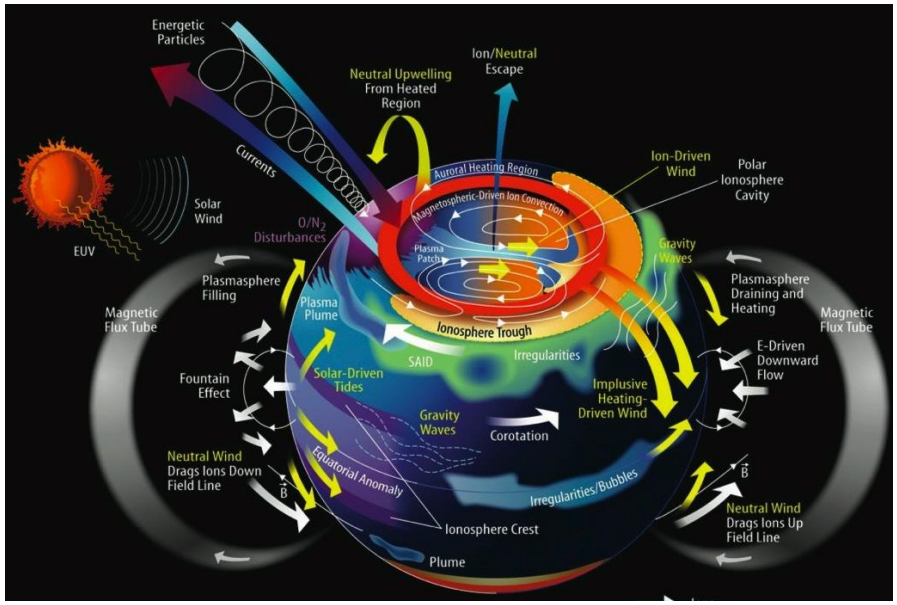
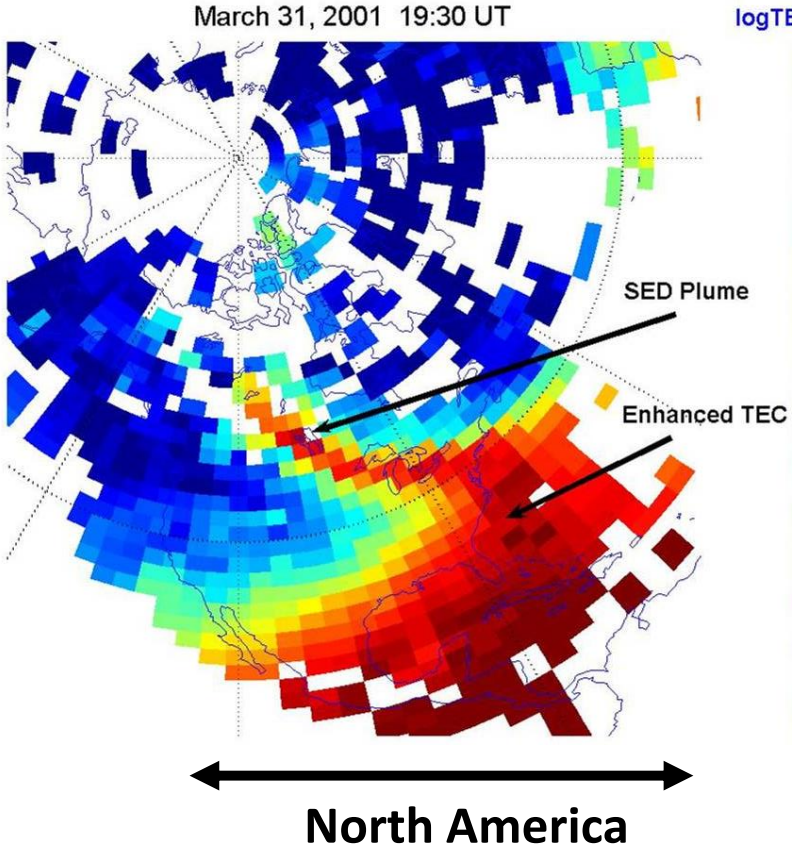
The Ionosphere and Thermosphere: a Geospace Perspective

John Foster, MIT Haystack Observatory





CEDAR Student Workshop
June 24, 2018

Introduction – My Geospace Background
(Who is the Lecturer? Where is he coming from?)

- Member of the TEAM that developed the CEDAR concept & program in the 1980s
- Antarctica - Relativistic wave-particle interactions – M/I coupling
- Canada – International Satellite for Ionospheric Study (ISIS)
- Utah State Univ. - Alaska incoherent scatter radar studies of auroral disturbances and electrodynamics
- Yosemite conferences – broad topics in Geospace system science
- MIT - Radio-physics research investigating M-I-T phenomena from the ground and space
- Van Allen Probes - Ionospheric effects on magnetospheric processes & NL radiation belt acceleration

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- I am data/observations oriented. I am NOT a modeler


MIT Haystack Observatory Complex
Westford, Massachusetts
Established 1956
Haystack Observatory
Radio Astronomy
Atmospheric Science
Space Surveillance
Radio Science
Education and Public Outreach
Millstone Hill
Observatory
Millstone Hill Radar
Firepond Optical
Facility

(Textbook Material - Aeronomy)

Ionosphere: Balance of production and loss

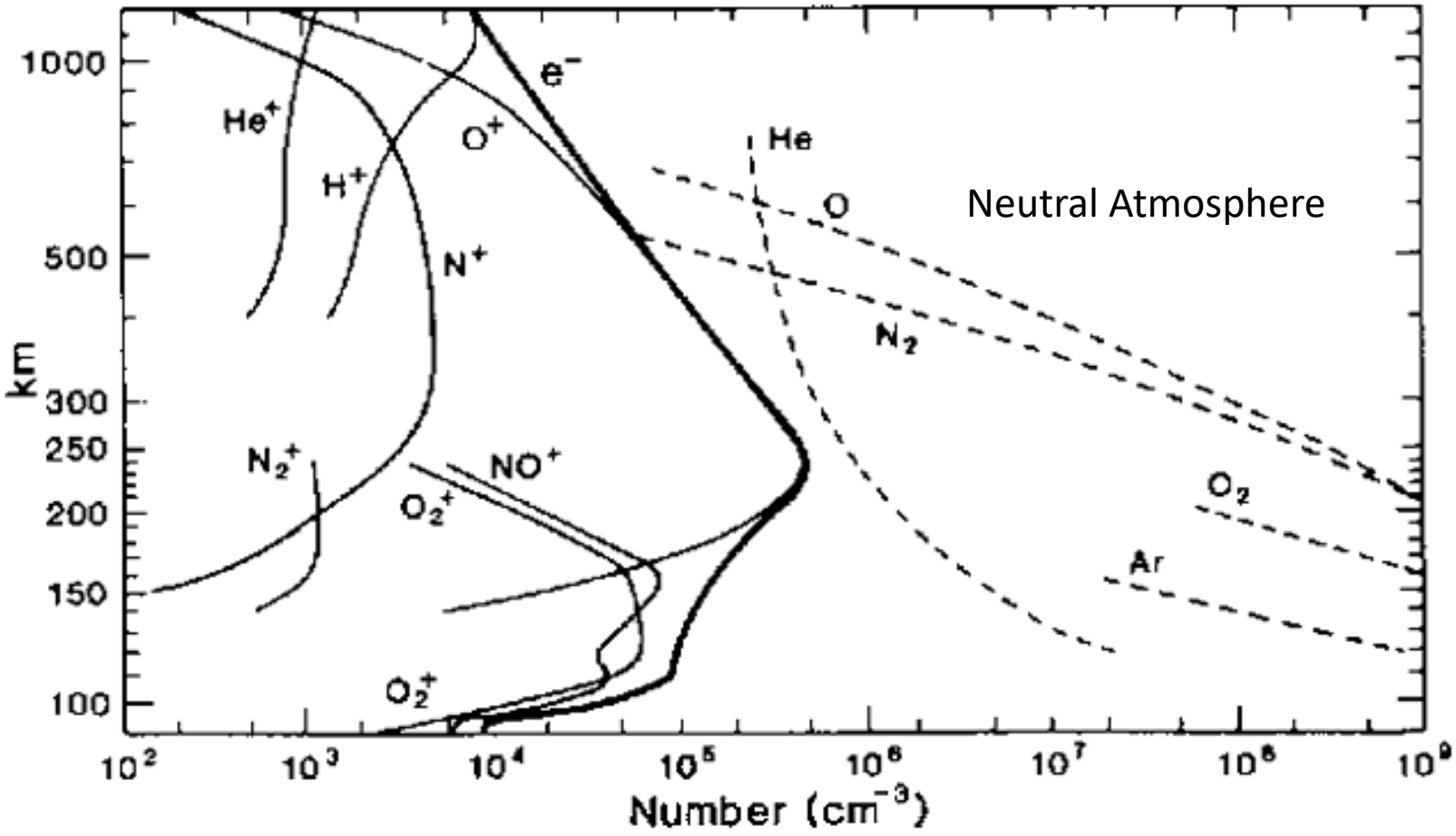
Production: by Solar EUV at F region heights

Loss: Recombination and Ionospheric Chemistry

Altitude Distribution: Species dependent partial **pressure balance with gravity**

Diffusive Equilibrium or outflow (refilling) on depleted flux tubes

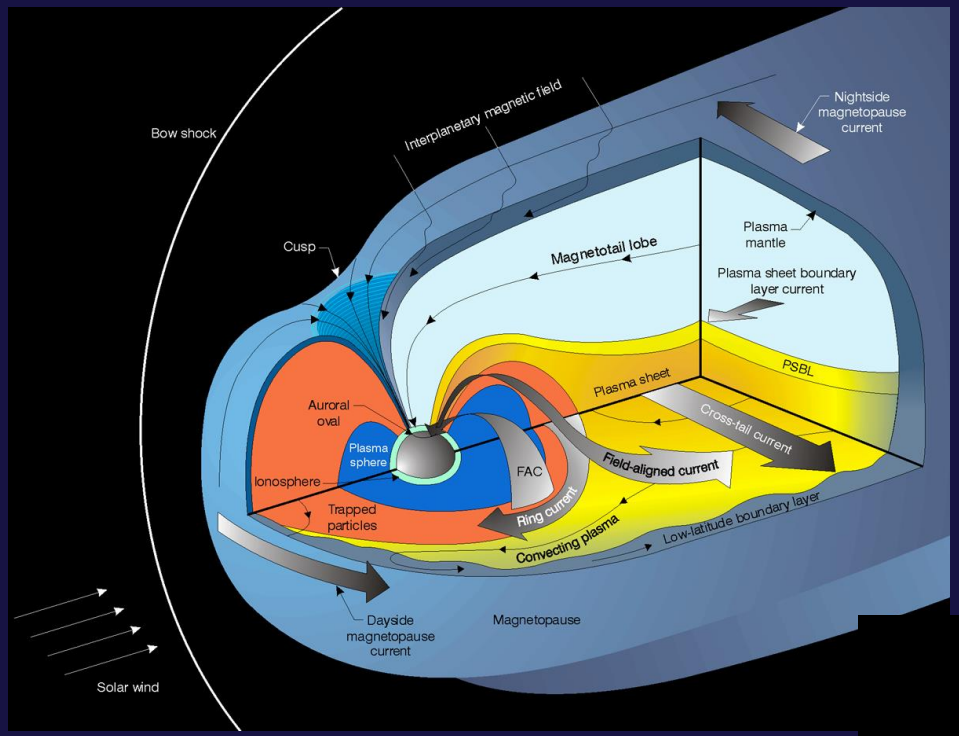
The Plasmasphere is an extension of the topside ionosphere

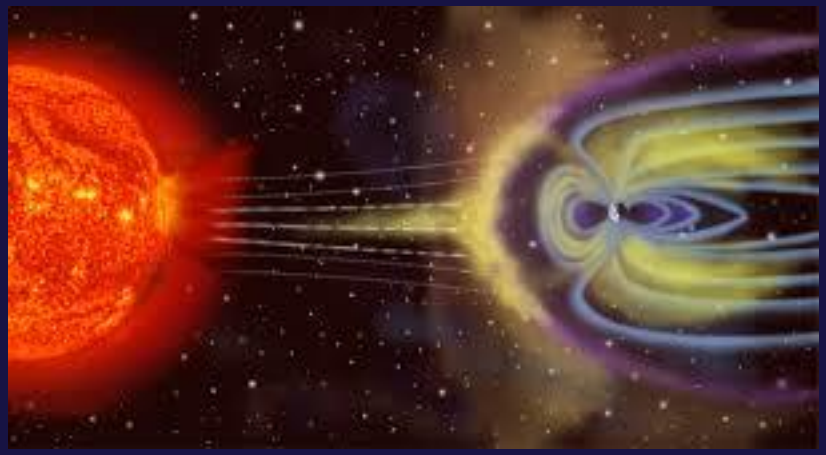


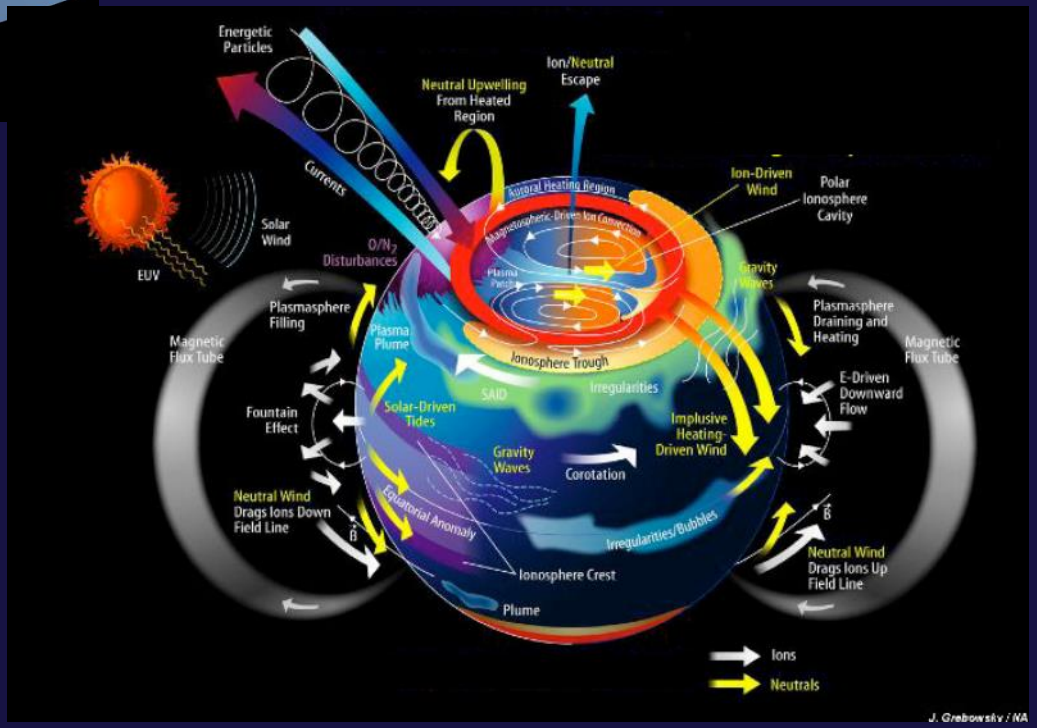
International quiet solar year daytime ionospheric and atmospheric composition based on mass spectrometer measurements [Johnson, 1969; Luhmann, 1995].

The Coupled Geospace System

That region of space around Earth enveloped by its magnetic field



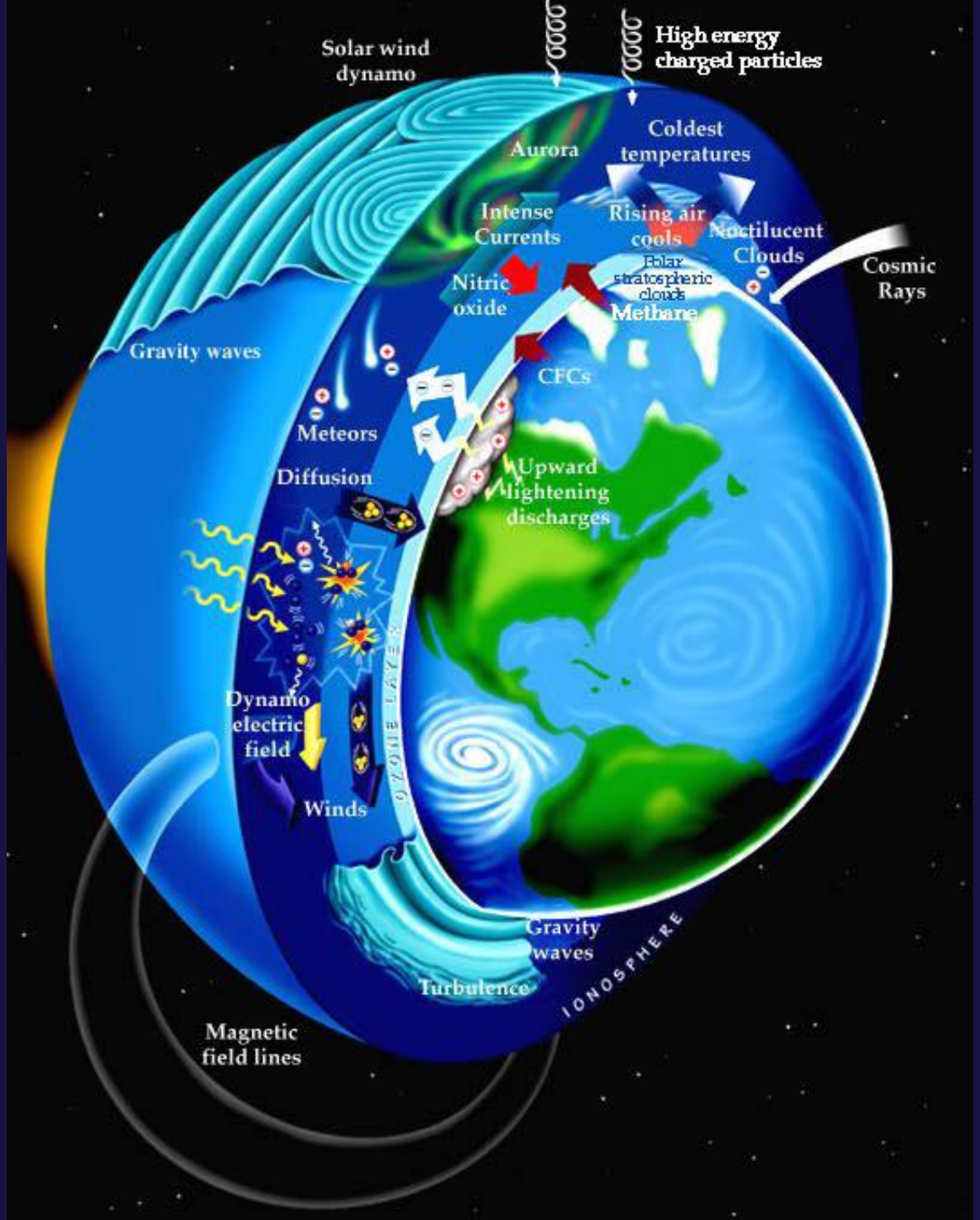


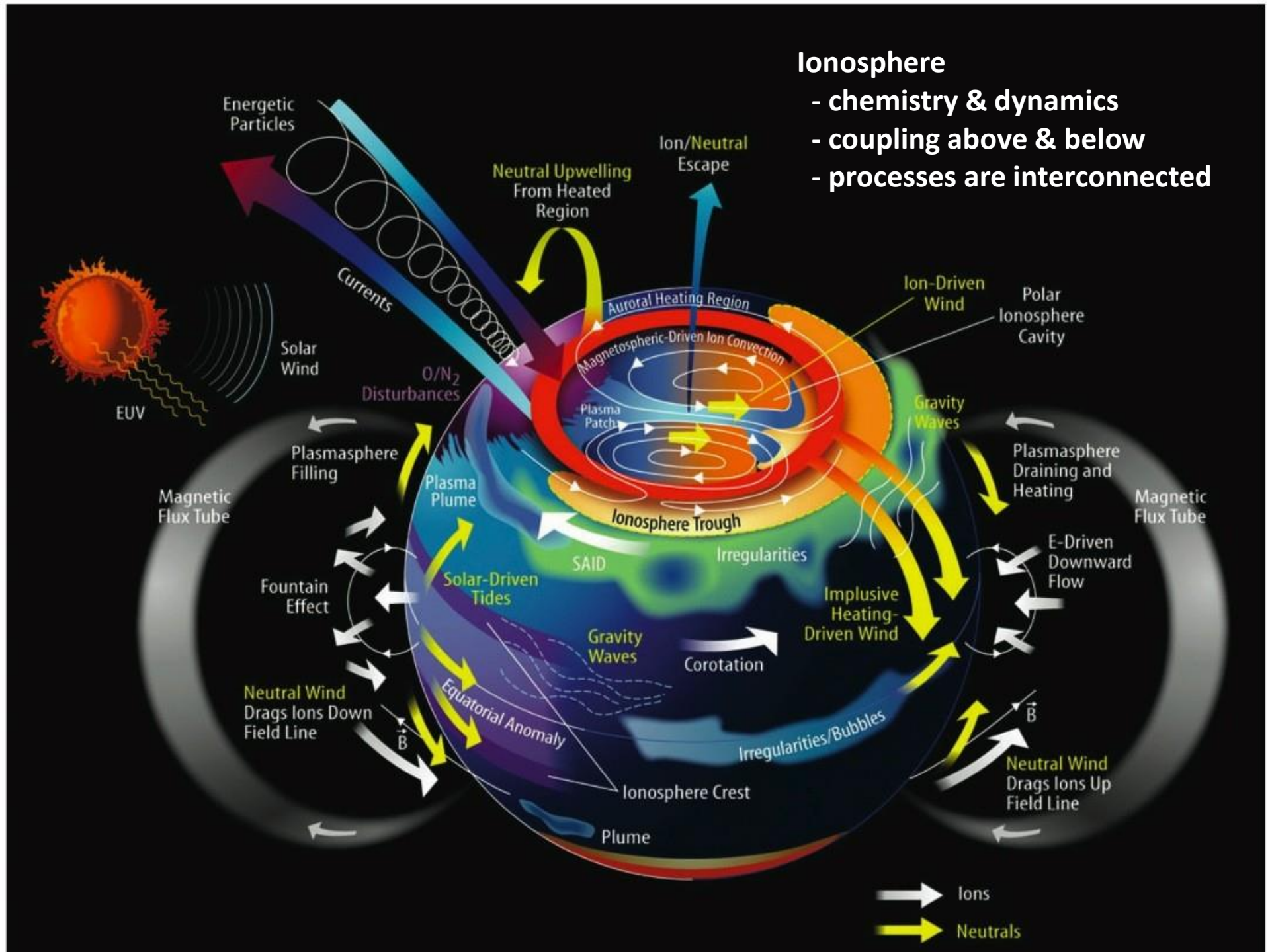


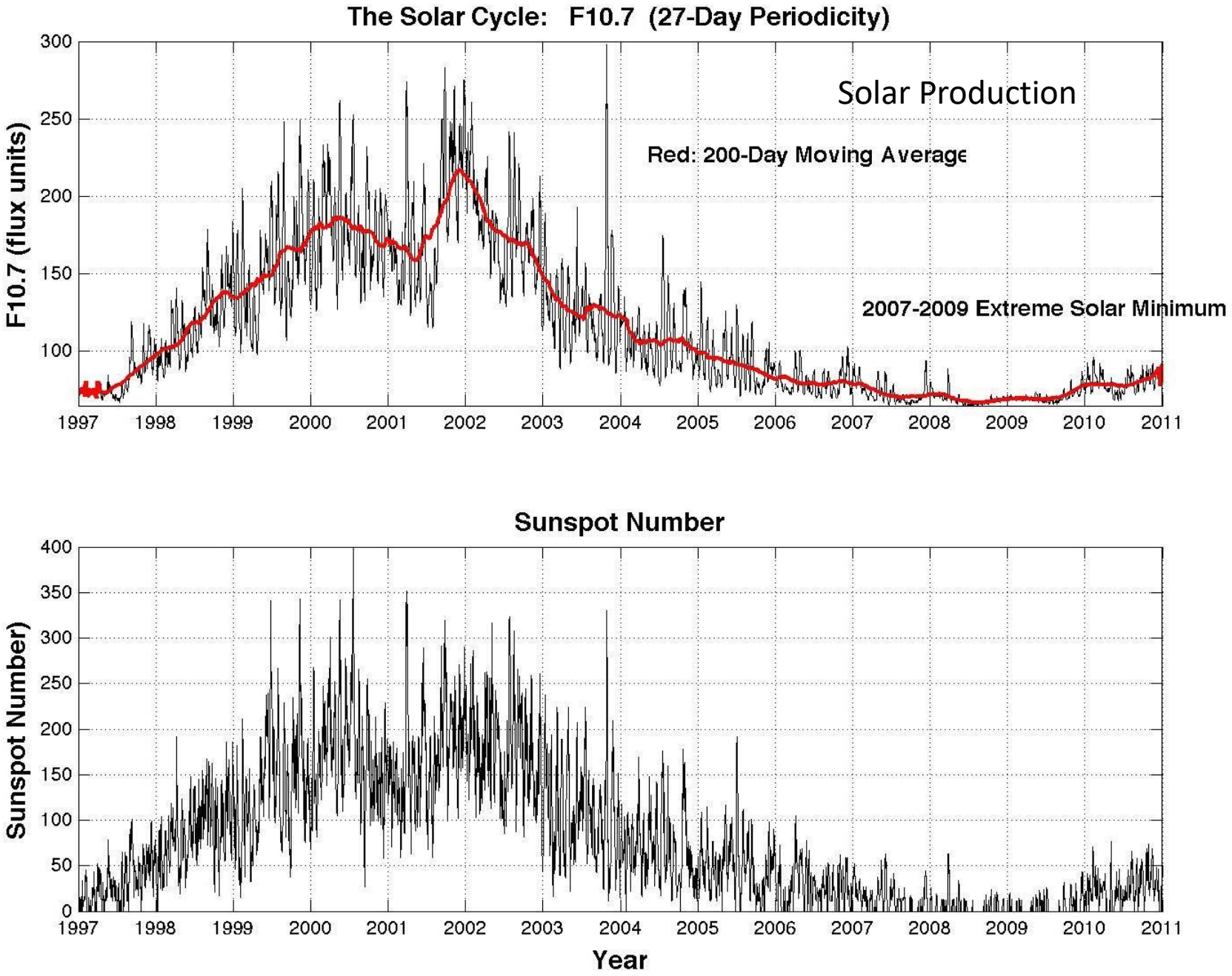
Geospace: The Inner Spheres

Earth - Biosphere,
- Human Impact
Oceans
Neutral Atmosphere

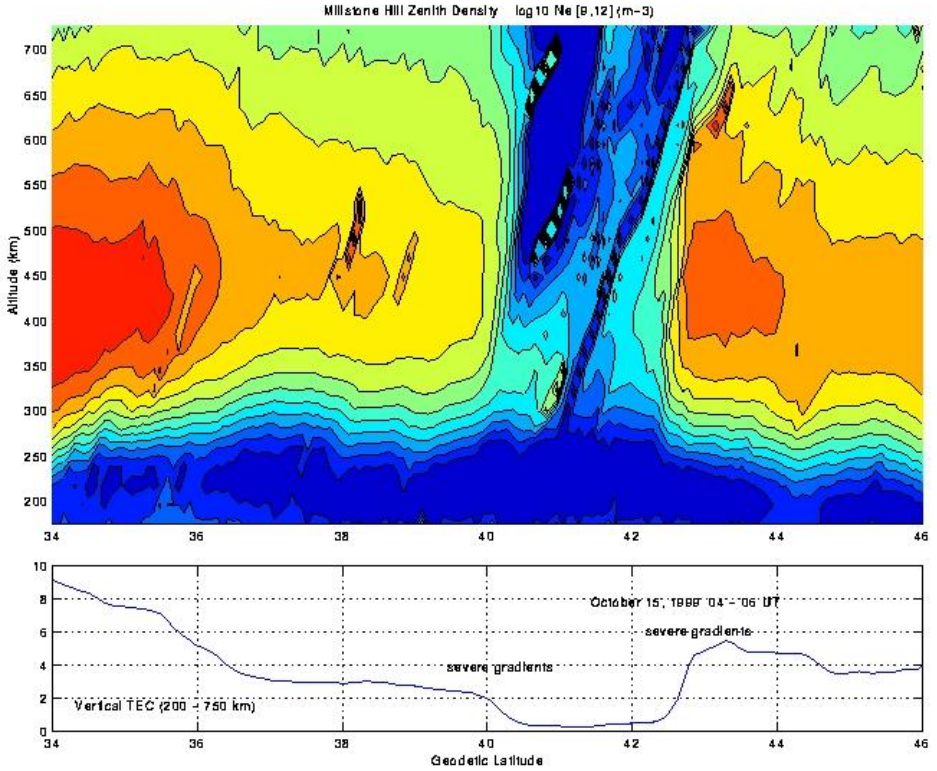
Internal & External Effects




Ionosphere
- chemistry & dynamics
- coupling above & below
- processes are interconnected
Energetic Particles
Ion/Neutral Escape
Neutral Upwelling From Heated Region
Currents
Auroral Heating Region
Magnetospheric-Driven Ion Convection
Ion-Driven Wind
Polar Ionosphere Cavity
Solar Wind
EUV
O/N2 Disturbances
Plasma Patch
Gravity Waves
Plasmasphere Filling
Plasmasphere Draining and Heating
Magnetic Flux Tube
Plasma Plume
Ionosphere Trough
Magnetic Flux Tube
SAID
Irregularities
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
Ions
Neutrals


The Solar Cycle: F10.7 (27-Day Periodicity)
F10.7 (flux units)
300
250
200
150
100
Solar Production
Red: 200-Day Moving Average
2007-2009 Extreme Solar Minimum
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Sunspot Number
Sunspot Number)
400
350
300
250
200
150
100
50
0
Year

TEC: Integrated vertical column density of through ionosphere and plasmasphere



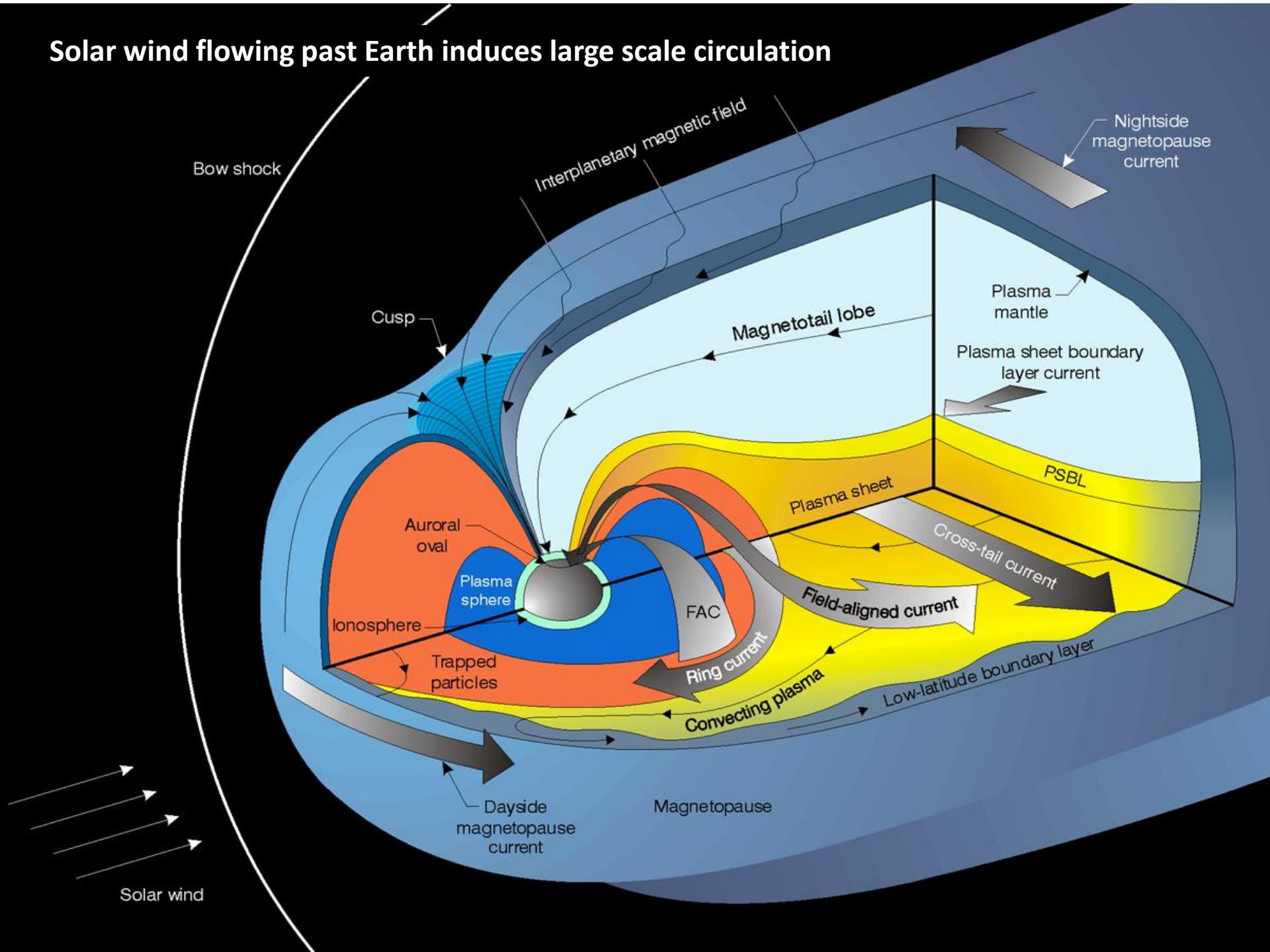
Ionospheric Radar (ISR)

Plasmasphere is the high altitude extension of the ionosphere

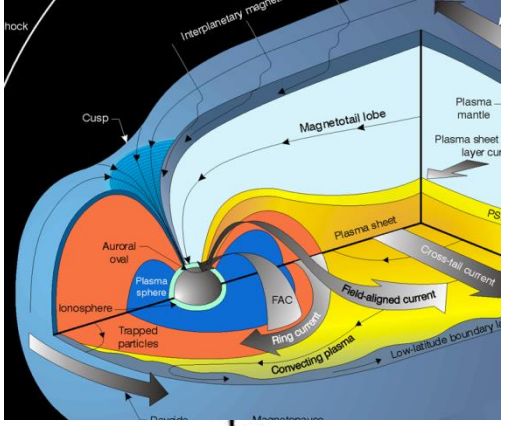
Diffusive equilibrium determines quiet time profiles

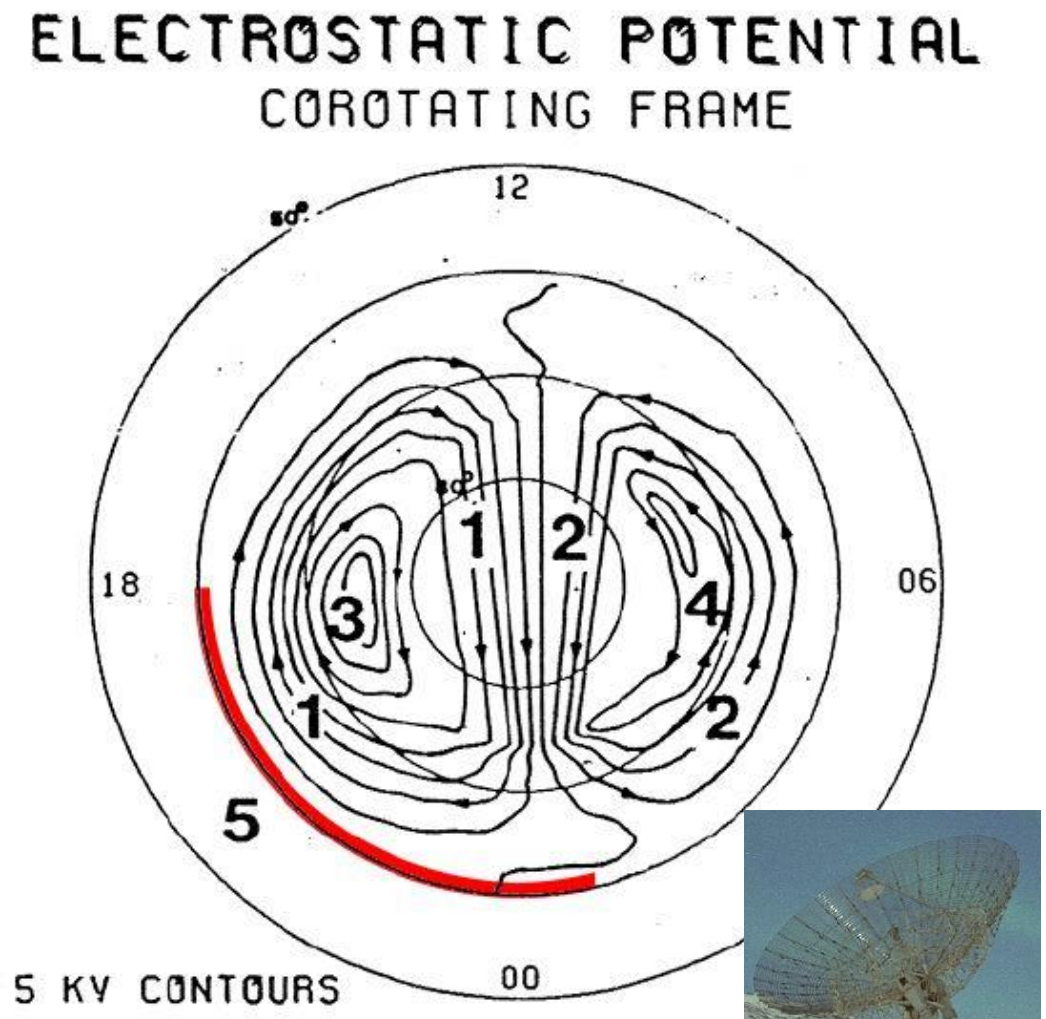
Significant spatial structure results from M-I coupling

Solar wind flowing past Earth induces large scale circulation

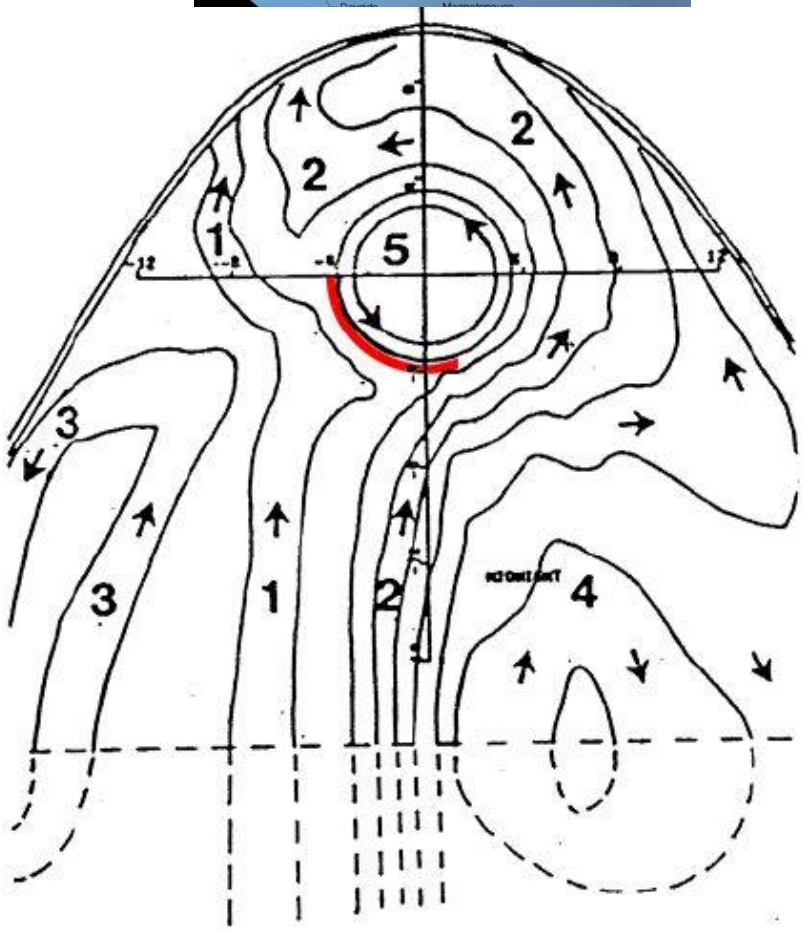


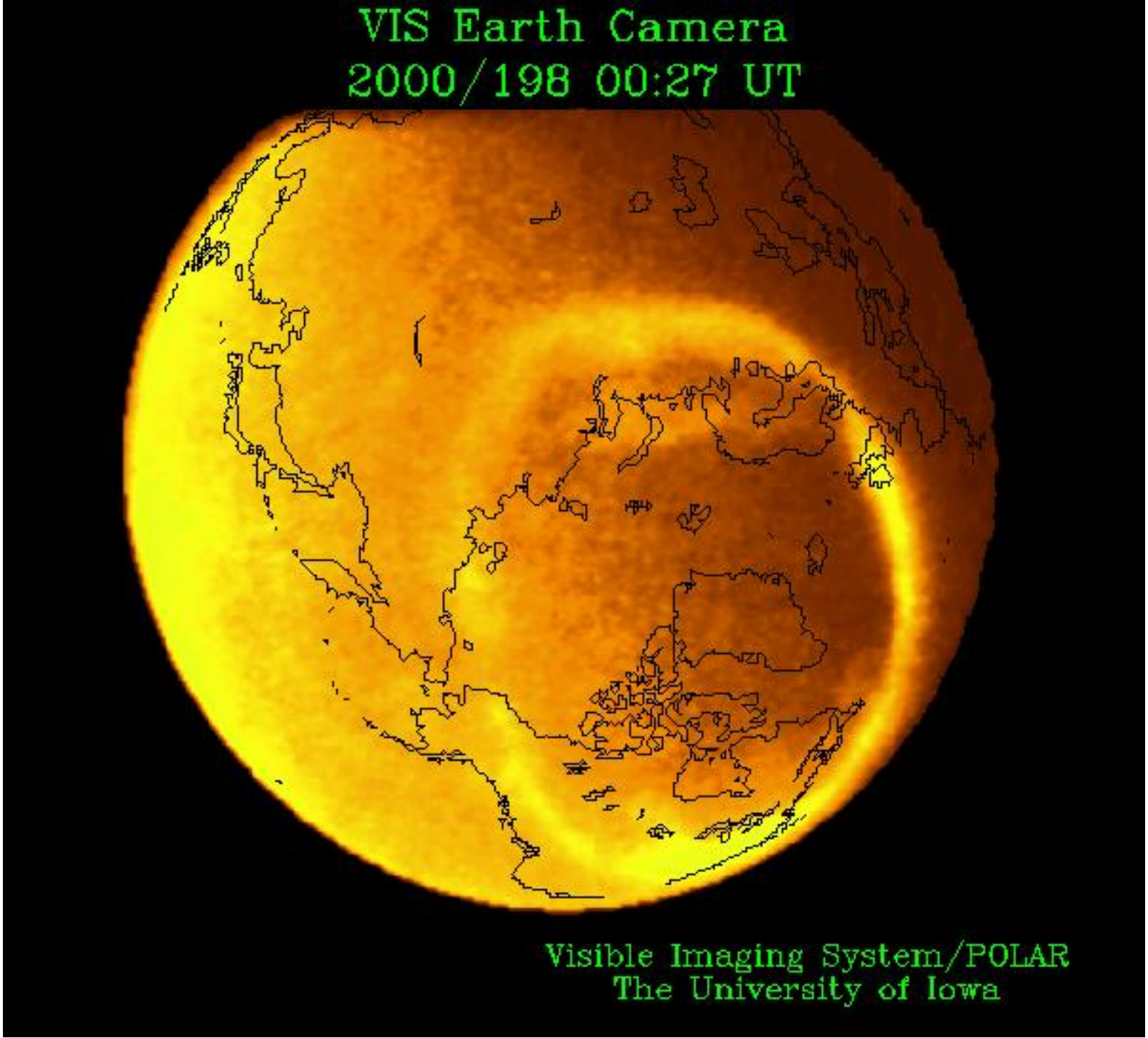
To first order, cold plasma redistribution proceeds such that plasma parcels at ionospheric heights and at the apex of a magnetic field line move together in the E x B direction maintaining their magnetic field alignment.





[Foster., 1984]

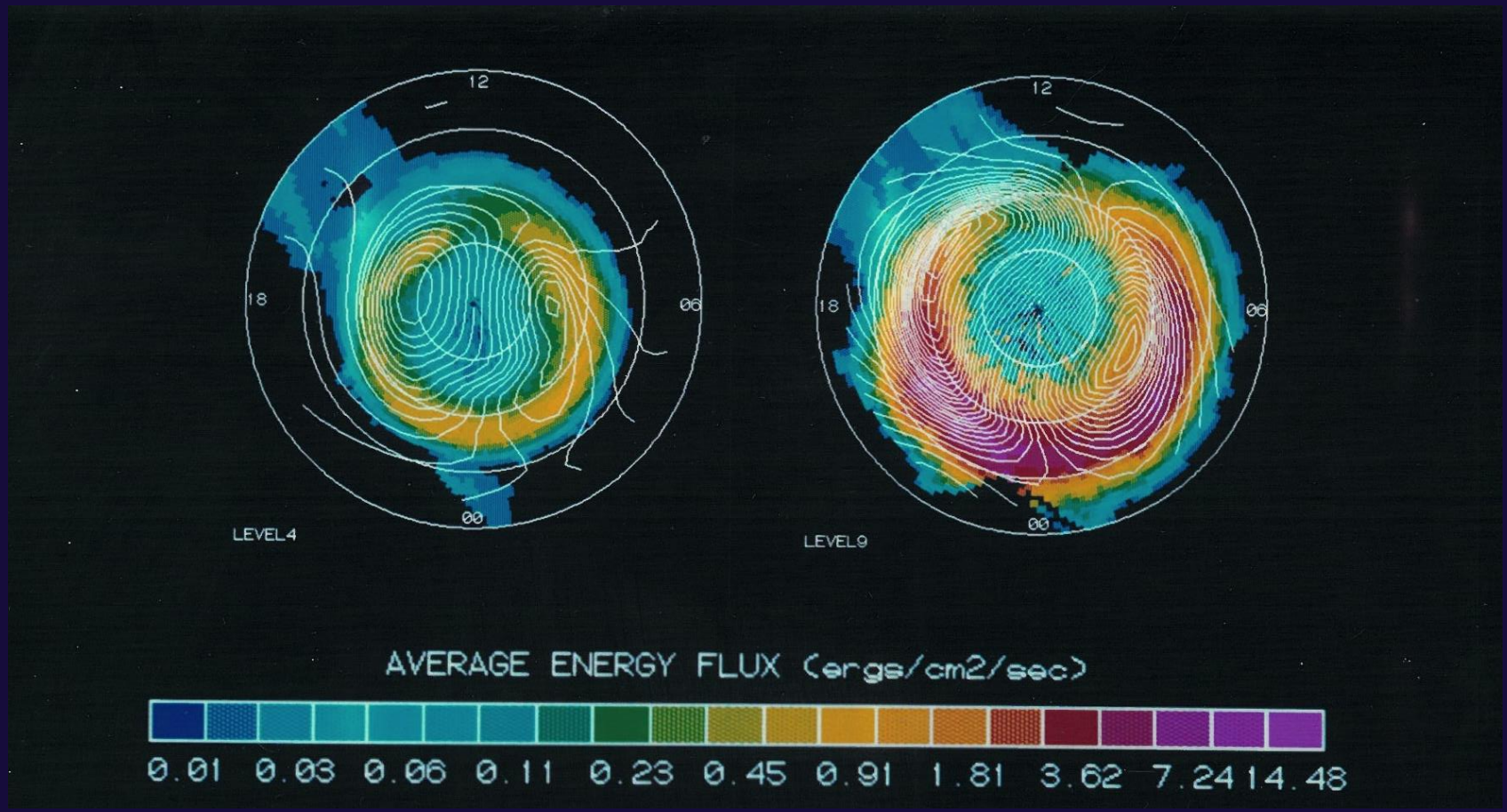


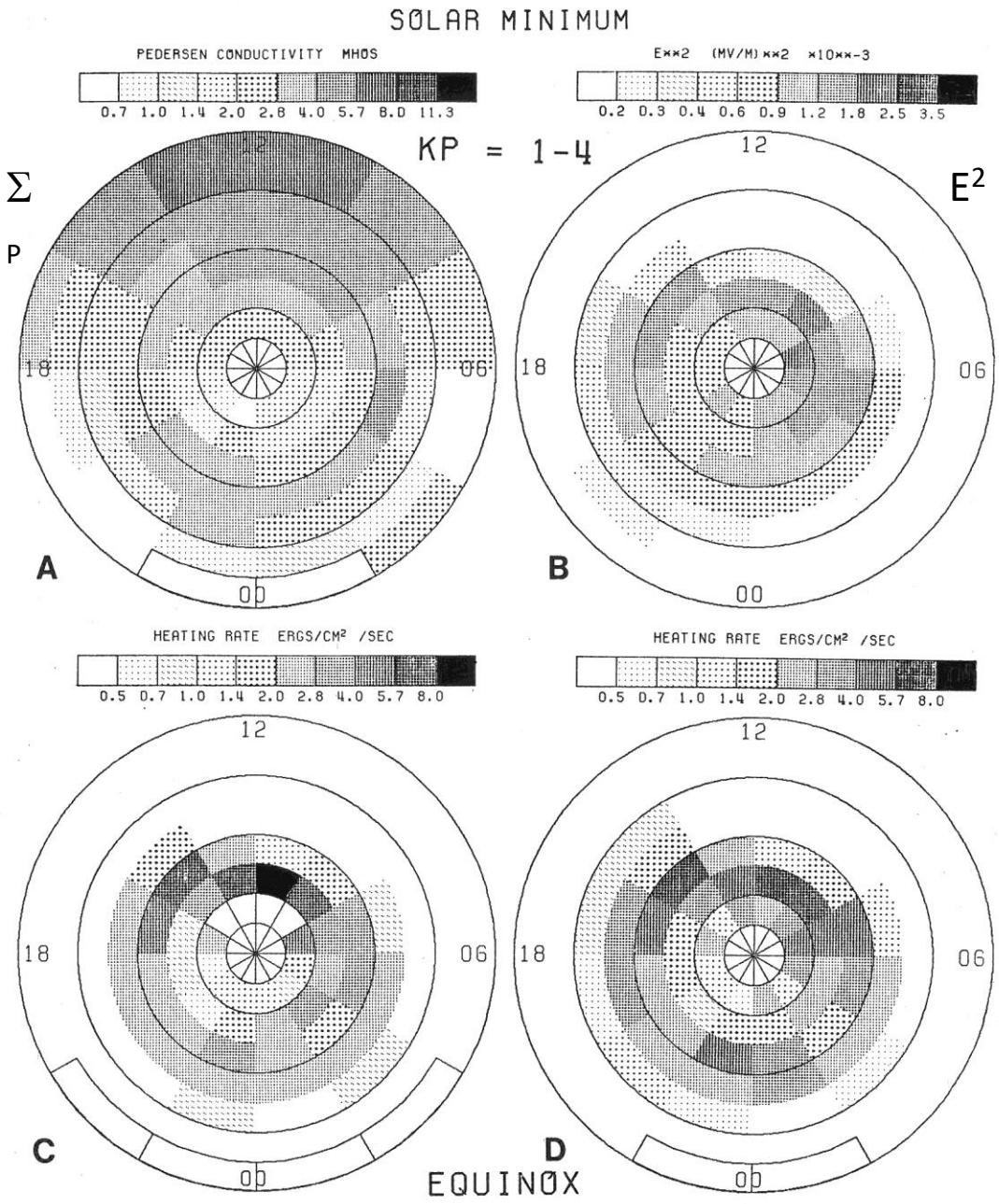

VIS Earth Camera
2000/198 00:27 UT
Visible Imaging System/POLAR
The University of Iowa

Relationship of Convection and Precipitation

Empirical models of ionospheric electric field (Millstone Hill IS Radar) sorted by Evans' auroral particle precipitation index (9 levels based on NOAA/Tiros data)

Equipotential contours of convection electric field are superimposed on patterns of precipitation energy flux. [Foster et al., 1986]





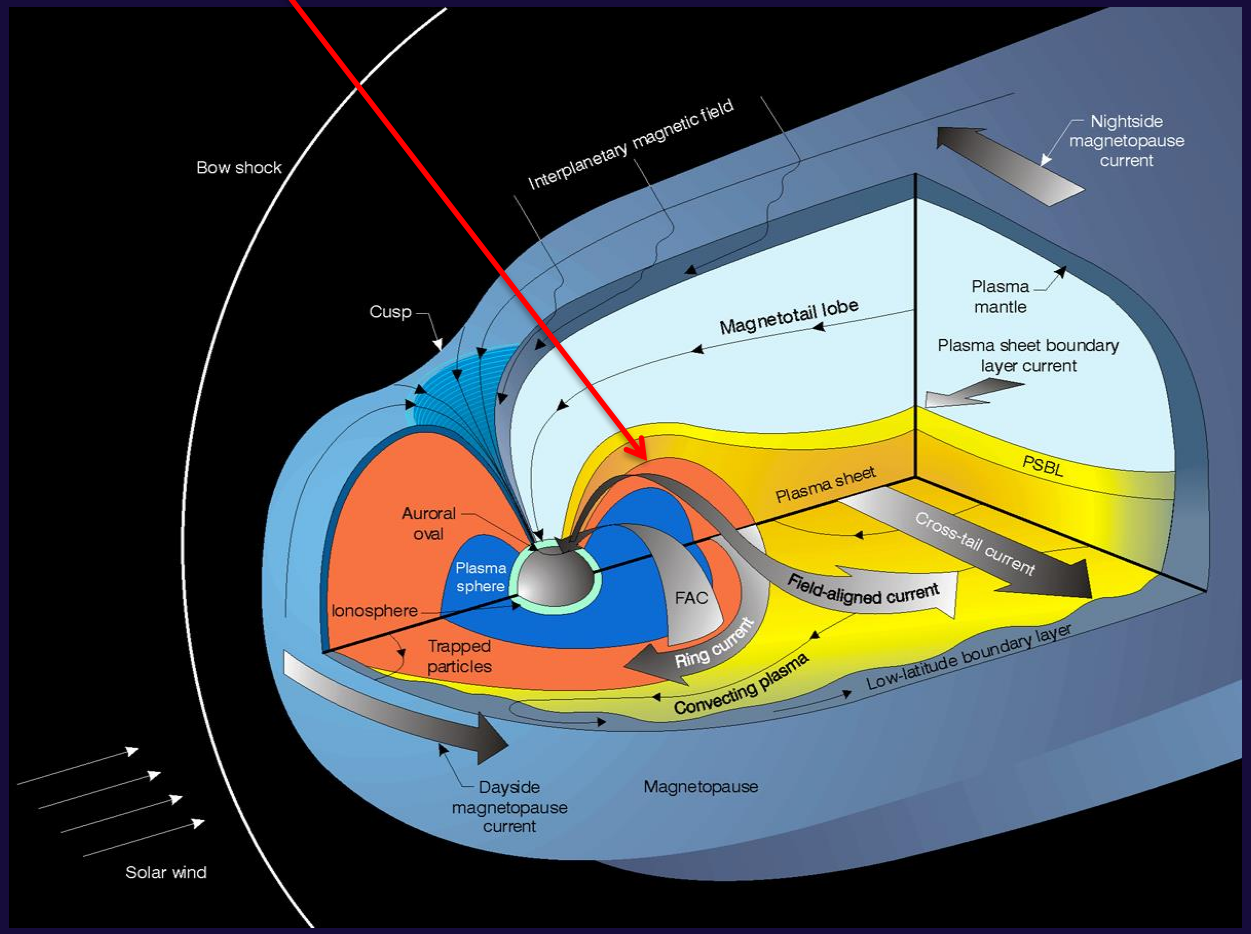
$\langle \Sigma_P E^2 \rangle$ $\langle \Sigma_P \rangle \langle E^2 \rangle$

Joule Heating Rate $\Sigma_P E^2$ is determined from individual observations of electric field and Pedersen conductivity over the lifetime of the AE-C satellite. [Foster et al, 1983]

The contribution of solar-produced dayside conductivity is important.

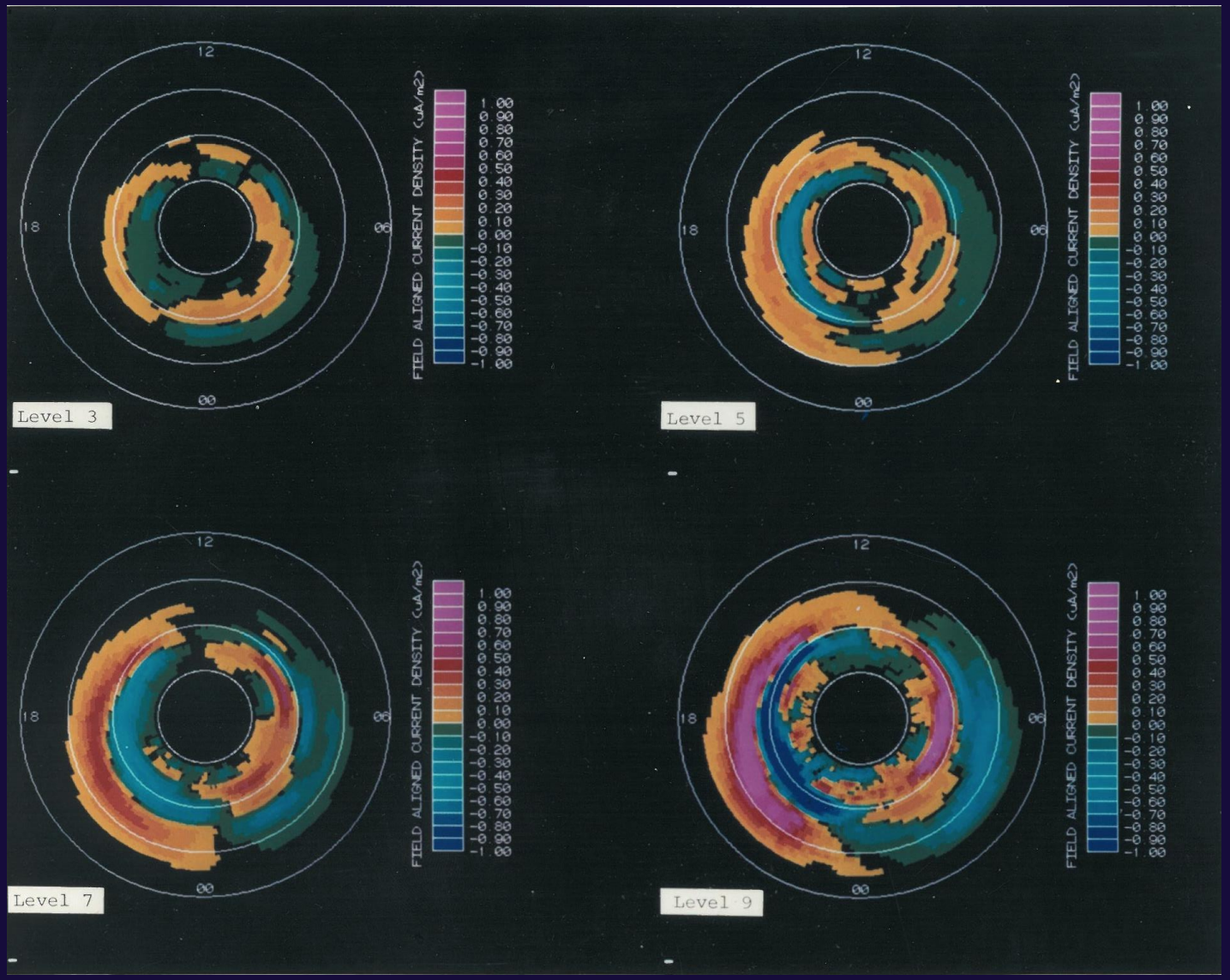
Joule energy deposition affects the dynamical properties of the thermosphere – winds, temperature, and composition.

Field-Aligned Currents Link the Magnetosphere and the Ionosphere

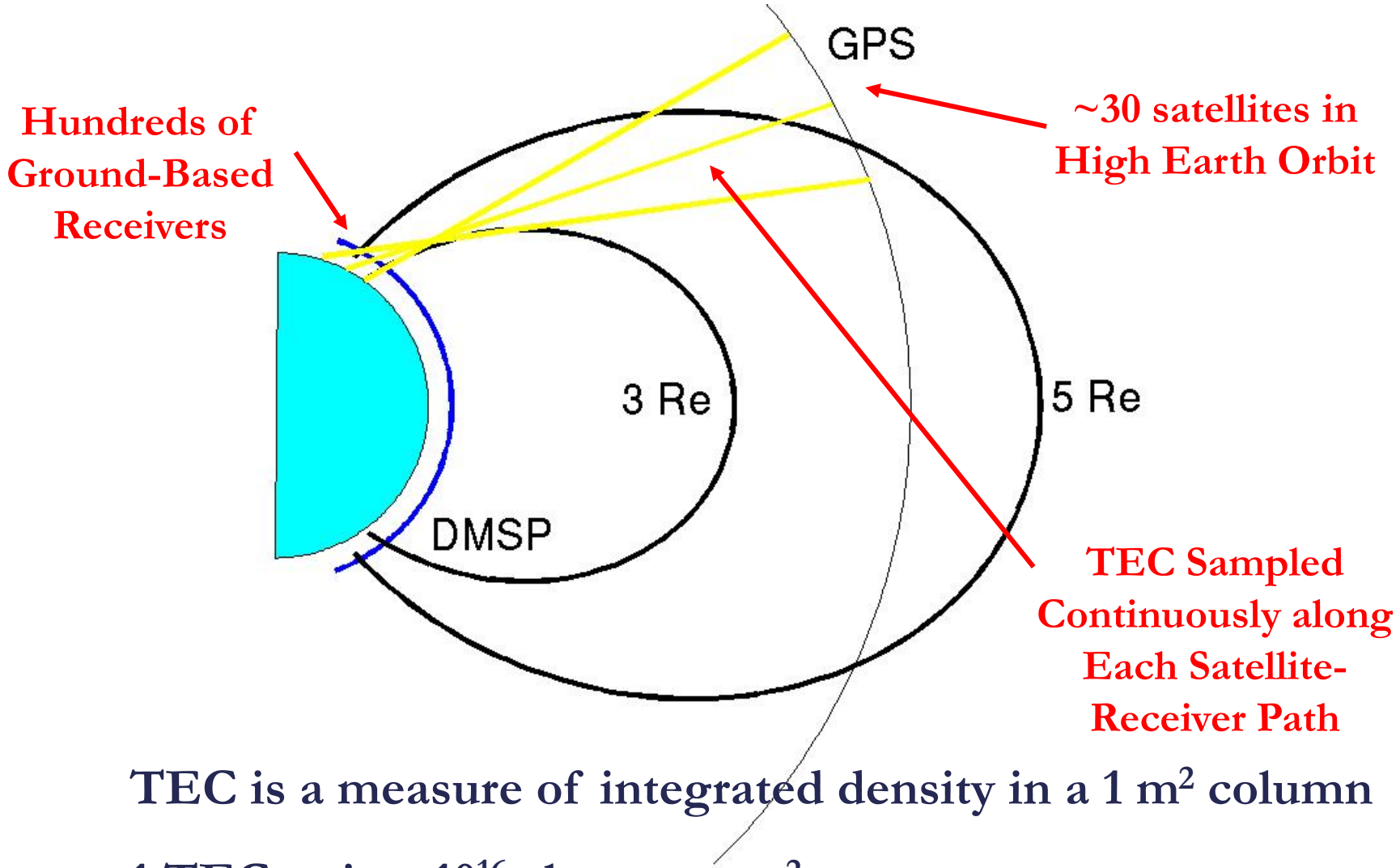


Joule dissipation of ionospheric currents is a major I – T energy source.

Quantitative patterns of field-aligned current density derived assuming that the total current is divergence free. Horizontal currents were derived from the empirical electric field models combined with conductances determined from precipitation particle energy flux and spectrum. [Foster et al., 1989]



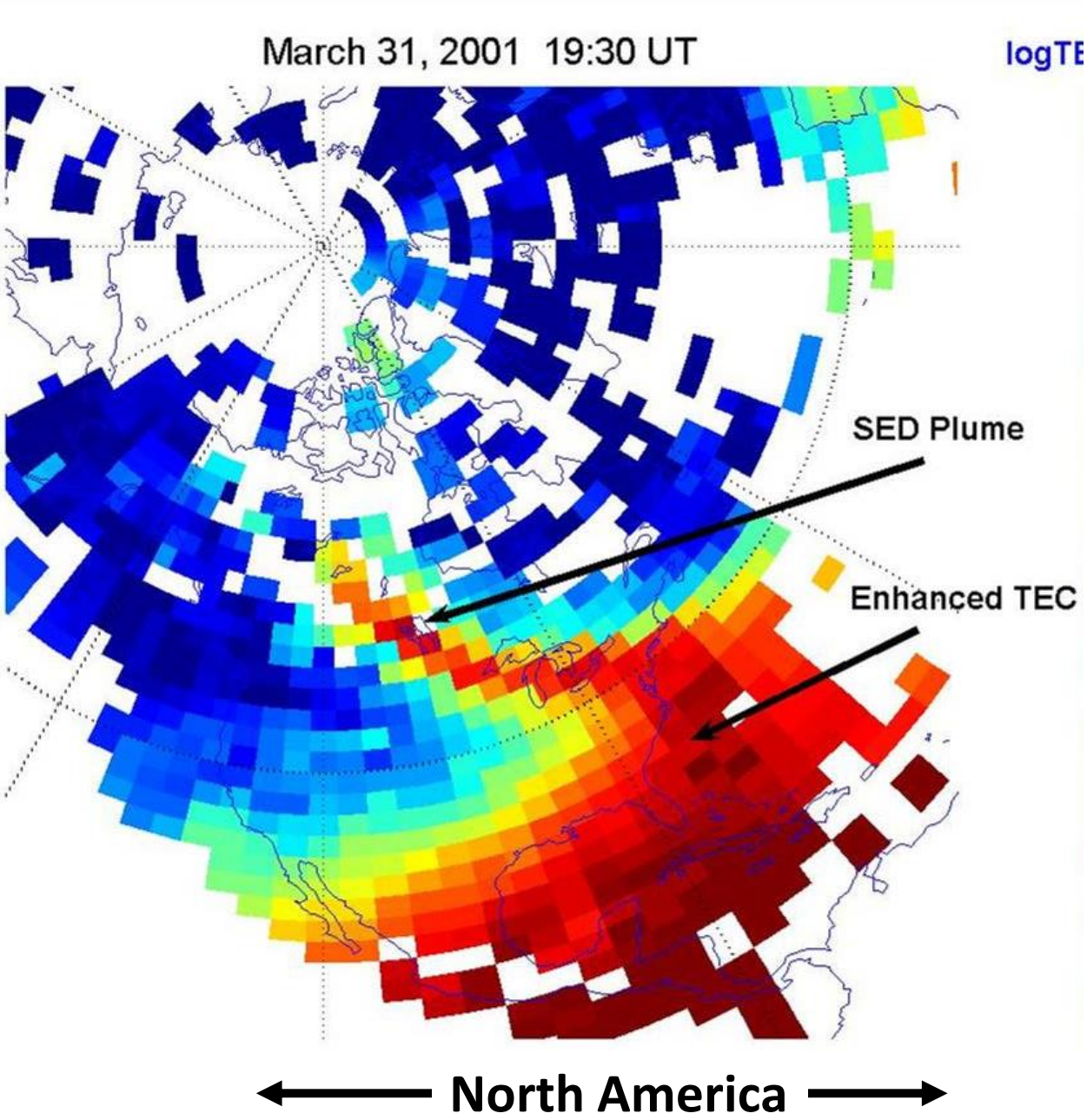
Observations: GPS samples the ionosphere and plasmasphere to ~20,000 km. Dual-frequency Faraday Rotation Observations give TEC (Total Electron Content)



TEC is a measure of integrated density in a 1 m^2 column

1 TEC unit = 10^{16} electrons m^{-2}

Storm Enhanced Density (SED) 5 min GPS TEC Snapshot



Equatorial Ion Fountain

- Equatorial electrojet (**E**) and horizontal magnetic field (**B**) give upward **E x B** velocity.
- Gravity (**g**) pulls ions downward along **B** to higher latitude.
- Off-equatorial peaks in ionospheric density result.

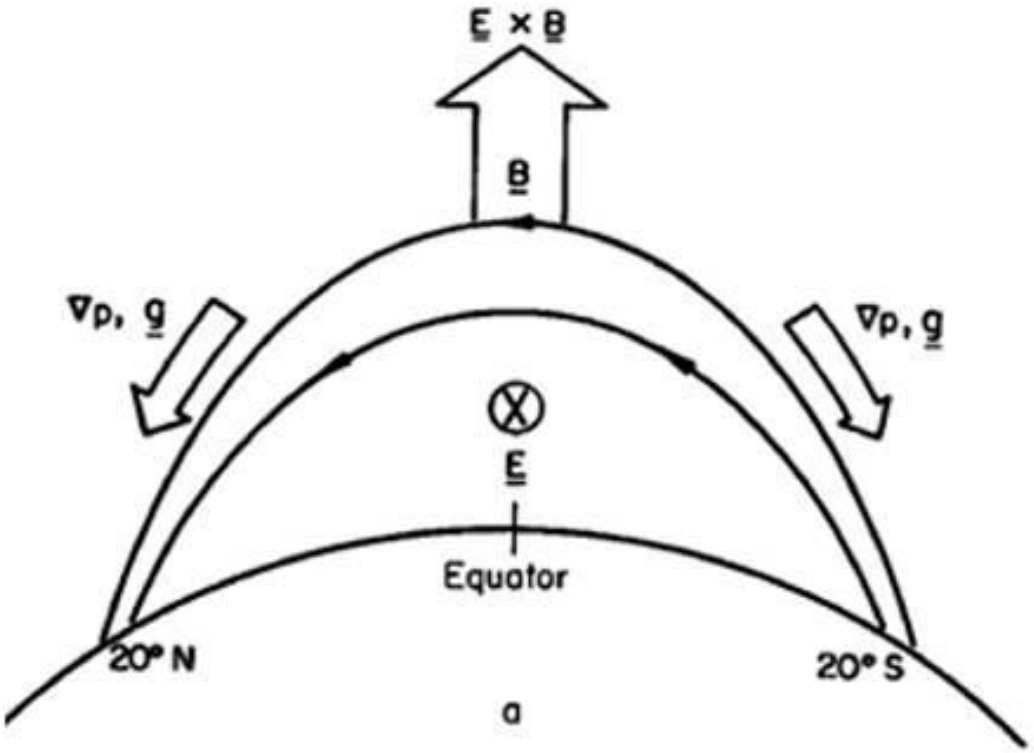
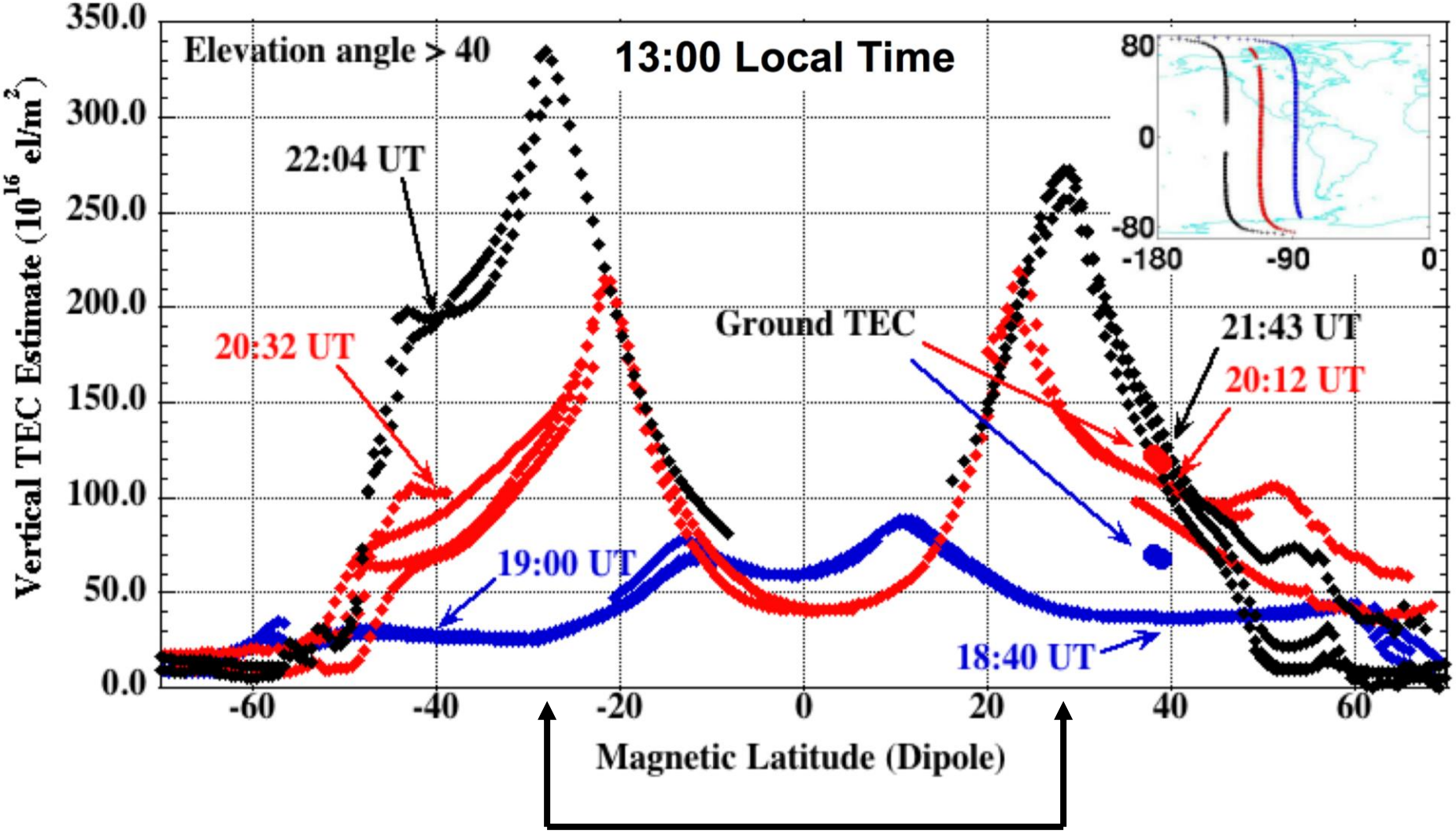


Figure 3 – Appleton Anomaly scheme.

Oct 30, 2003: CHAMP Buildup of TEC on the Dayside

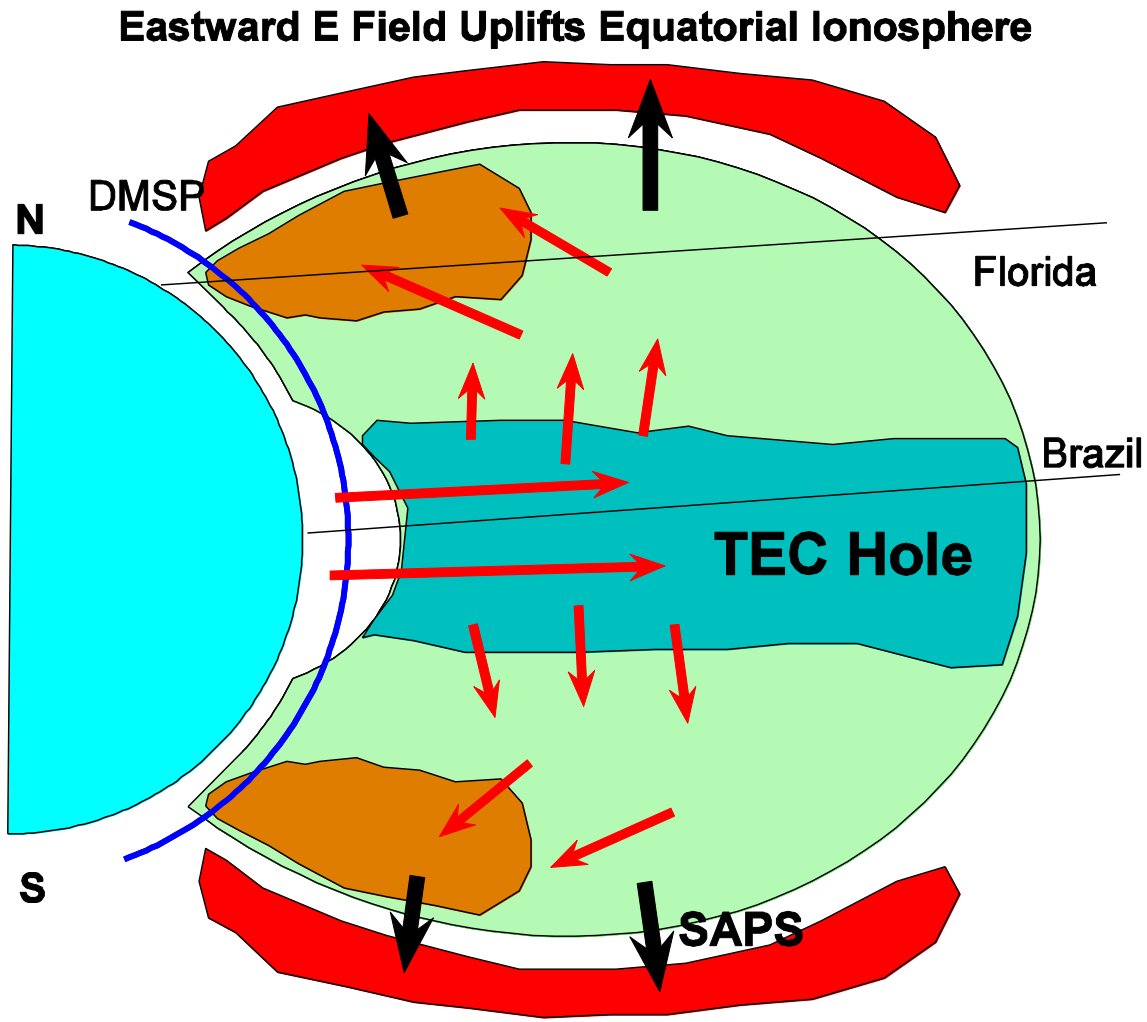


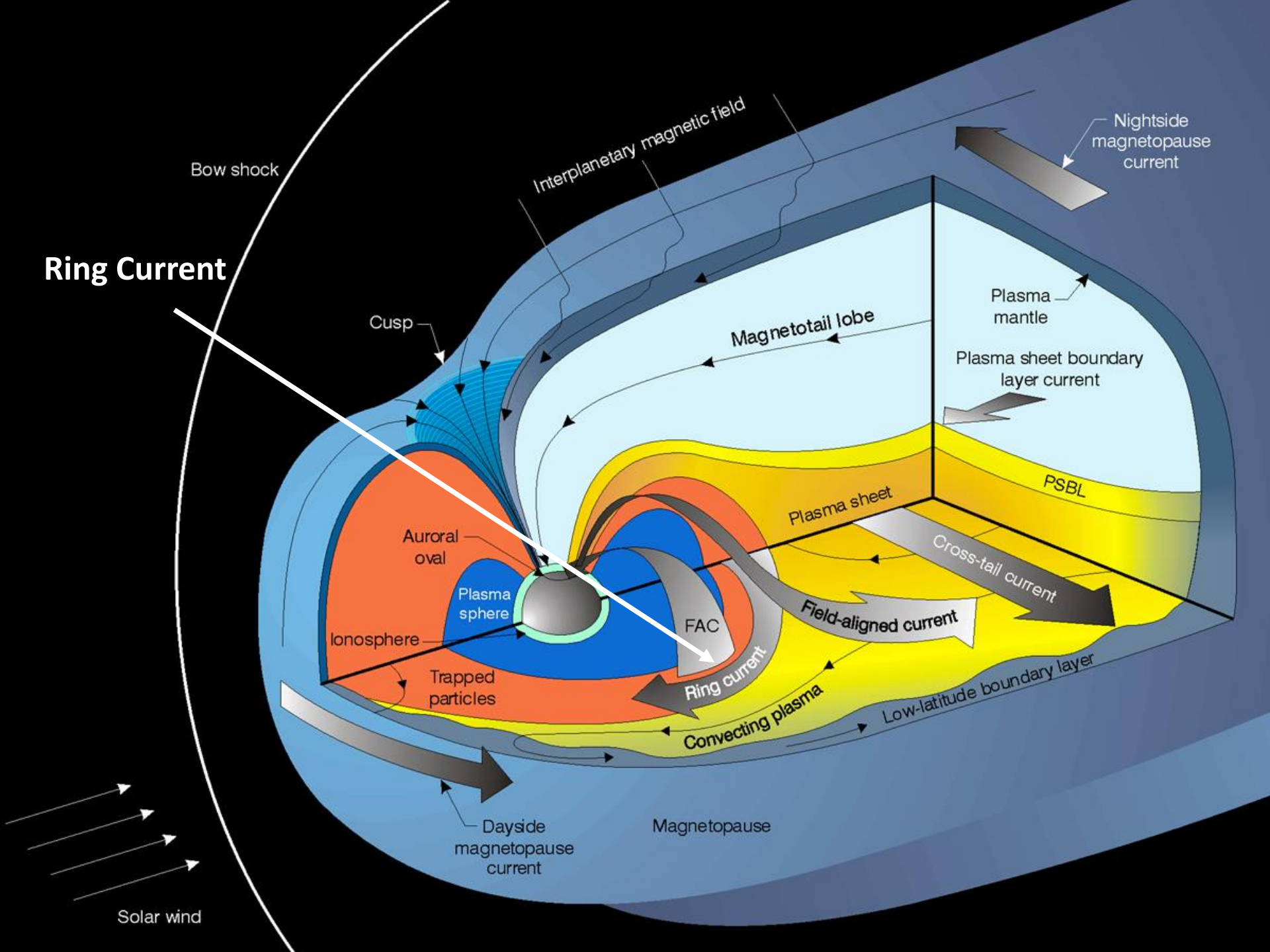
Spread EIA Crests

30 October, 2003

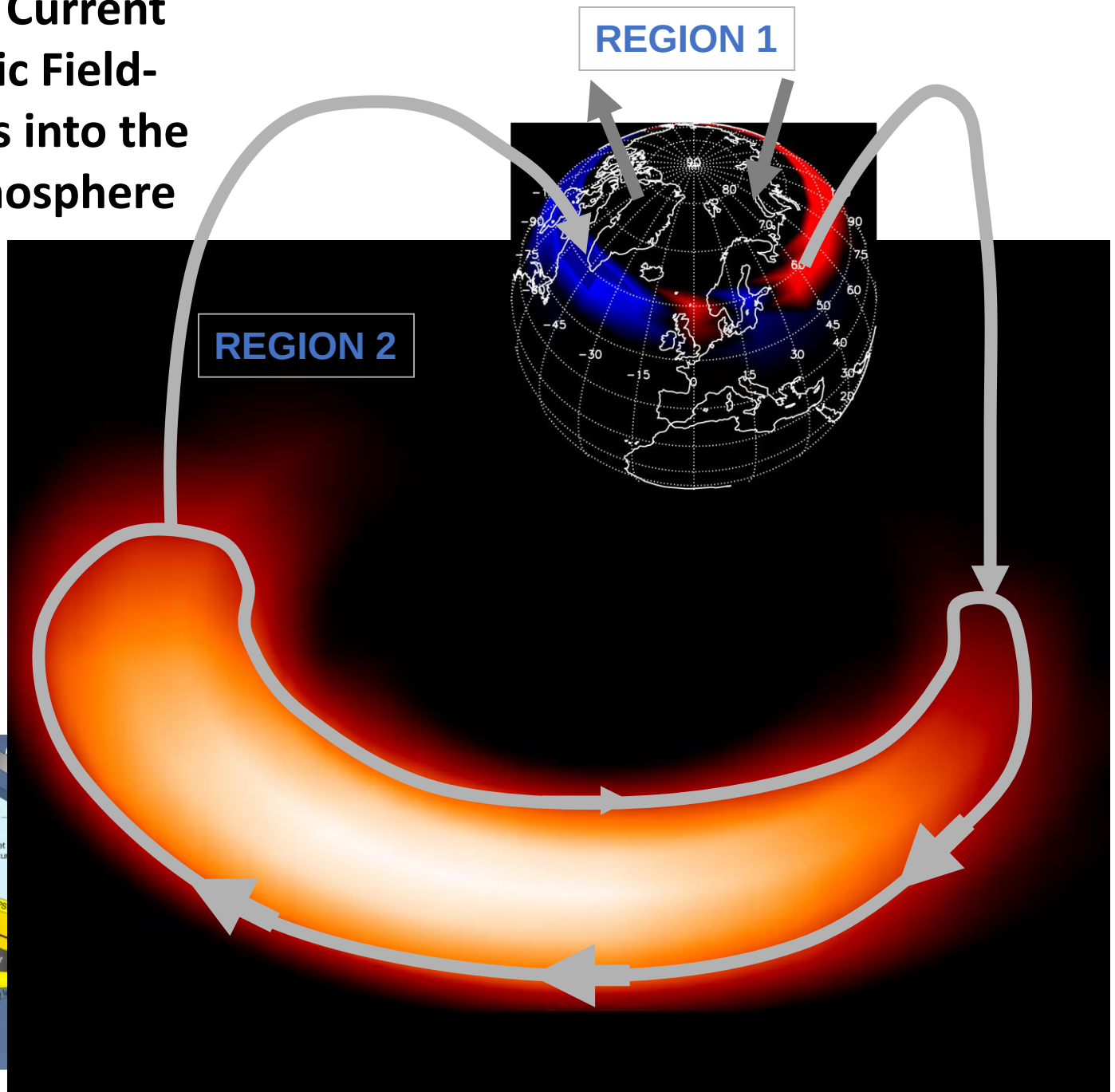
Global Coupled Effects

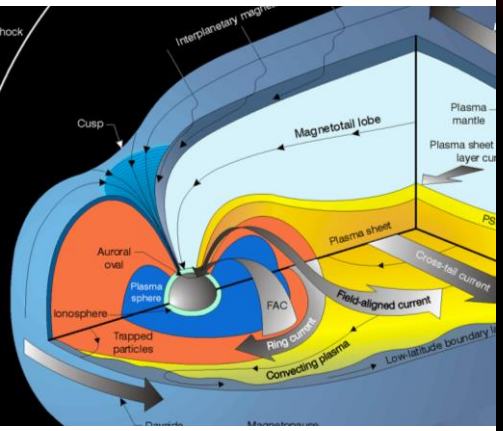
Redistribution Involves Significant Poleward Displacement of the EIA-Crest Plasma



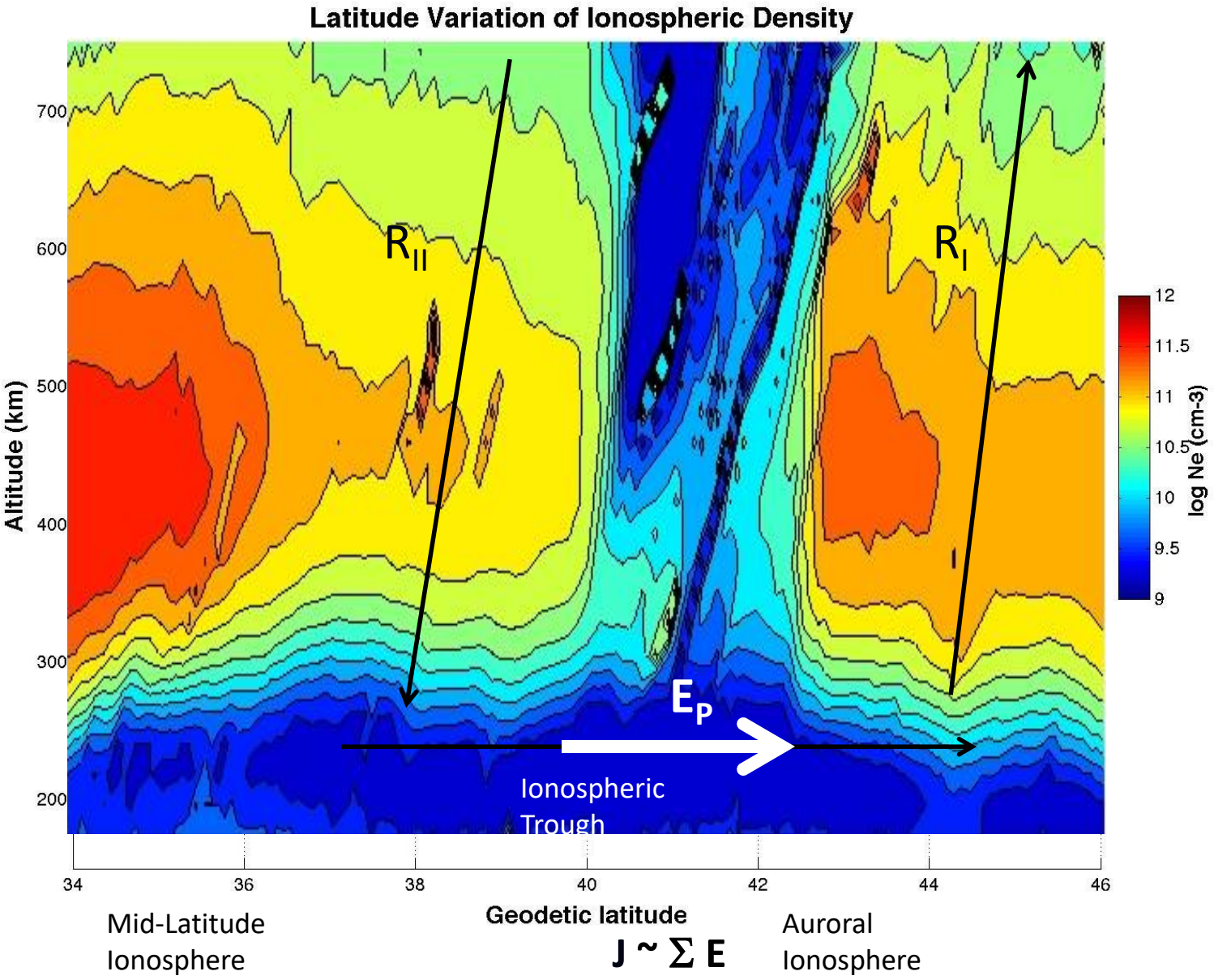

Ring Current
Bow shock
Interplanetary magnetic field
Nightside magnetopause current
Cusp
Magnetotail lobe
Plasma mantle
Plasma sheet boundary layer current
PSBL
Plasma sheet
Auroral oval
Plasma sphere
Ionosphere
Trapped particles
FAC
Field-aligned current
Cross-tail current
Ring current
Convecting plasma
Low-latitude boundary layer
Dayside magnetopause current
Magnetopause
Solar wind

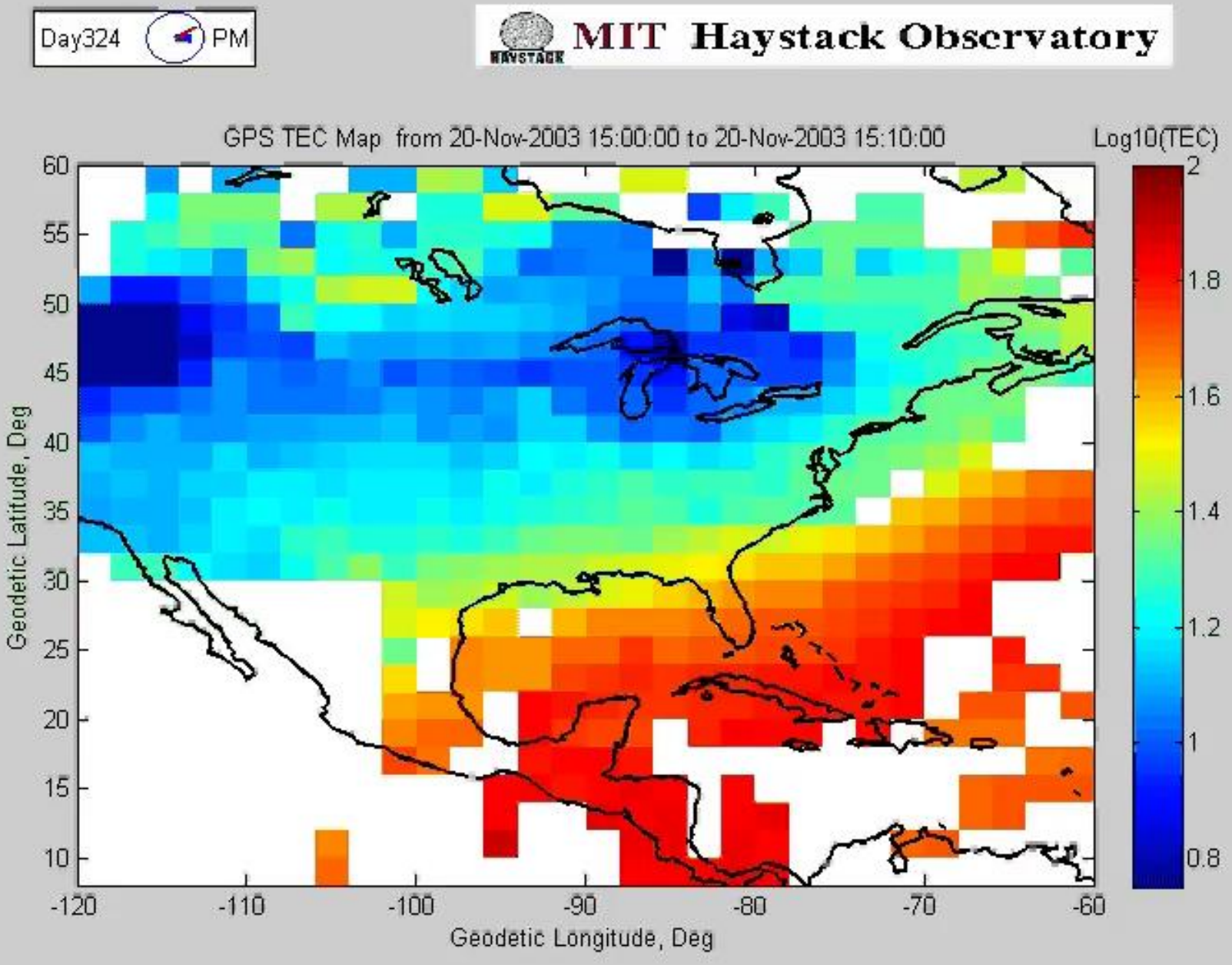
Disturbed Ring Current drives Magnetic Field-Aligned Currents into the Sub-Auroral Ionosphere





Ionospheric Conductance is Low in the Trough

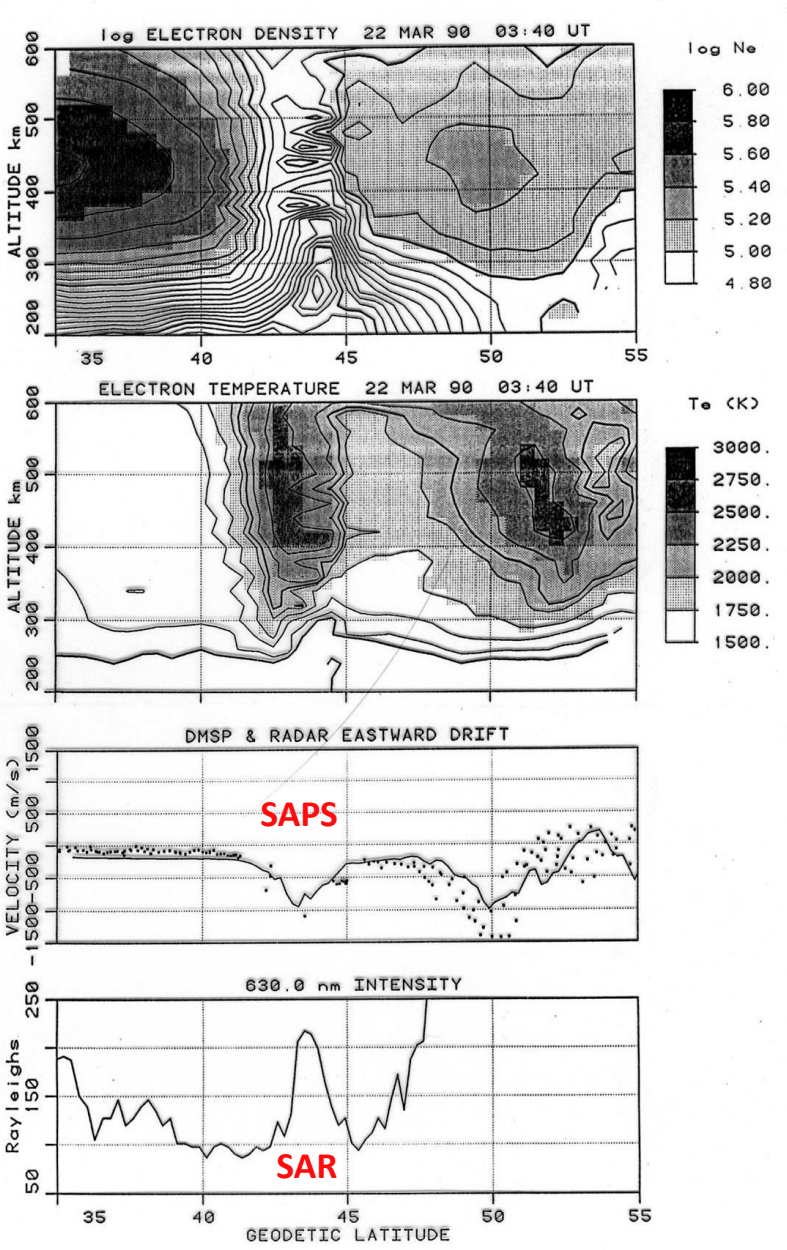


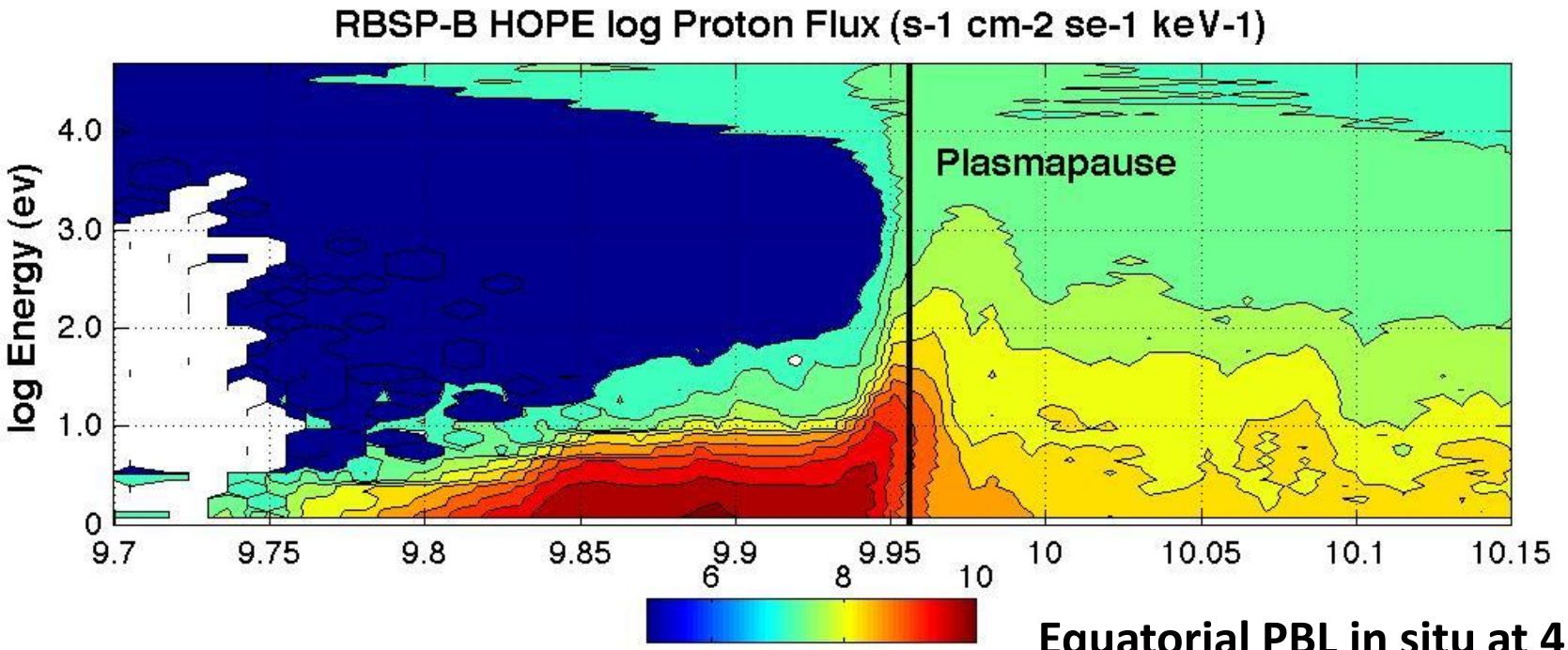

Day324
PM
MIT Haystack Observatory
GPS TEC Map from 20-Nov-2003 15:00:00 to 20-Nov-2003 15:10:00
Log10(TEC)
2
1.8
1.6
1.4
1.2
1
0.8
Geodetic Latitude, Deg
60
55
50
45
40
35
30
25
20
15
10
-120
-110
-100
-90
-80
-70
-60
Geodetic Longitude, Deg

The Plasmasphere Boundary Layer (PBL) at Ionospheric Altitudes

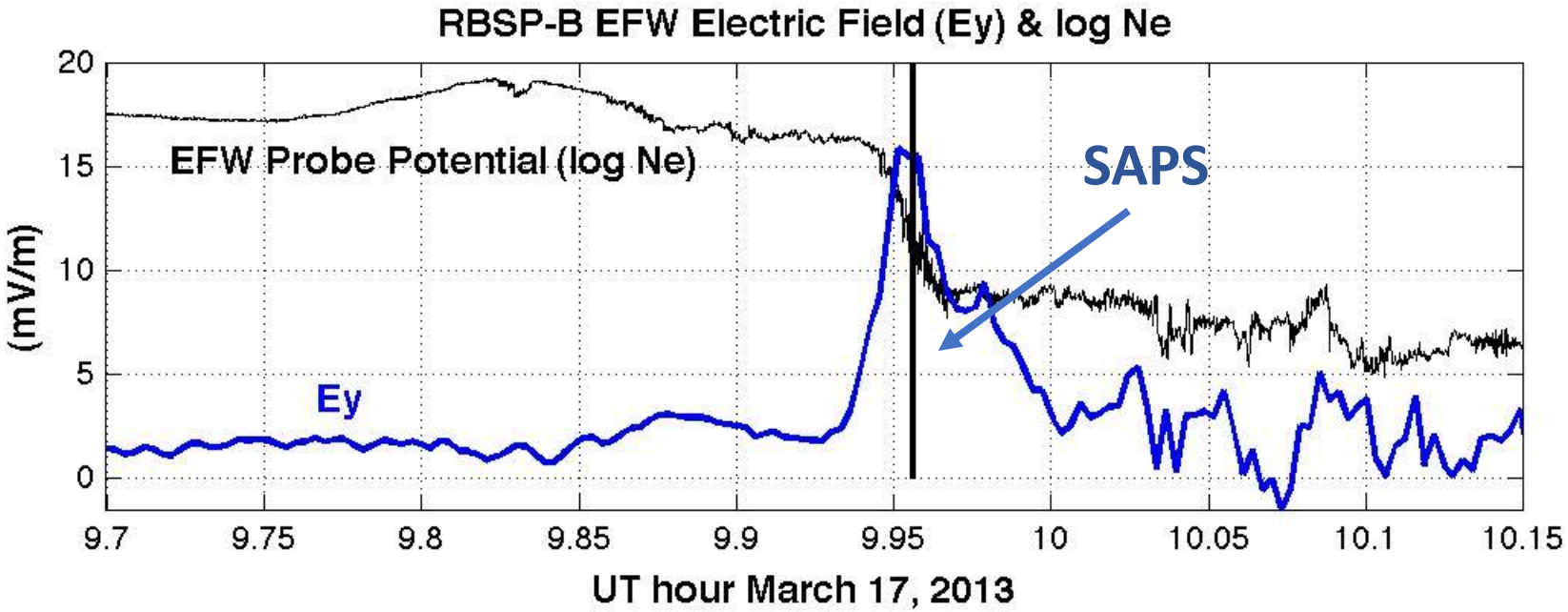
SAR (Stable Auroral Red) Arc

Millstone Hill Radar Observations

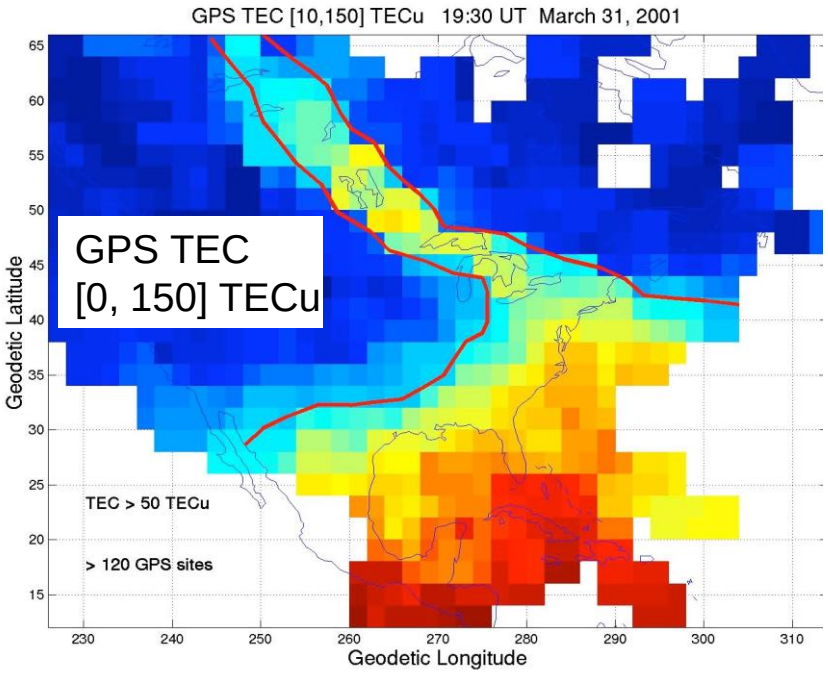


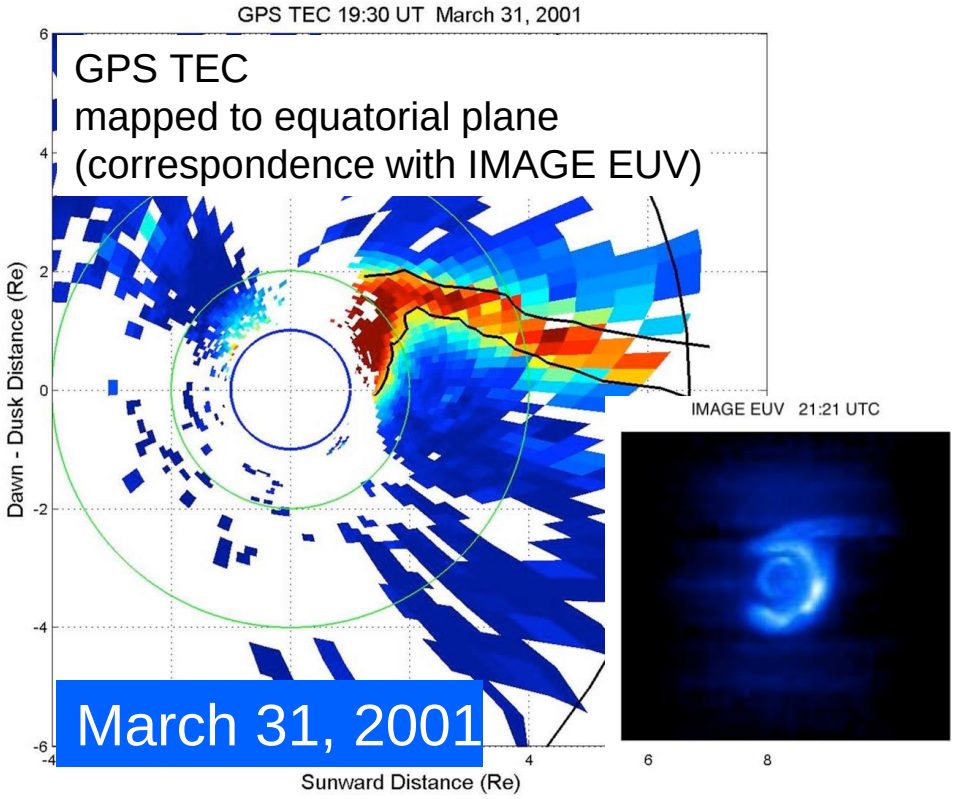


Equatorial PBL in situ at 4 R_E



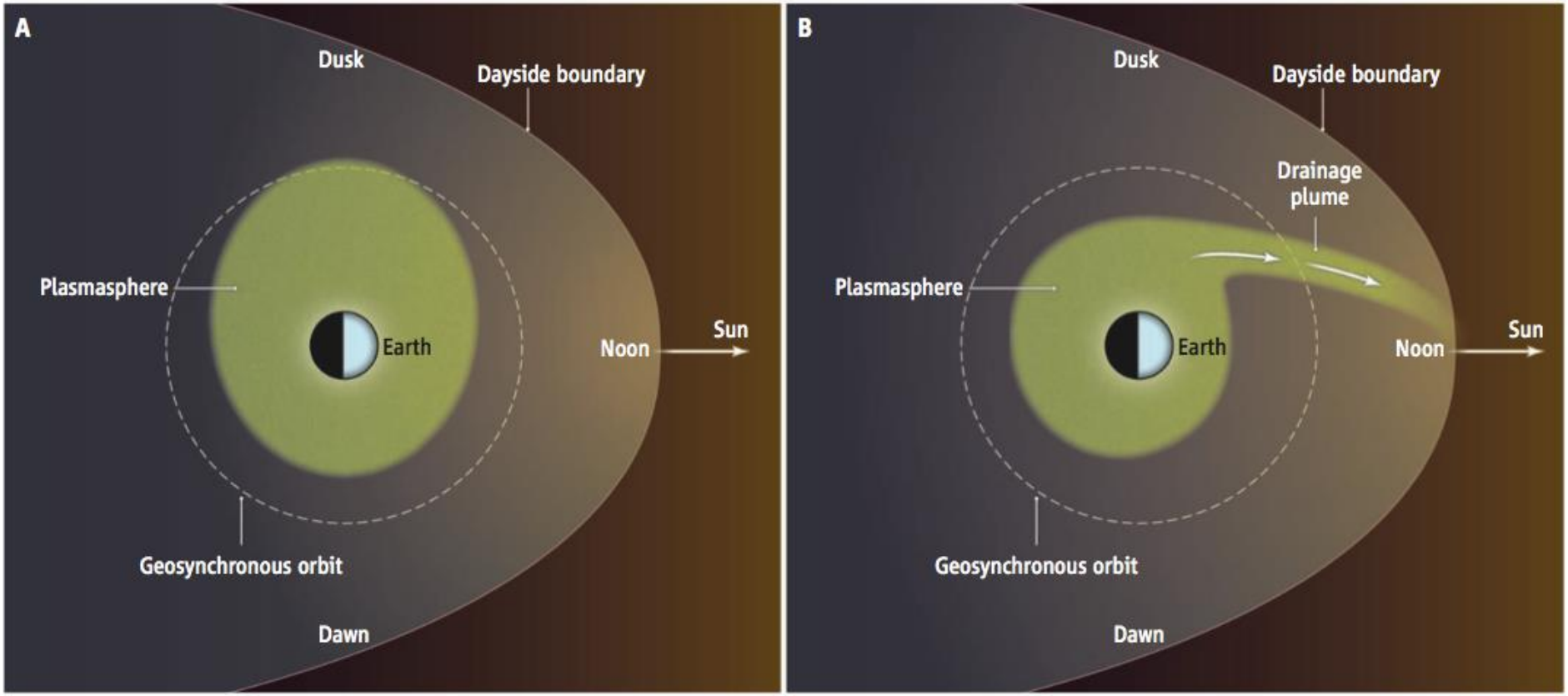
Ionospheric Structure Mirrors Magnetosphere Processes and Dynamics,





(e.g. Foster et al 2004)

Plasmaspheric drainage plumes: Mass-loading the magnetopause

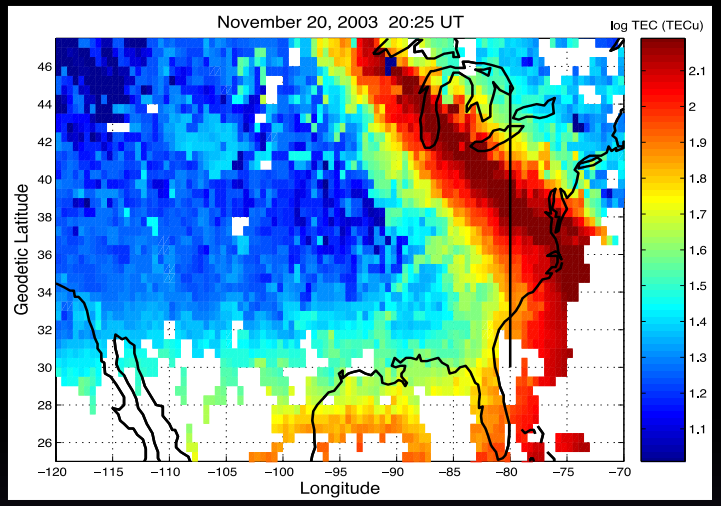


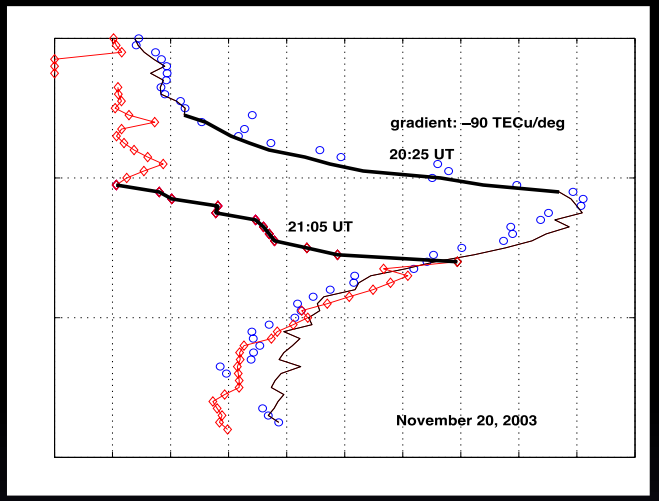
Pushing back. From a perspective high over the North Pole of Earth, the cold plasma in the equatorial plane of Earth's magnetosphere is sketched at two different times. (**A**) When solar-wind coupling is weak, the near-Earth reservoir (plasmasphere) is shown in green. (**B**) When coupling becomes stronger, the plume of sunward-convecting cold plasma eroding from the reservoir is seen. The cold plasma of the plume flows to the dayside boundary of the magnetosphere, where it interferes with the reconnection process. Space-based ultraviolet images of this cold-plasma movement can be seen in Goldstein (*7*).

Ionospheric plasma populates Earth's plasmasphere

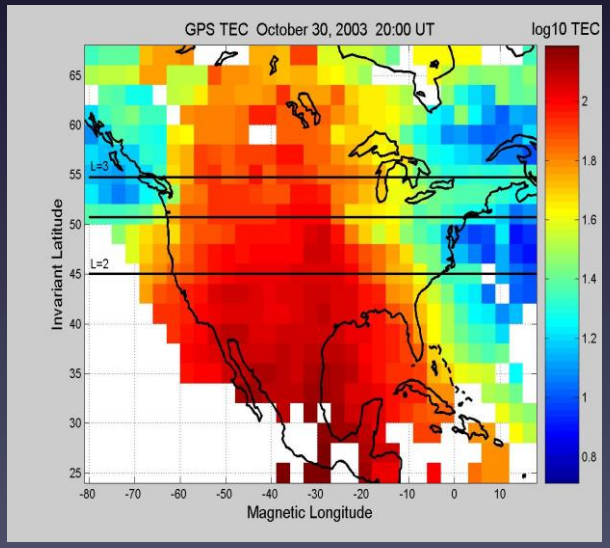
The plasmasphere drainage plume extends to the dayside magnetopause

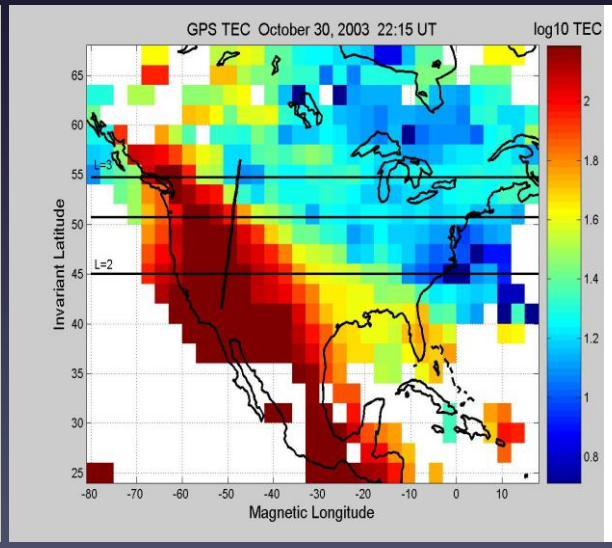
[Borovsky, Science, 2014]

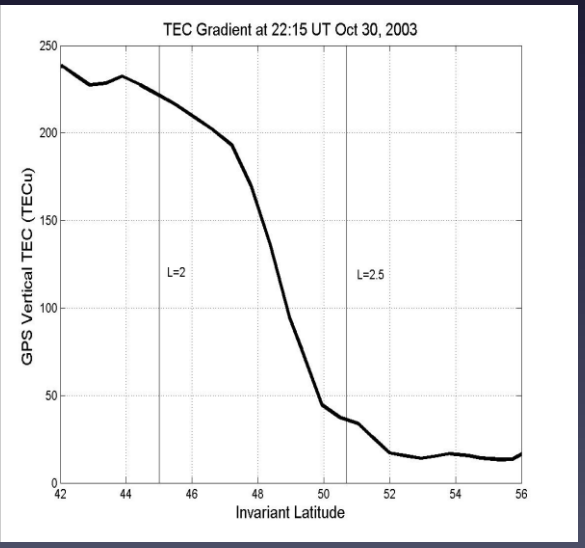




Space Weather Effects: Stormtime SED plumes develop steep TEC gradients along their edges, particularly at their poleward border where the SED overlaps the SAPS flow channel. Immediately poleward of the SED, collisional recombination in the high-speed SAPS flow reduces ion density and creates a deep ionospheric density trough and steepens the TEC gradient.







A Few Last Minute Facts about the Geospace Aspects of the Ionosphere

- **Cold plasma of ionospheric origin populates Earth's plasmasphere**.
- **Cold plasma circulation in the dayside magnetosphere maps to high latitude F region ionosphere dynamics**
- Ionospheric plasma structure, gradients, and dynamics are intimately **related to geospace processes** and have considerable **space weather consequences**.