatorial anomaly).



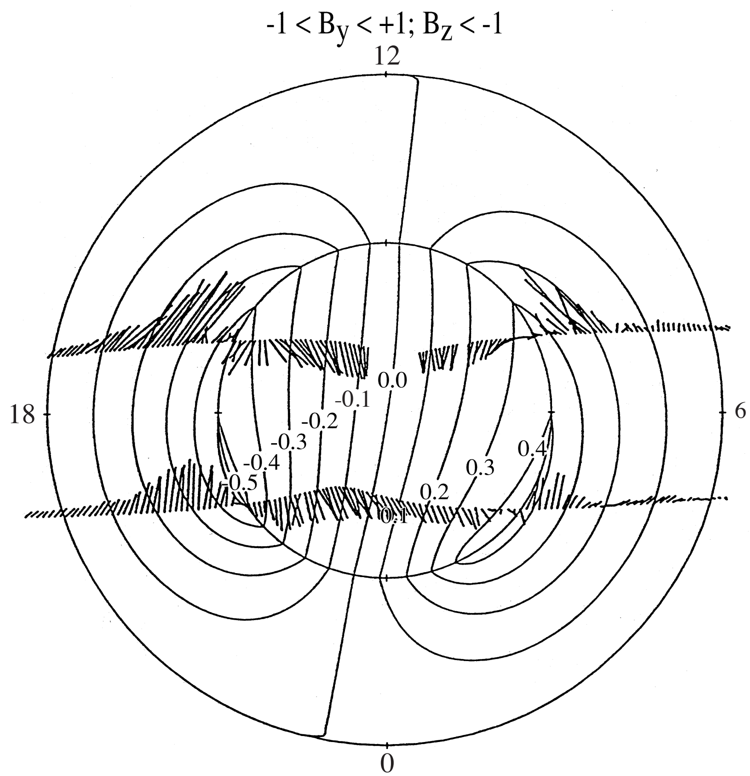
The Appleton anomalies also known as the Equatorial anomalies.

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

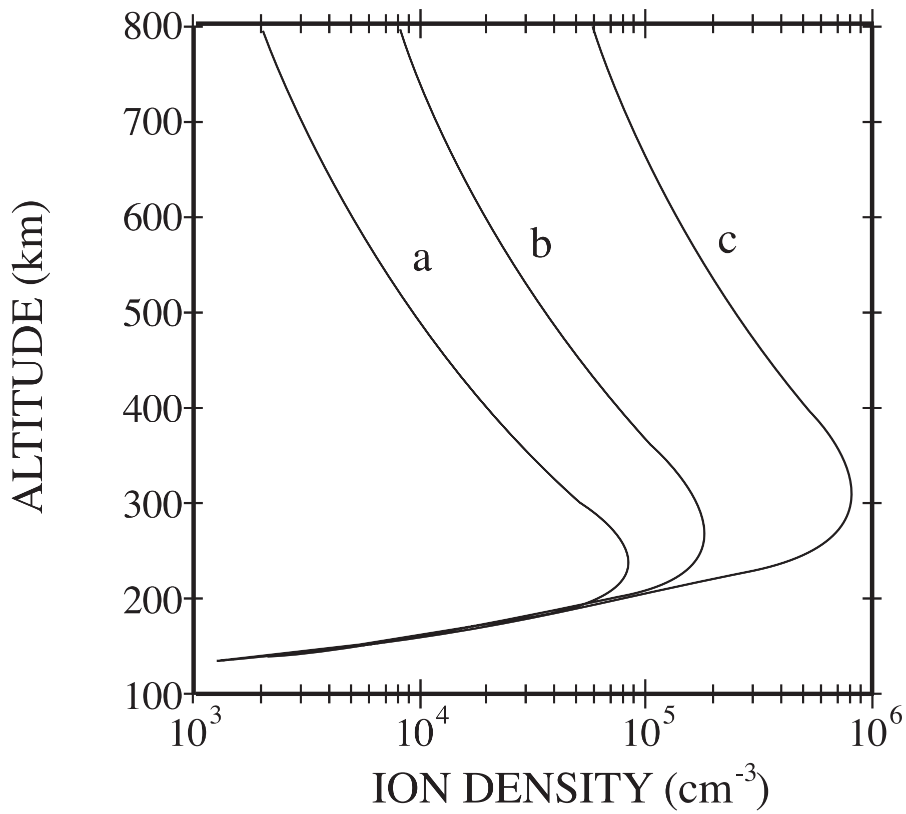


Schematic polar plot of the electric field called a 2-cell pattern.

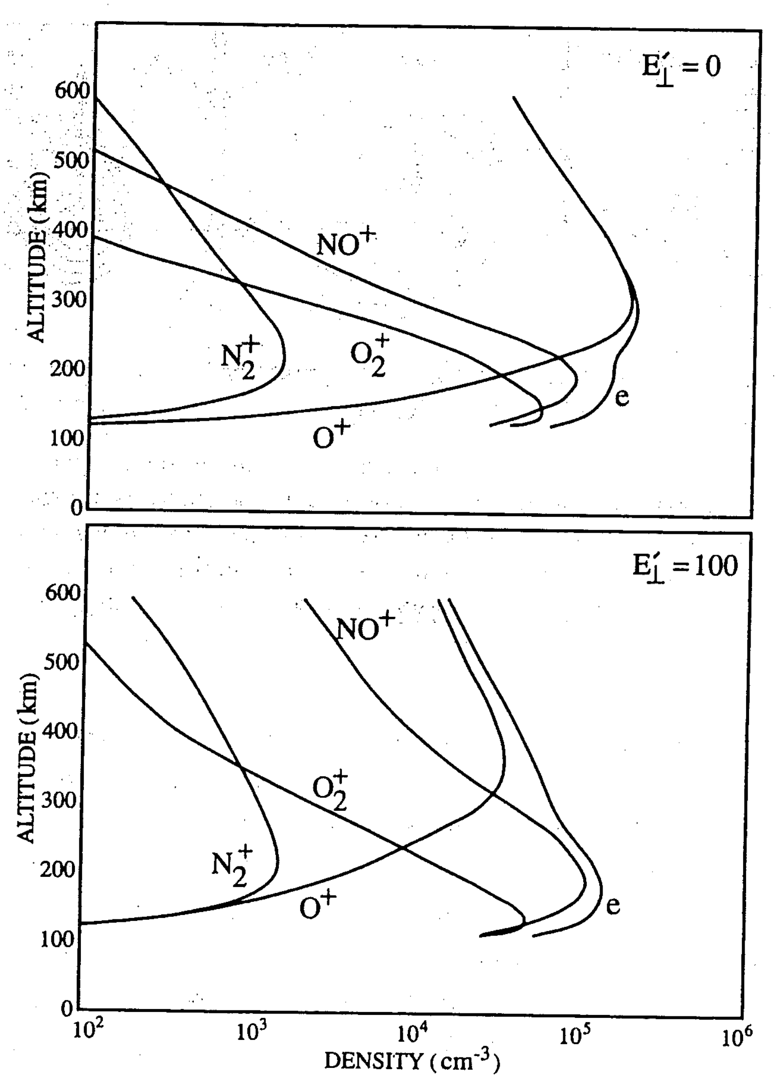
The F-region plasma E X B drift trajectory directions are shown by the arrows.



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



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

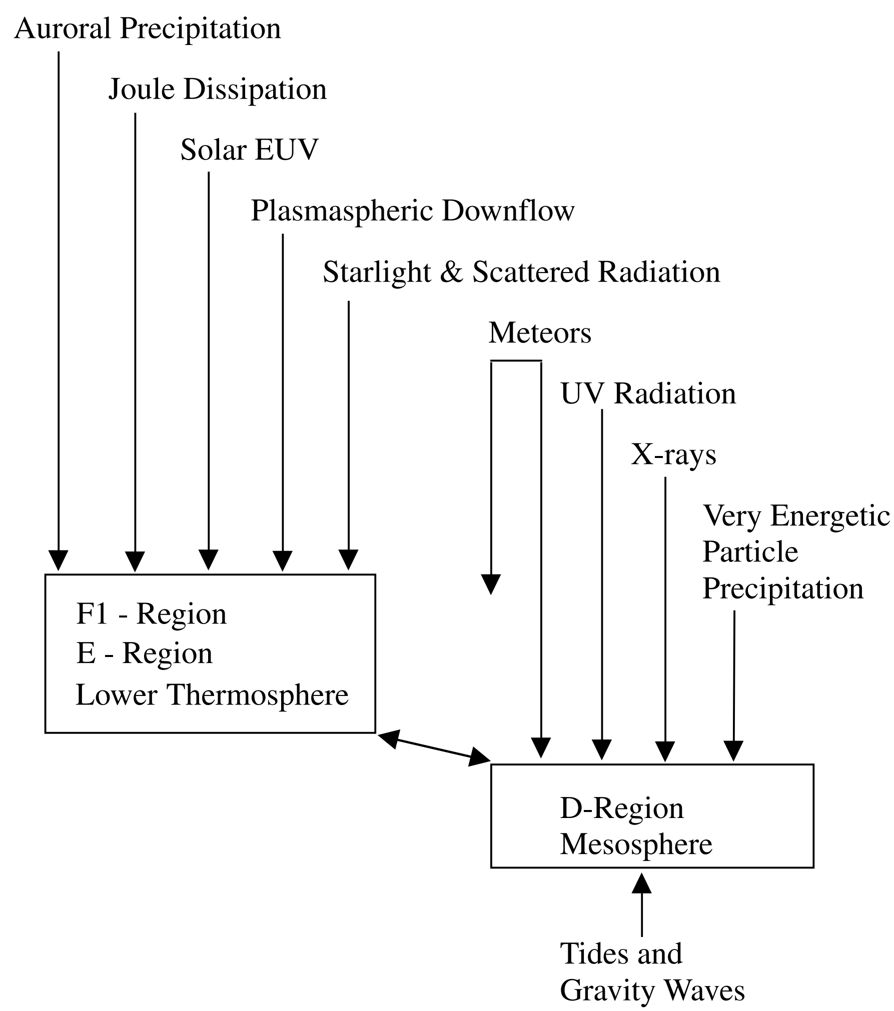


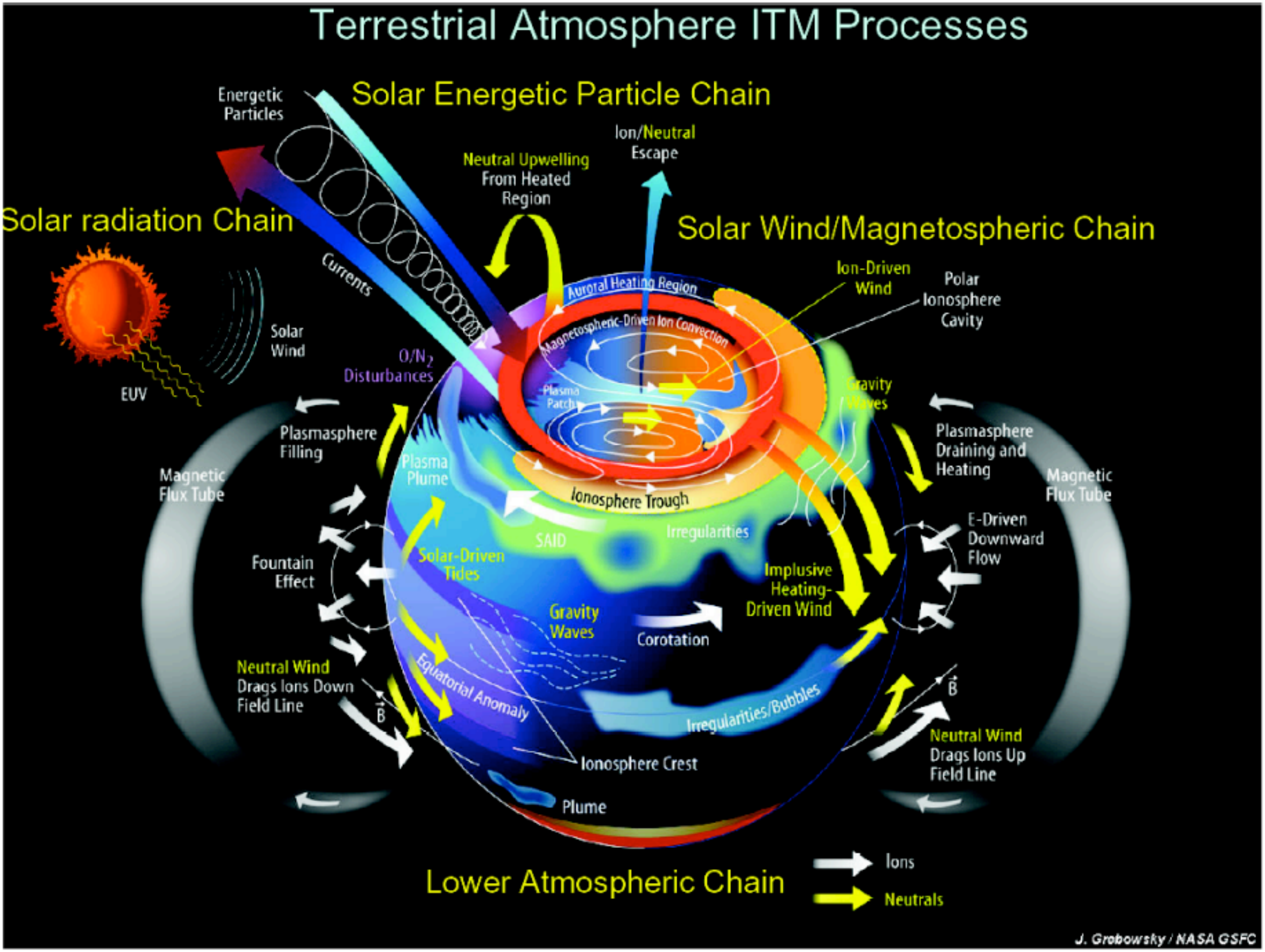
O+ F2-layer is the dominant ionospheric layer under quiet geomagnetic conditions.

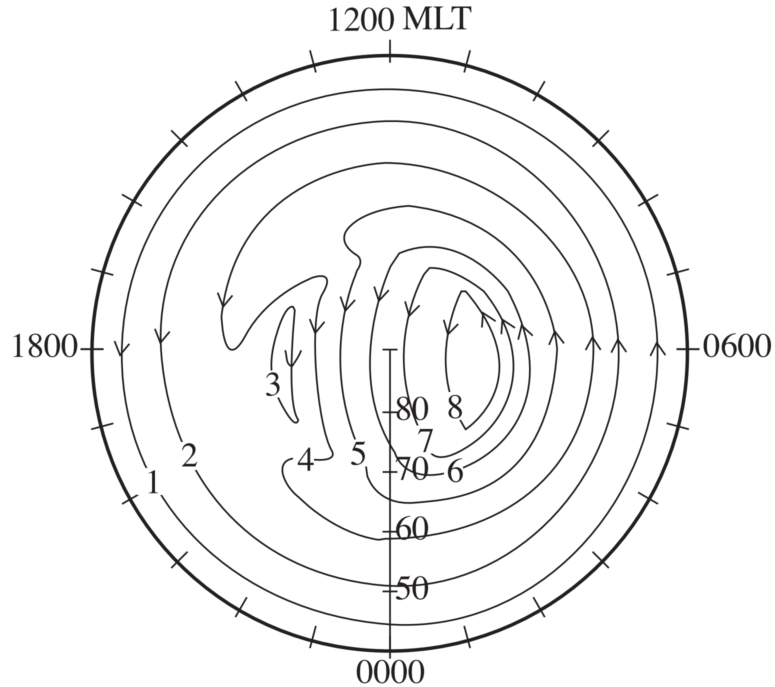
However, during very disturbed geomagnetic conditions the rapid conversion of O+ into NO+ leads to a E/F1 layer becoming dominant.

PART-II

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


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

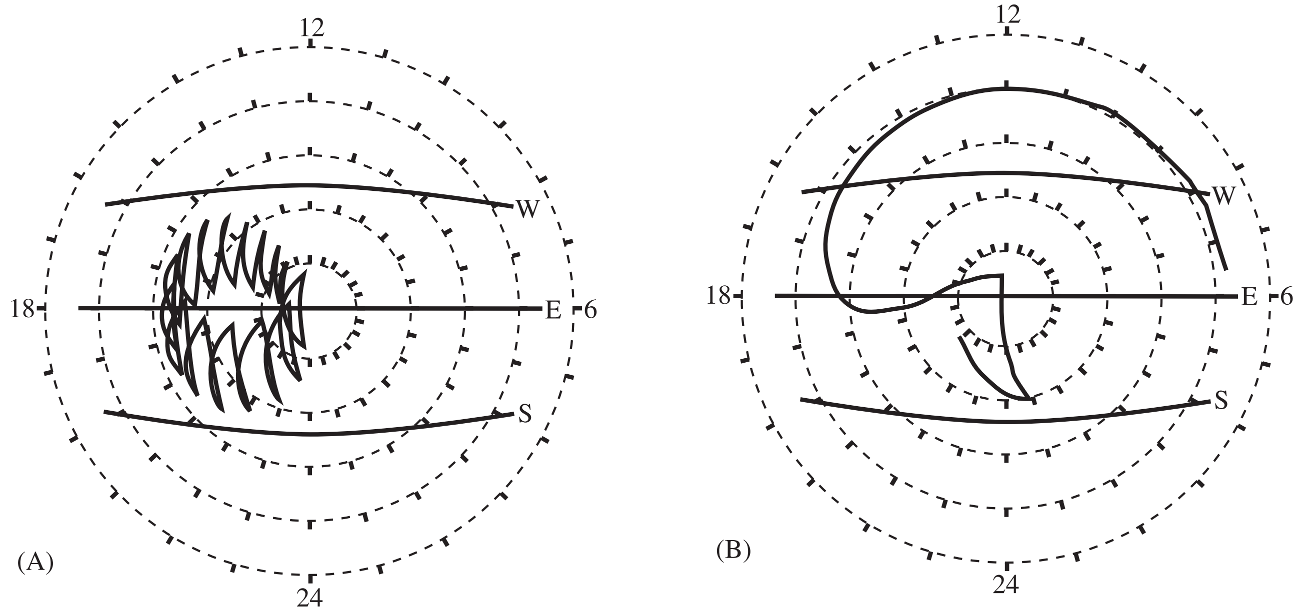


LABEL	1	2	3	4	5	6	7	8
CIRCULATION PERIOD (day)	1.00	1.01	0.10	1.34	0.50	0.31	0.18	0.11

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

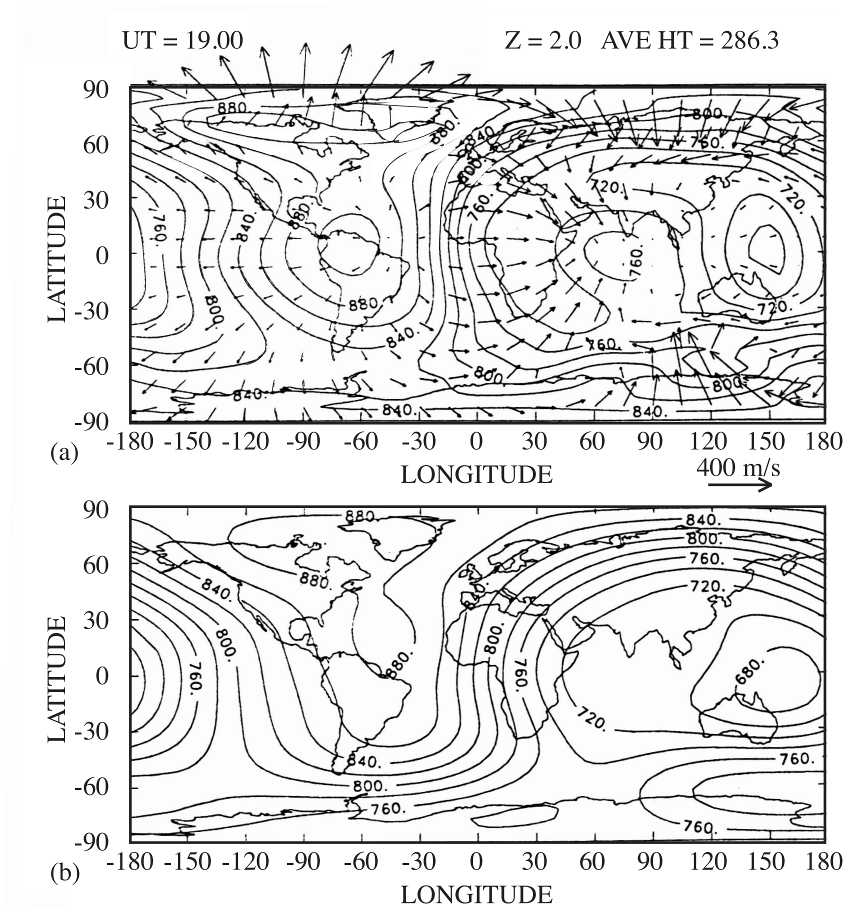
The ionosphere co-rotates, implying an E field, and then the magnetosphere's E field maps into the ionsophere and an atmospheric dynamo generated yet Another E field.

GEOGRAPHIC LOCAL TIME COORDINATES



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

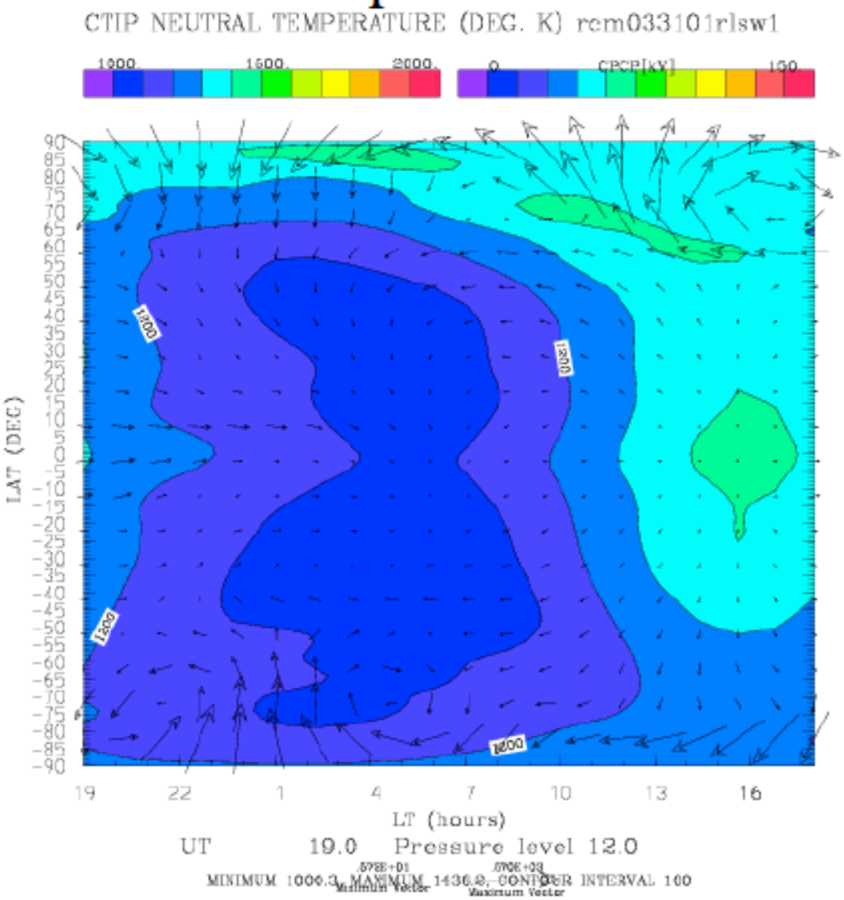
This means that a ground based observatory at high latitudes is not monitoring the same plasma flux tube continually, and hence the observer is not seeing the plasma evolution!



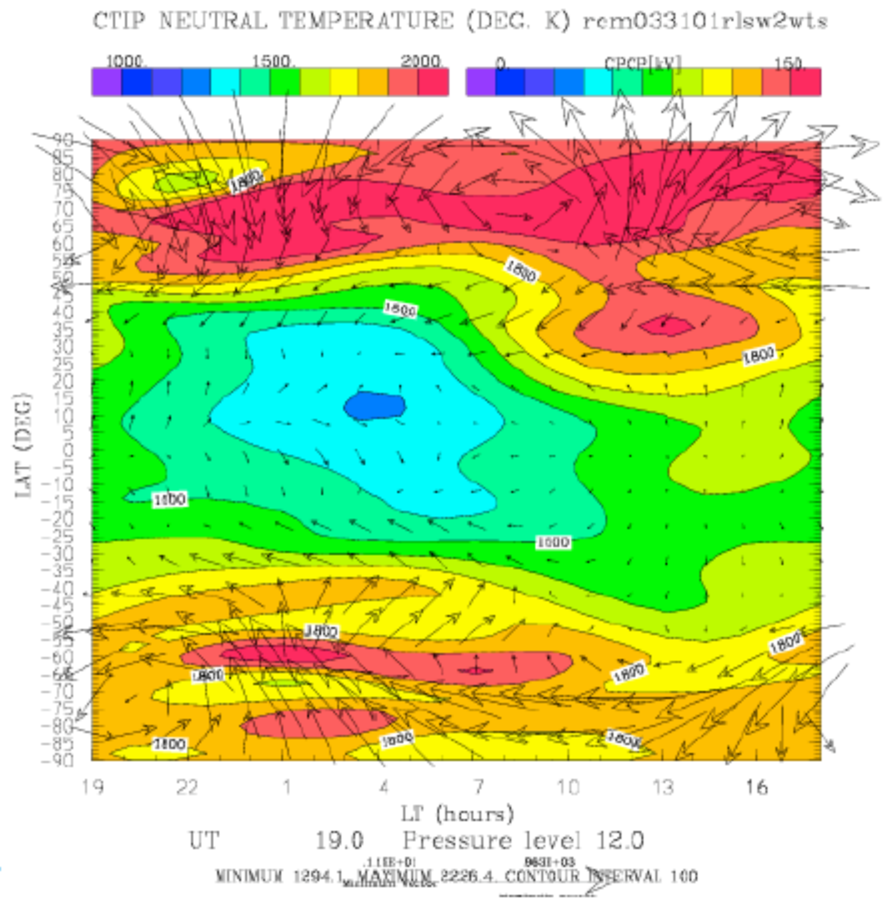
Thermospheric wind field are altitude dependent and responsive to Changes in magnetospheric energy input, STORMS.

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

quiet



disturbed



Energy Flow

magnetospheric energy
500 - 1000 GW

particle precipitation <20%

heat, ionization, airglow e.g. auroral illumination

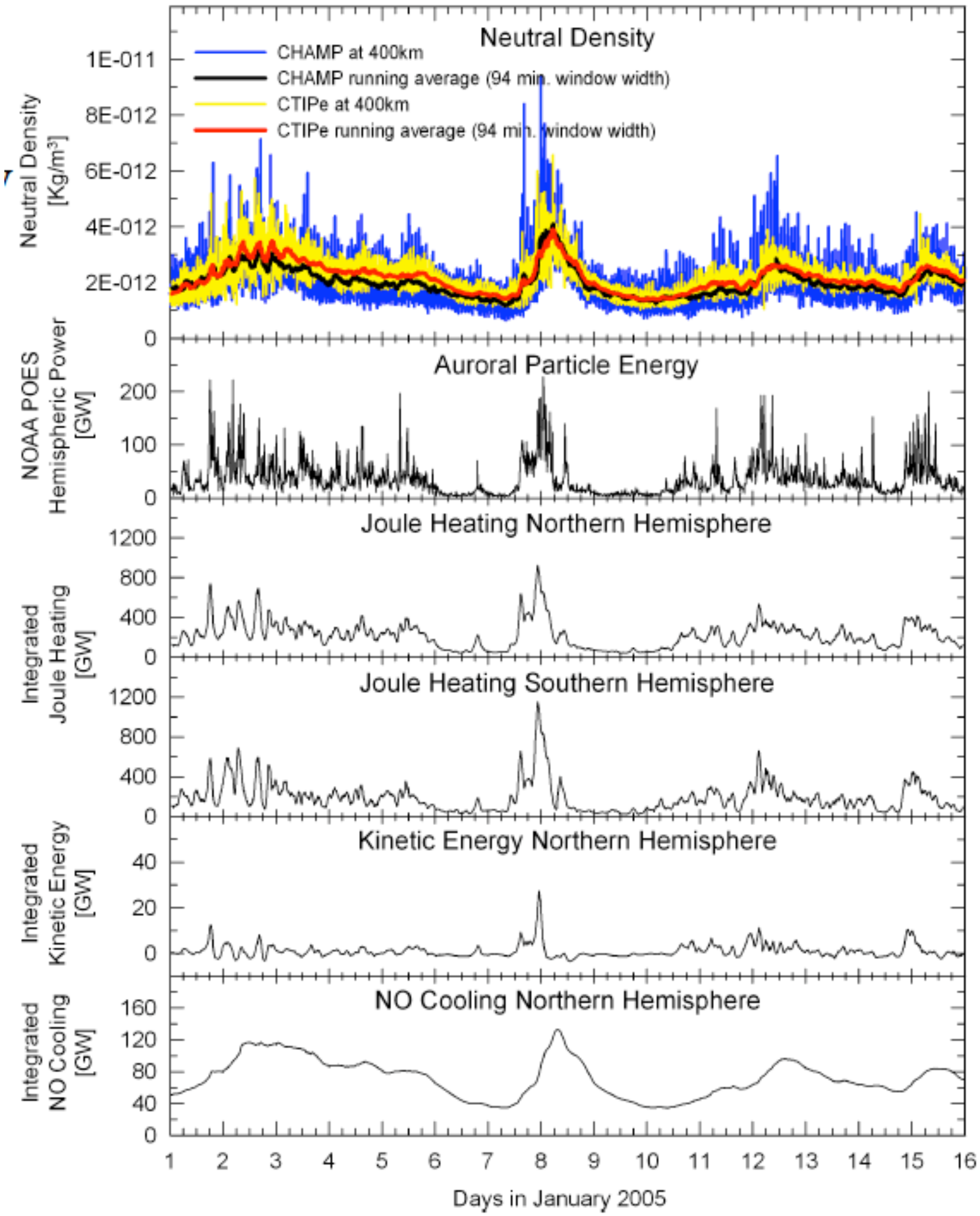
electromagnetic energy >80%

Joule heating
J . (E + UxB)
>80%

heat, pressure gradients, winds, etc.

kinetic energy
U . (JxB)
<20%

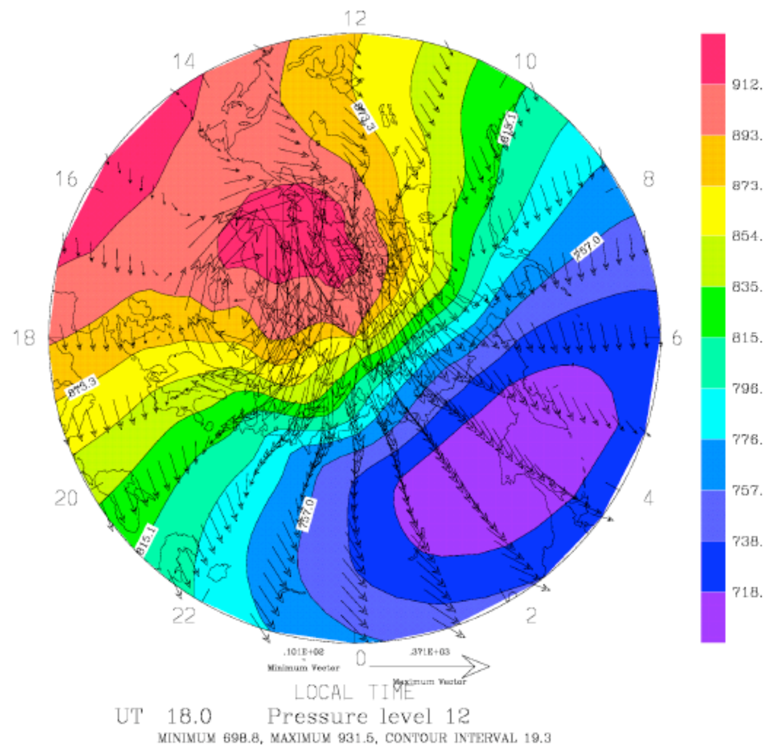
Ion drag drives neutral winds



Neutral Density
CHAMP at 400km
CHAMP running average (94 min. window width)
CTIPe at 400km
CTIPe running average (94 min. window width)
Neutral Density [Kg/m³]
1E-011
8E-012
6E-012
4E-012
2E-012
0
Auroral Particle Energy
NOAA POES Hemispheric Power [GW]
200
100
0
Joule Heating Northern Hemisphere
Integrated Joule Heating [GW]
1200
800
400
0
Joule Heating Southern Hemisphere
1200
800
400
0
Kinetic Energy Northern Hemisphere
Integrated Kinetic Energy [GW]
40
20
0
NO Cooling Northern Hemisphere
Integrated NO Cooling [GW]
160
120
80
40
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Days in January 2005

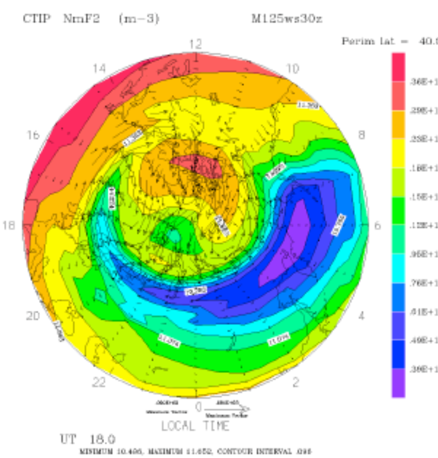
Ion-neutral collisions in upper thermosphere frequent enough to drive high velocity neutral wind

Neutral Winds and Temperature: 300 km altitude



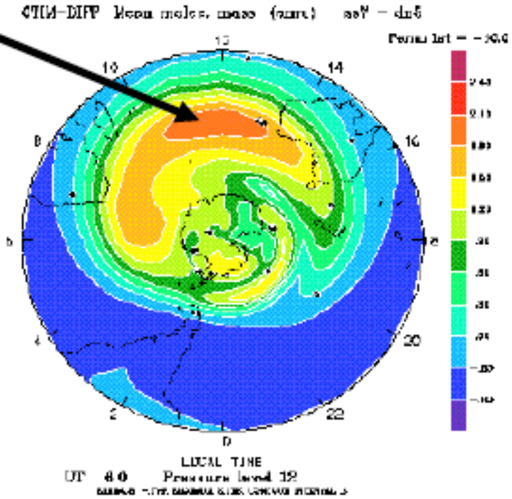
Maximum wind speed observed by DE-2 ~ 1400 m/s

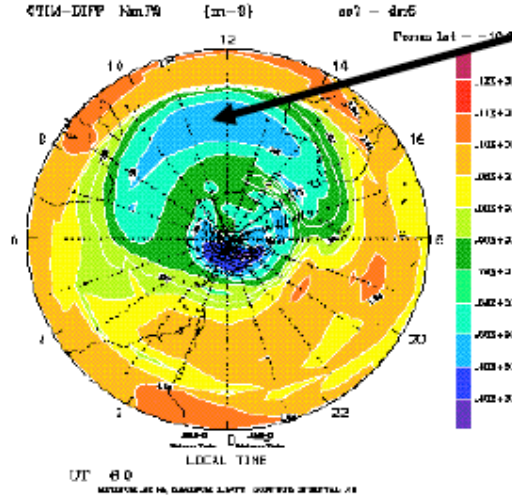
ExB ion drift and NmF2



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

Increase in N_2

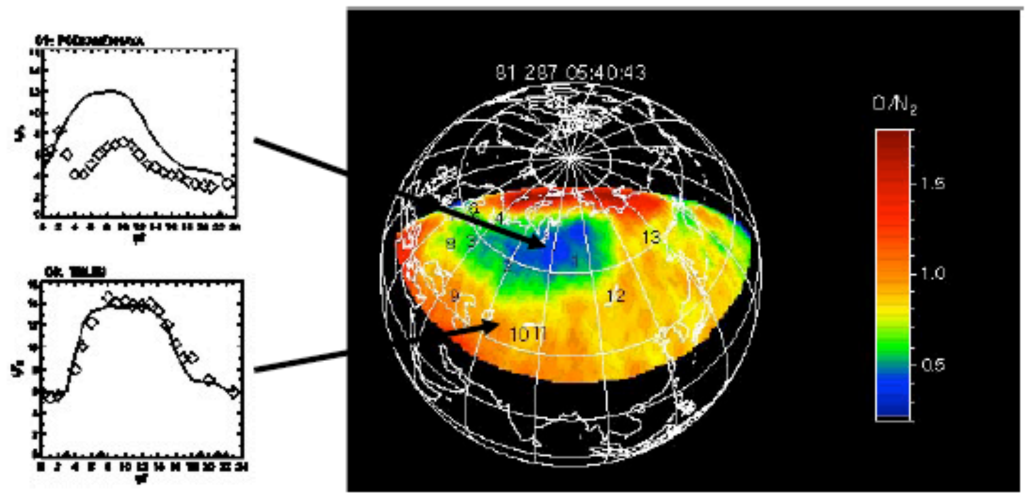




Ionospheric depletion

Modeling

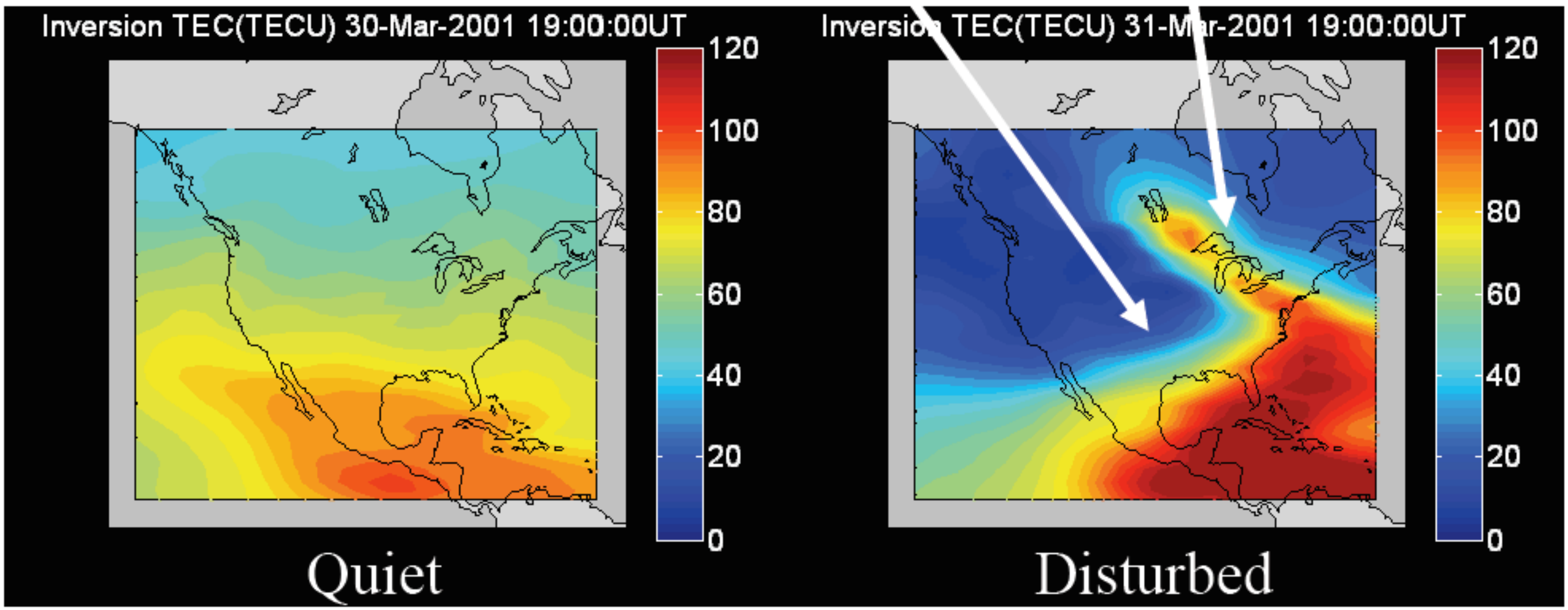
Observations



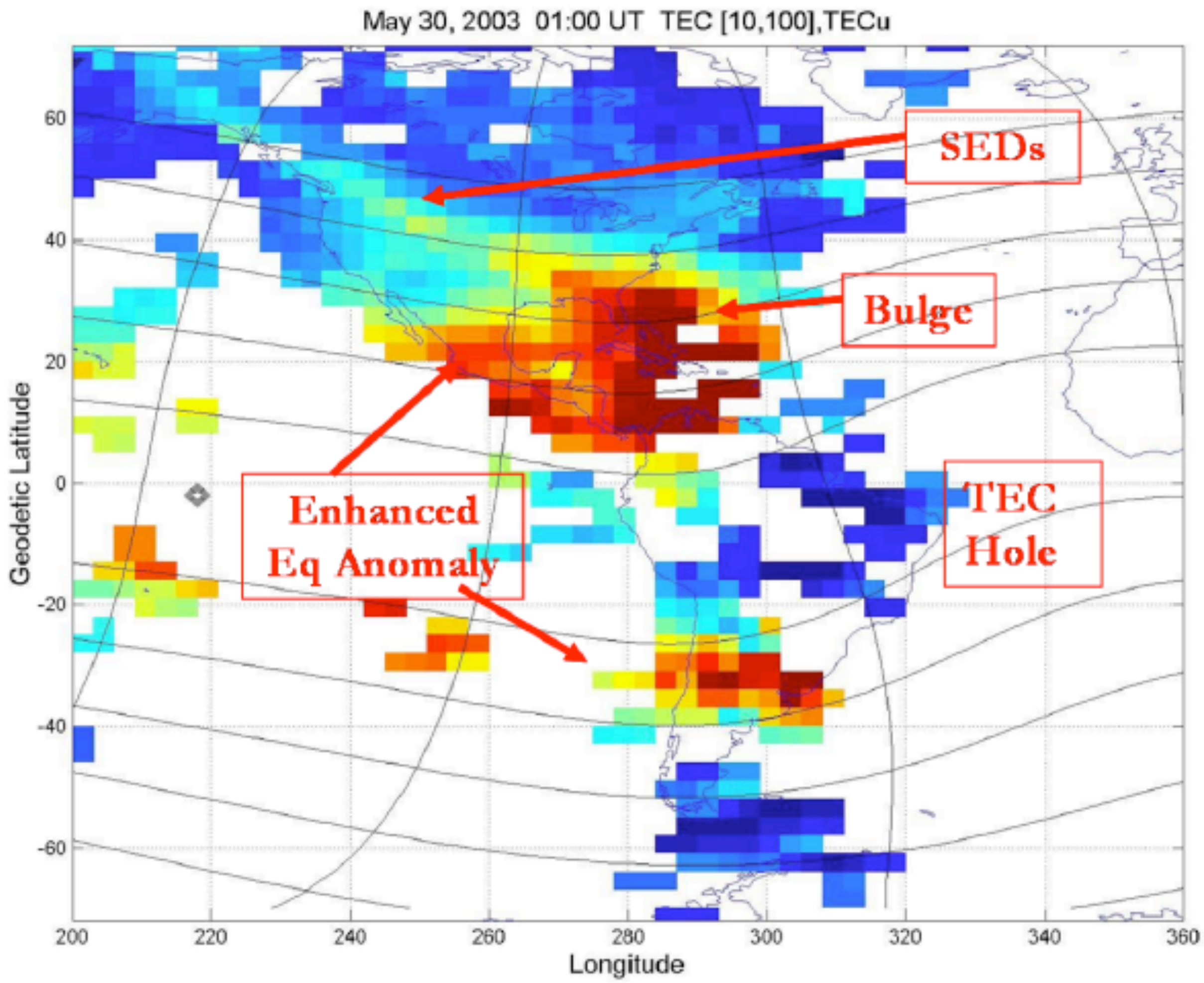
US-TEC – SWPC
IRI plus data

"positive phase"
and tongue of ionization

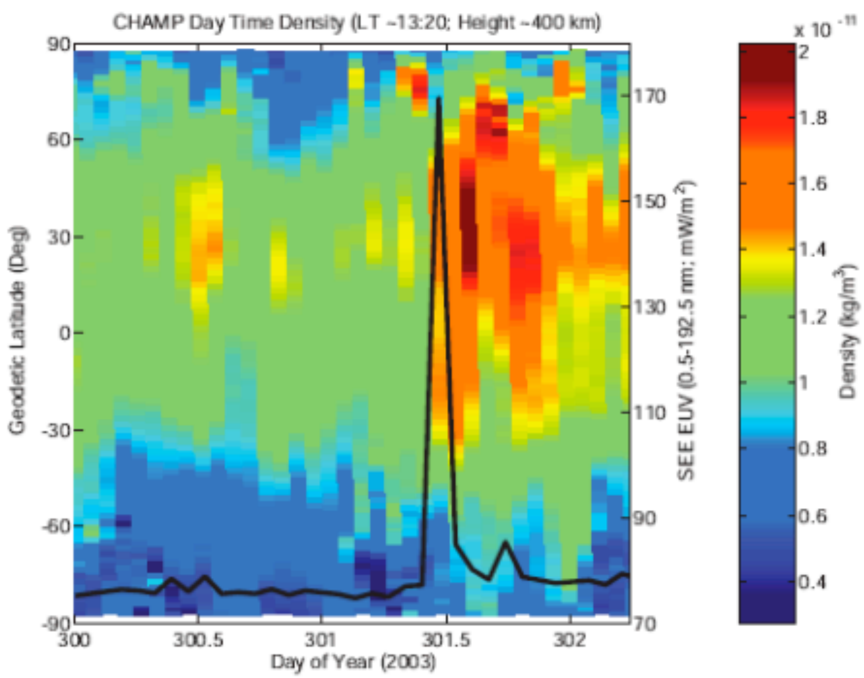
"negative phase"

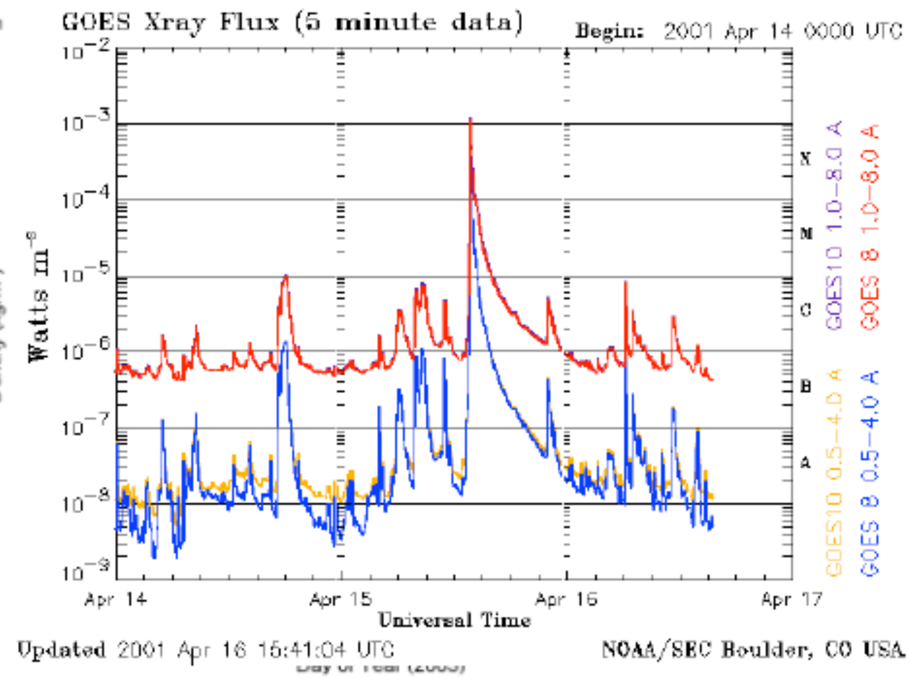


Plasma "bulge" and Storm Enhanced Density



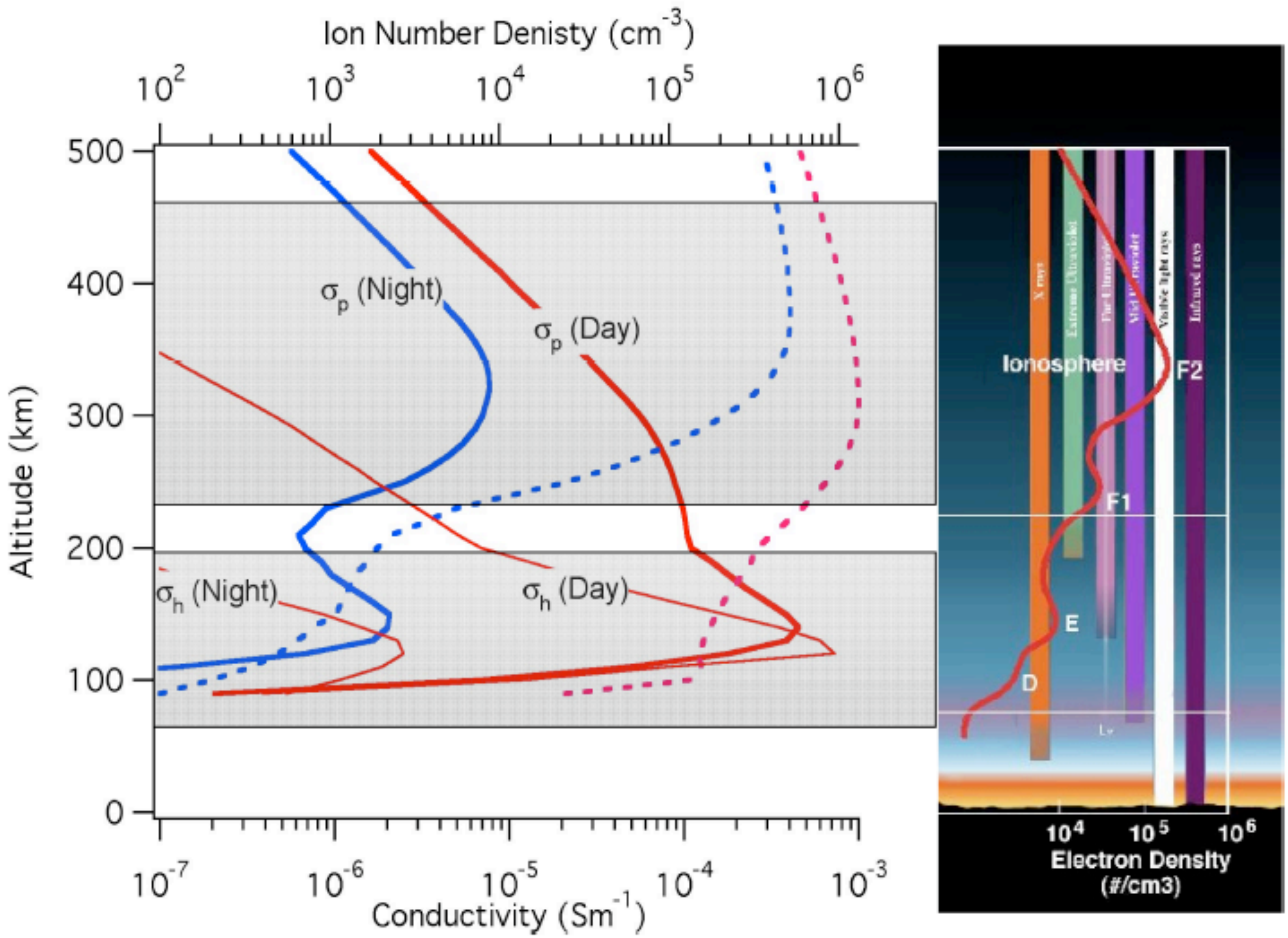
Neutral density response to flares
(Sutton and Forbes)





CHAMP satellite data

Pedersen and Hall Conductivity



And there is lots more!