Ionosphere: Past, Present and Future Problems

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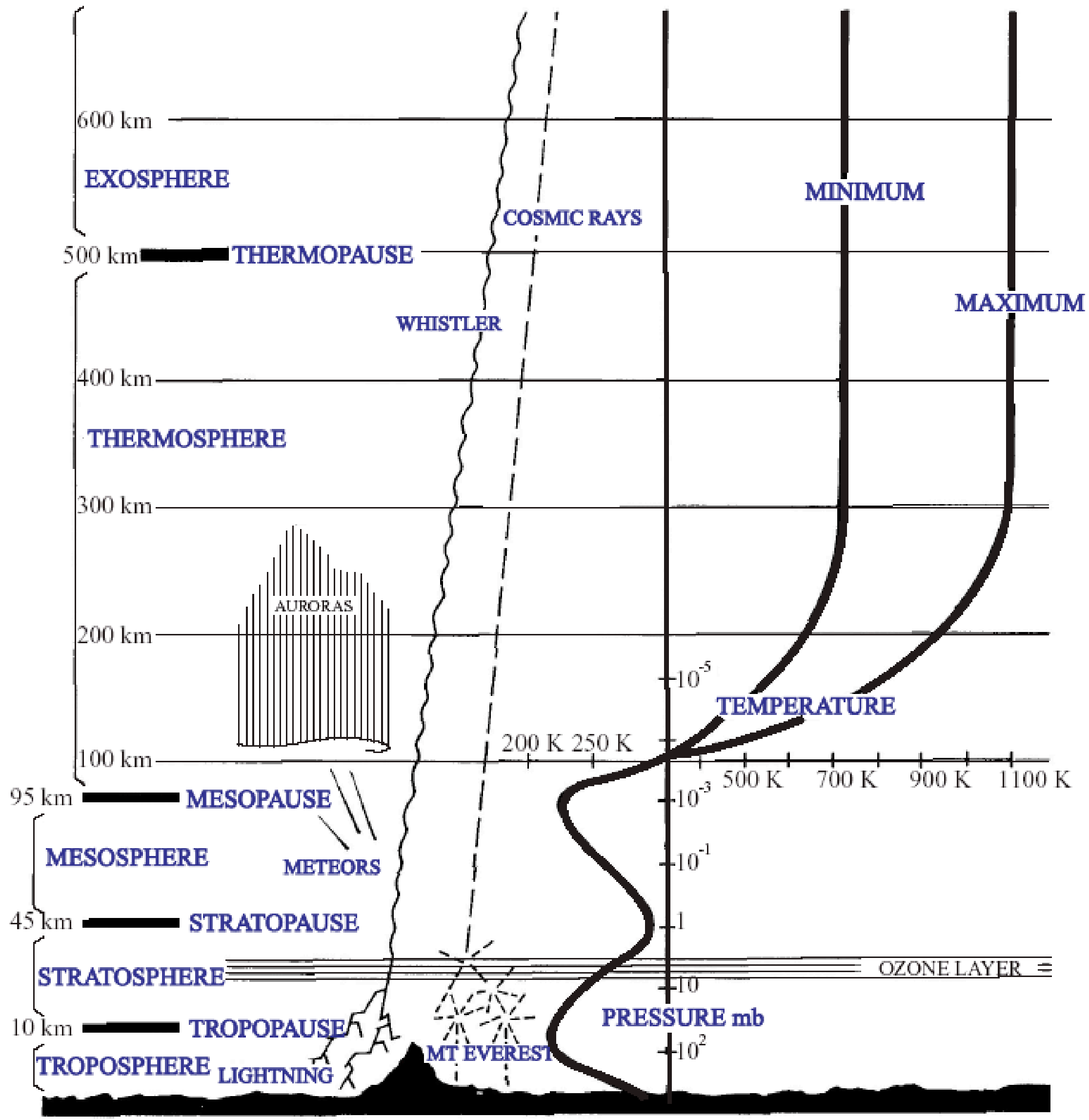
CEDAR Meeting
June 23, 2006

Outline

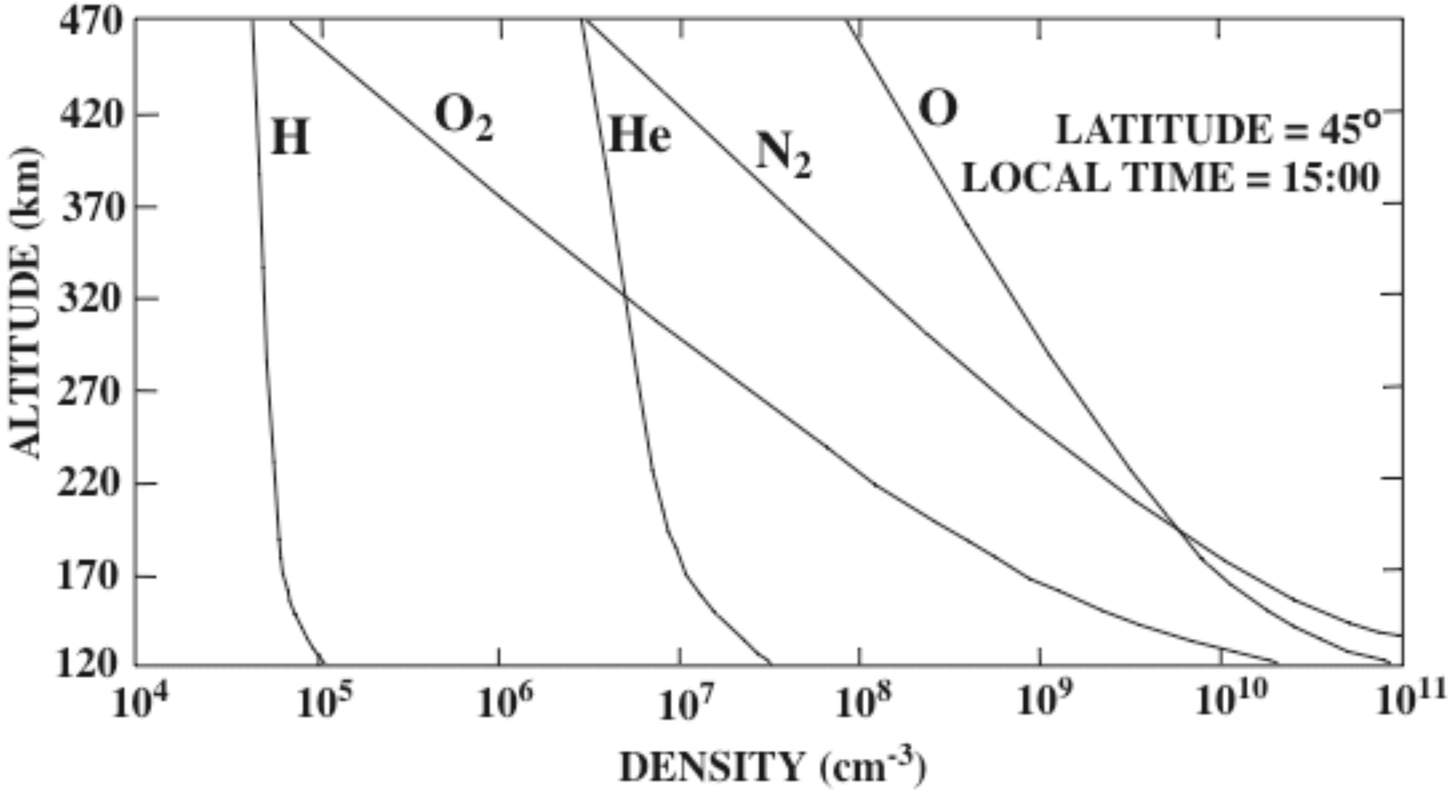
- Ionospheric Environment
- Status
- High Latitudes
- Middle Latitudes
- Low Latitudes
- Summary

Ionospheric Environment

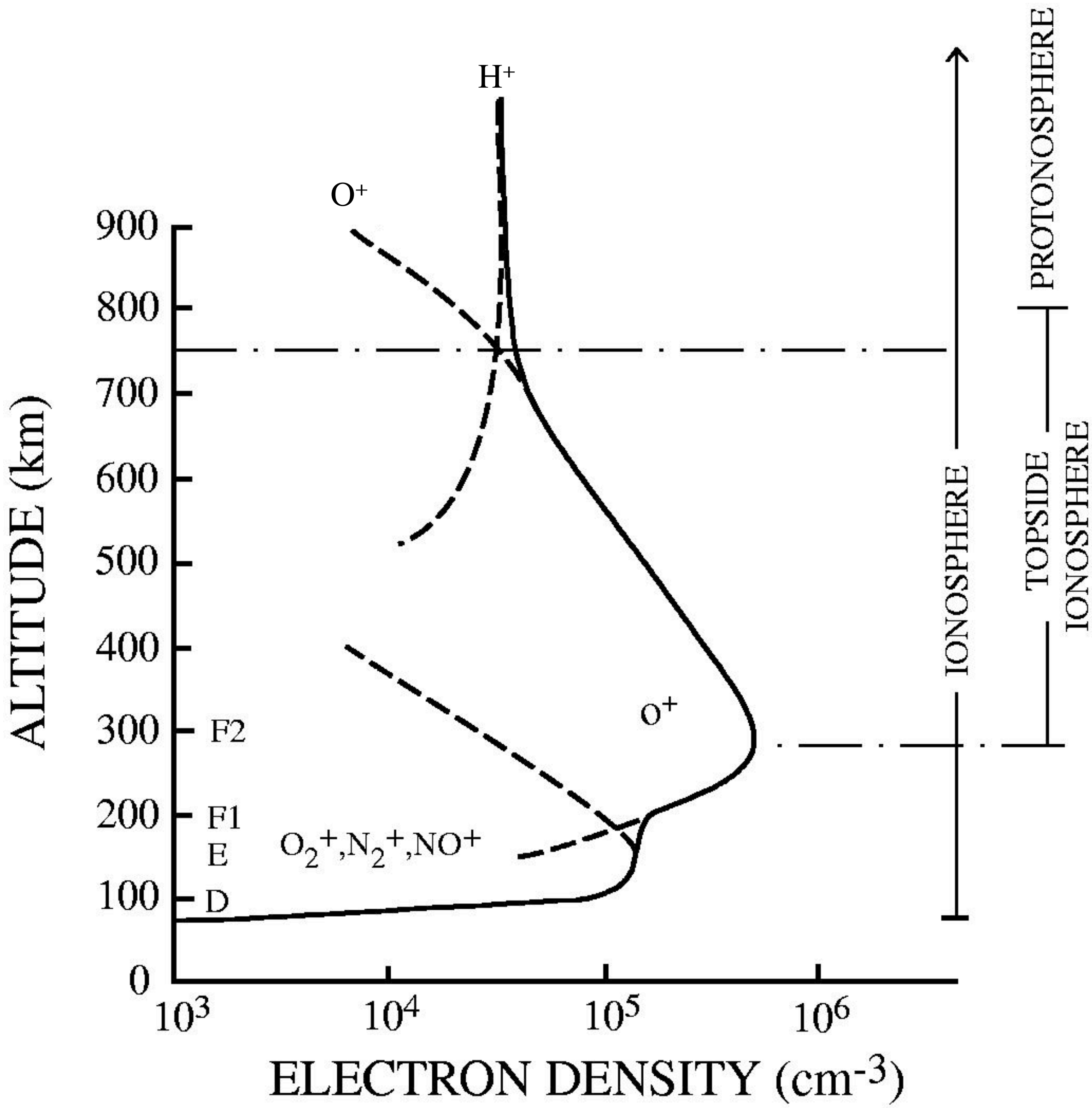
ATMOSPHERE



600 km
EXOSPHERE
COSMIC RAYS
MINIMUM
500 km
THERMOPAUSE
WHISTLER
MAXIMUM
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
METEORS
10^{-1}
45 km
STRATOPAUSE
1
STRATOSPHERE
OZONE LAYER
10
10 km
TROPOPAUSE
PRESSURE mb
MT EVEREST
10^{2}
TROPOSPHERE
LIGHTNING



470
420
370
320
270
220
170
120
ALTITUDE (km)
H
O2
He
N2
O
LATITUDE = 45°
LOCAL TIME = 15:00
10^4
10^5
10^6
10^7
10^8
10^9
10^10
10^11
DENSITY (cm^-3)



F-Region

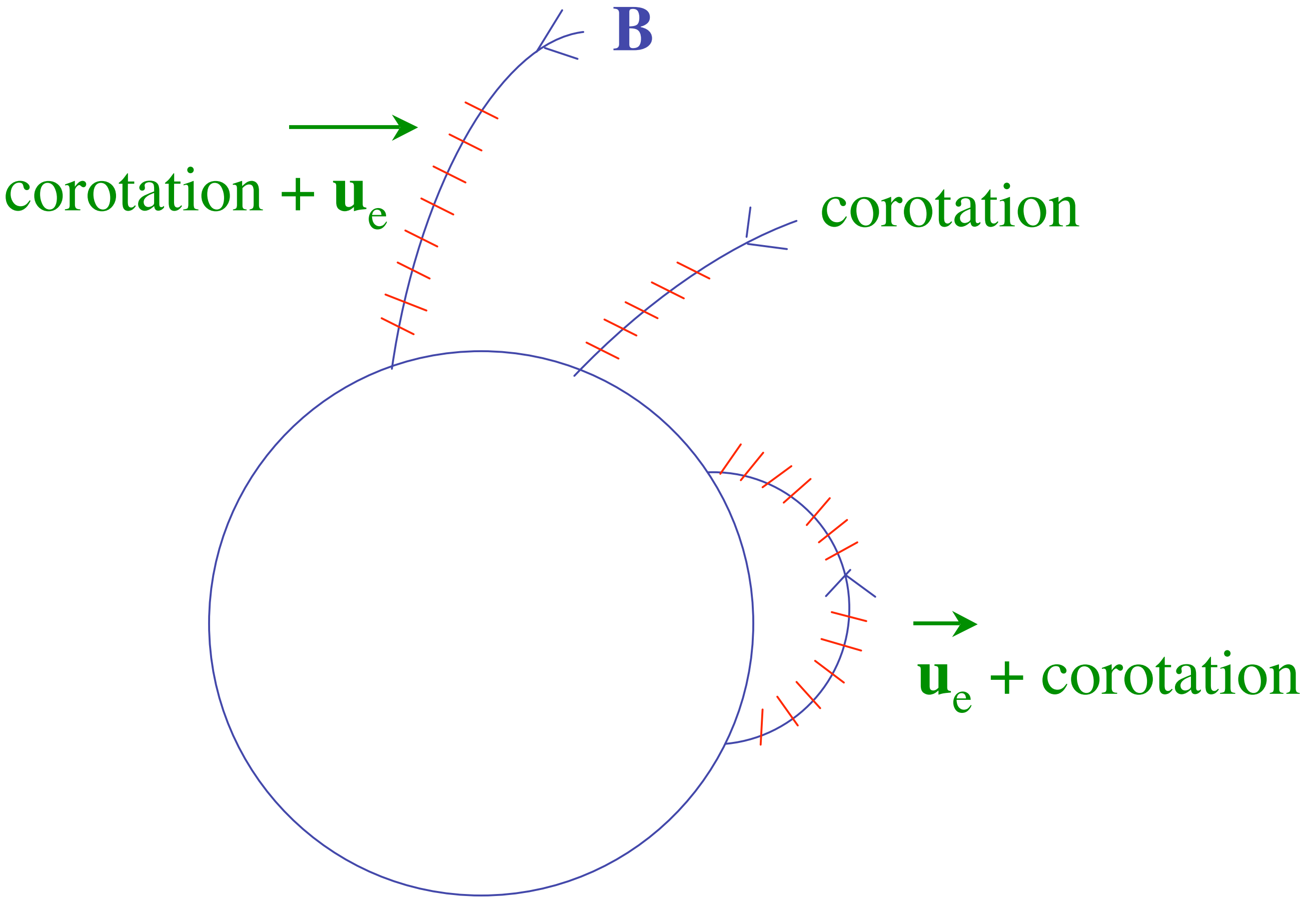
$O + h\nu \rightarrow O^+ + e^*$

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

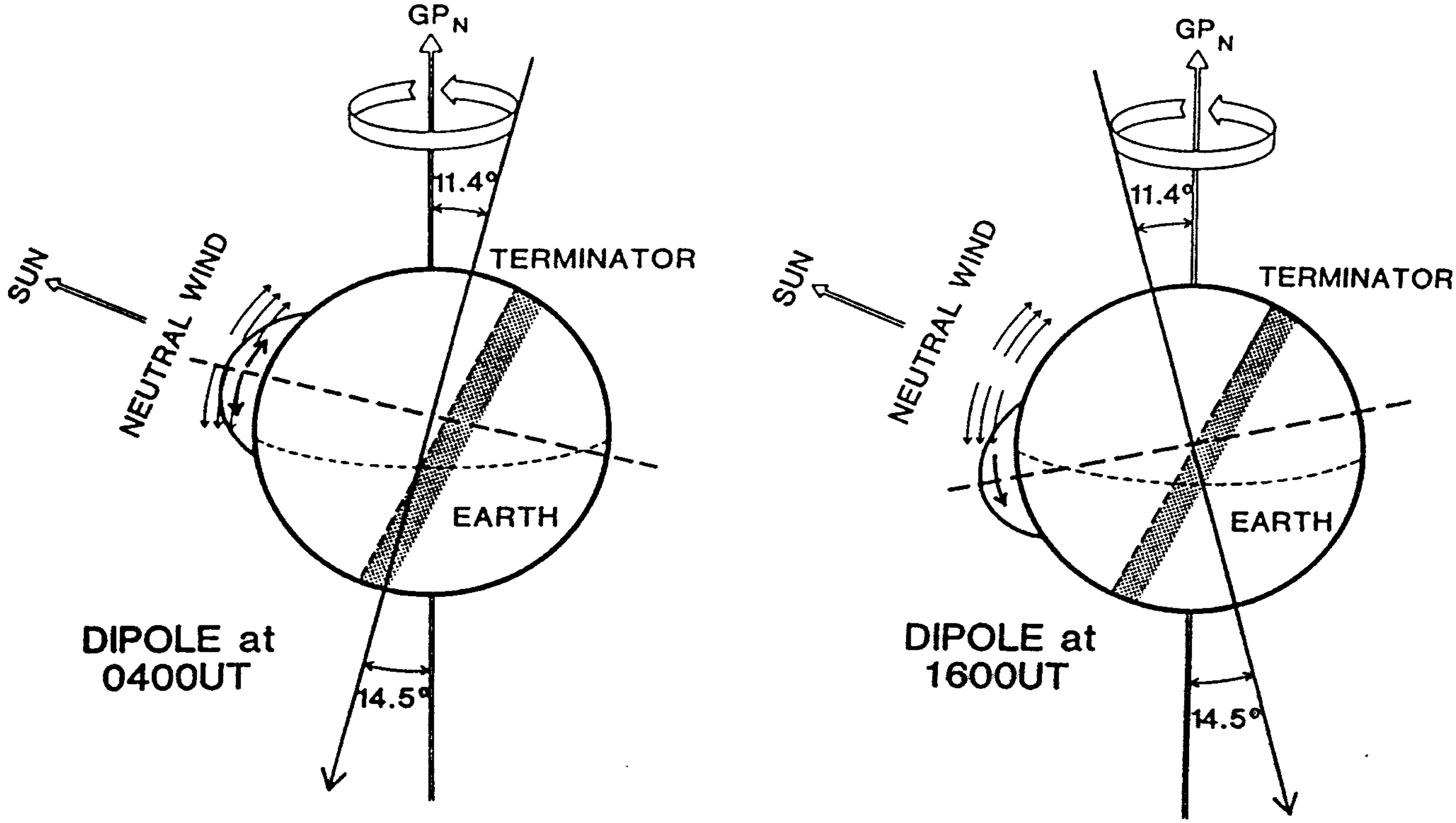
$O^+ + O_2 \rightarrow O_2^+ + O$

Topside

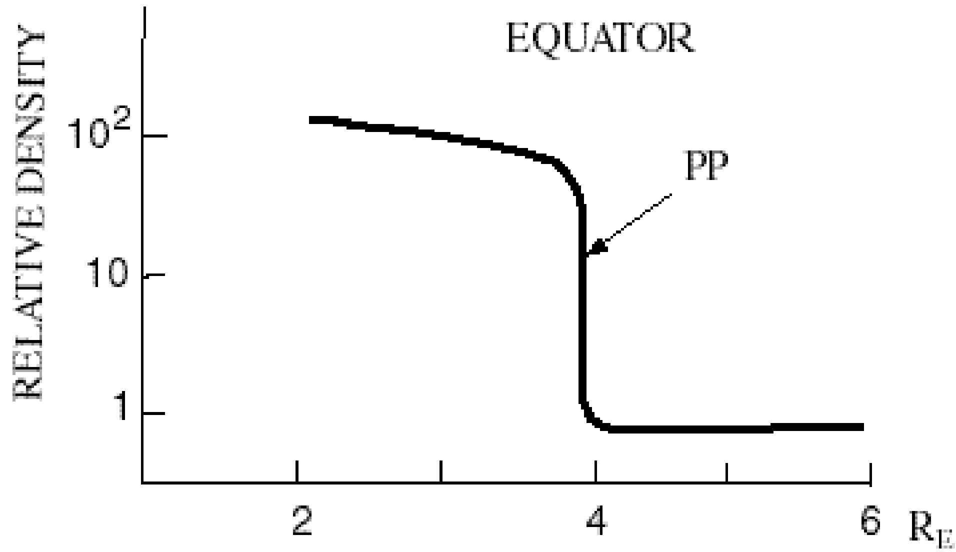
$O^+ + H \Leftrightarrow H^+ + O$

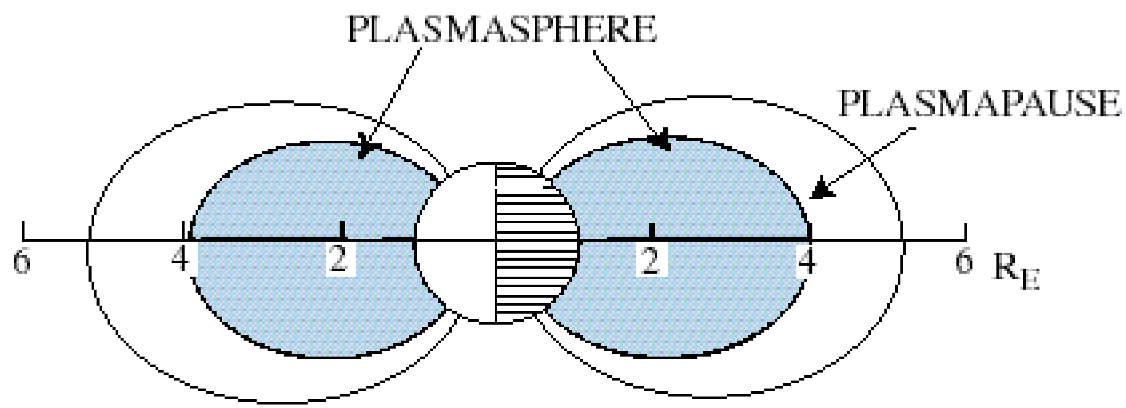


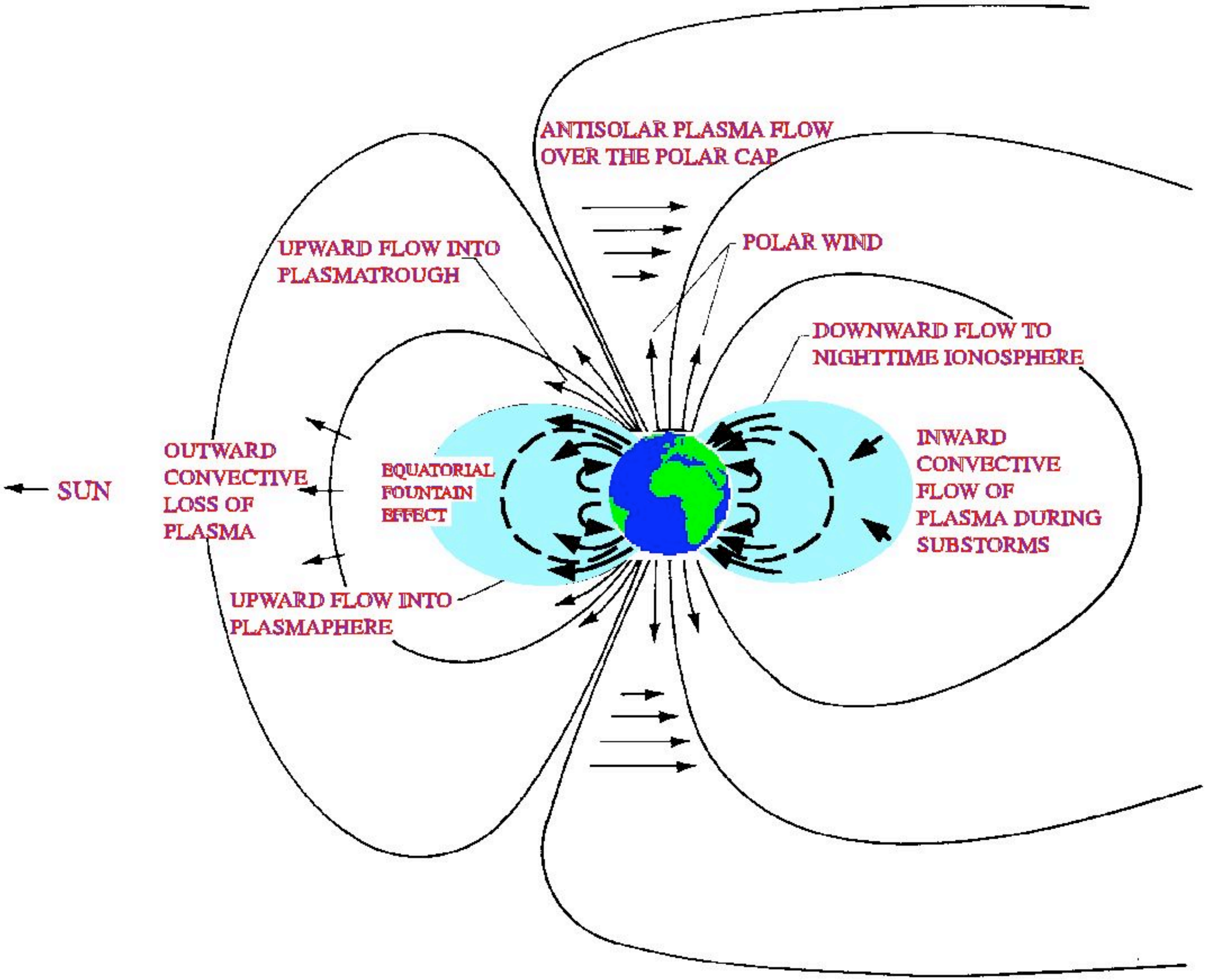
Diffusion and Wind-Induced Flow Along B



Sojka and Schunk (1979)


EQUATOR
RELATIVE DENSITY
10^2
10
1
PP
2
4
6
R_E


PLASMASPHERE
PLASMAPAUSE
6
4
2
2
4
6
R_E


ANTISOLAR PLASMA FLOW
OVER THE POLAR CAP
POLAR WIND
UPWARD FLOW INTO
PLASMATROUGH
DOWNWARD FLOW TO
NIGHTTIME IONOSPHERE
OUTWARD
CONVECTIVE
LOSS OF
PLASMA
SUN
EQUATORIAL
FOUNTAIN
EFFECT
INWARD
CONVECTIVE
FLOW OF
PLASMA DURING
SUBSTORMS
UPWARD FLOW INTO
PLASMAPHERE

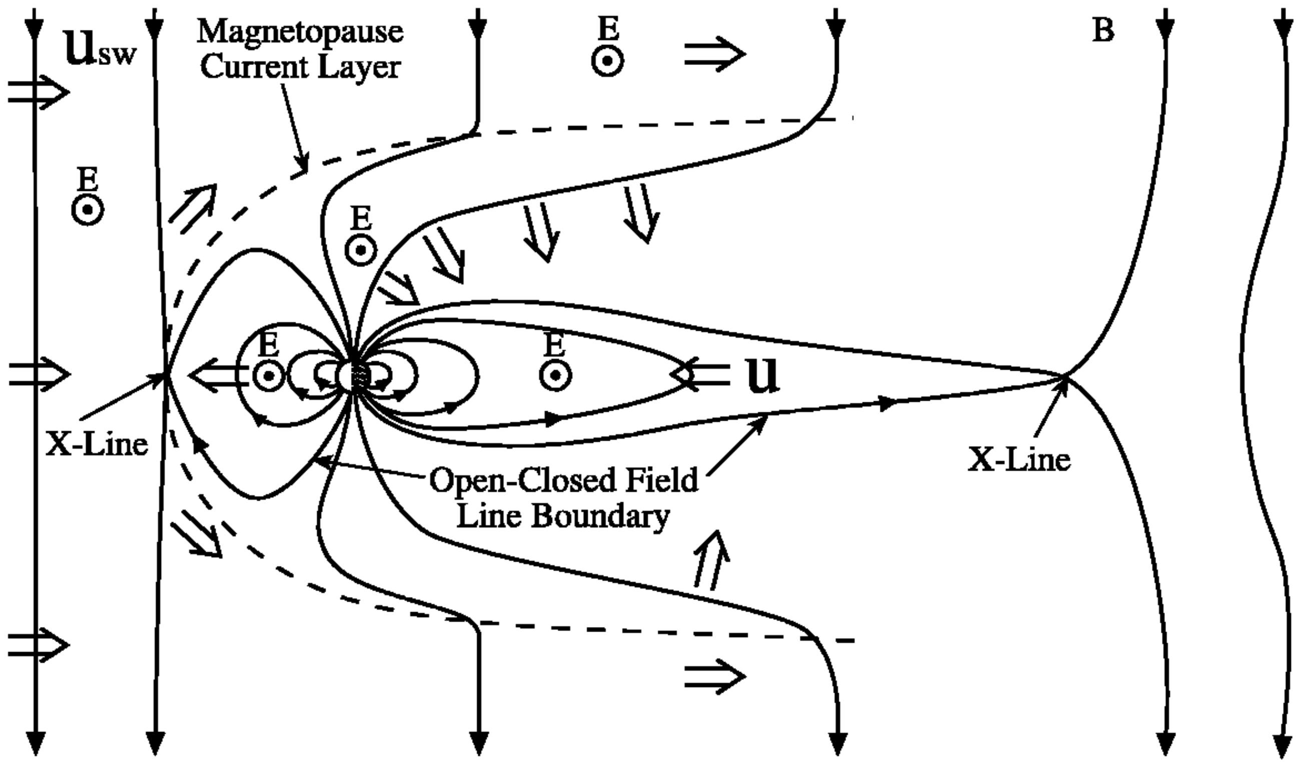
Ionospheric Variations

- Altitude
- Latitude
- Longitude
- Universal Time
- Season
- Solar Cycle
- Geomagnetic Activity

Status

- Ionosphere has both a Background State (Climatology) and a Disturbed State (Weather)
- Climatology is Basically Understood
- Weather Involves Storms, Substorms, Plasma Structures, Wave Activity, and Plasma Instabilities
- Main Research Focus is on Weather

High Latitudes



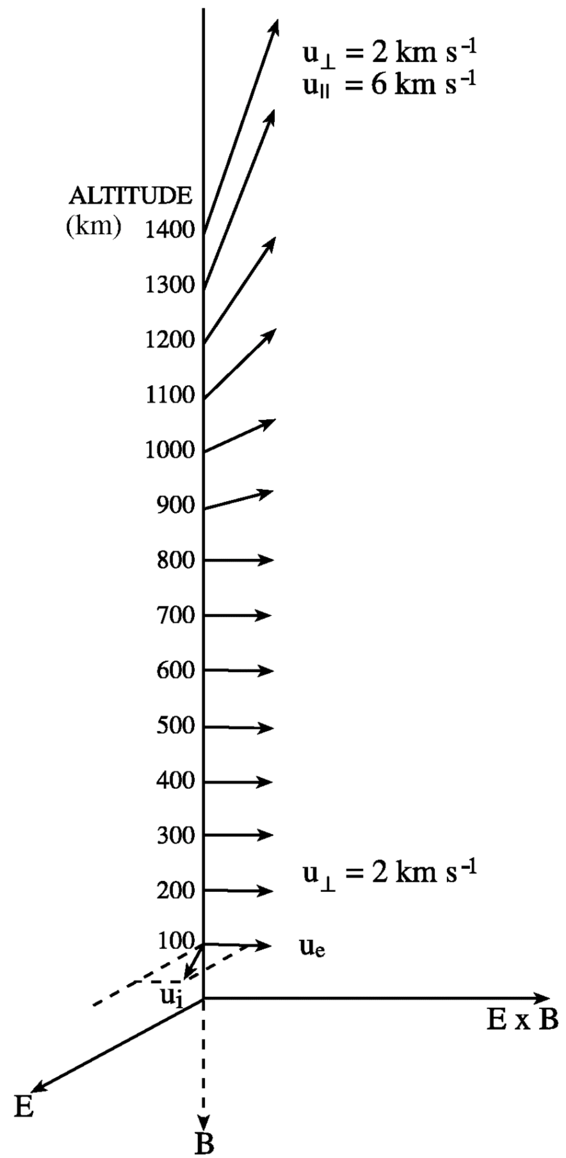
u_sw
Magnetopause
Current Layer
E
B
E
E
E
E
u
X-Line
Open-Closed Field
Line Boundary
X-Line

Lyons (1992)

Polar Wind

F-Region
Convection

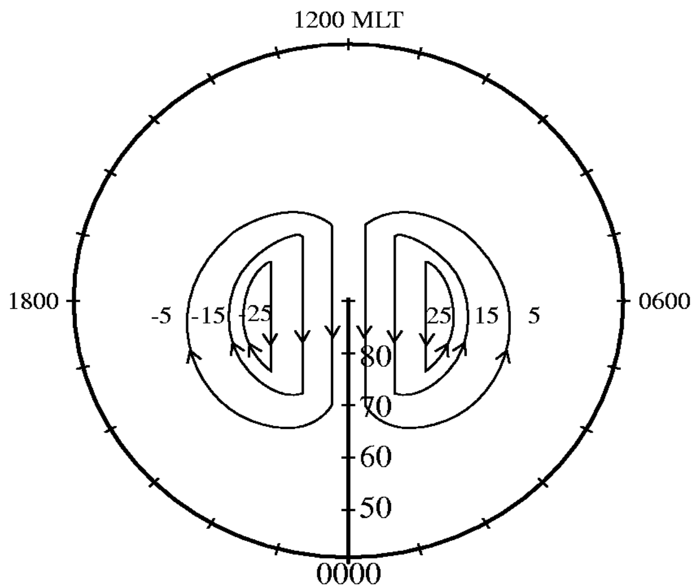
E-Region
Currents

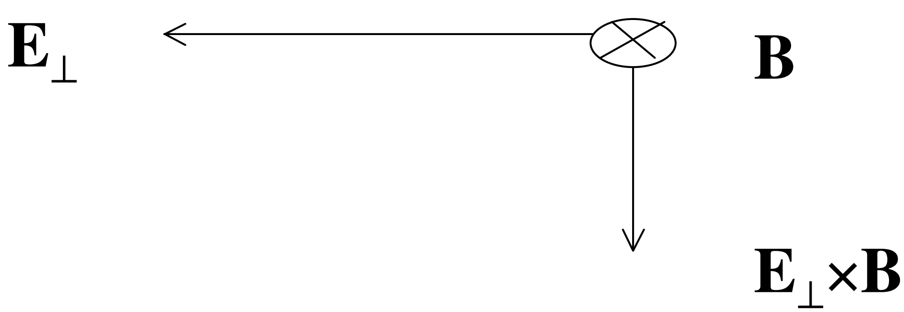


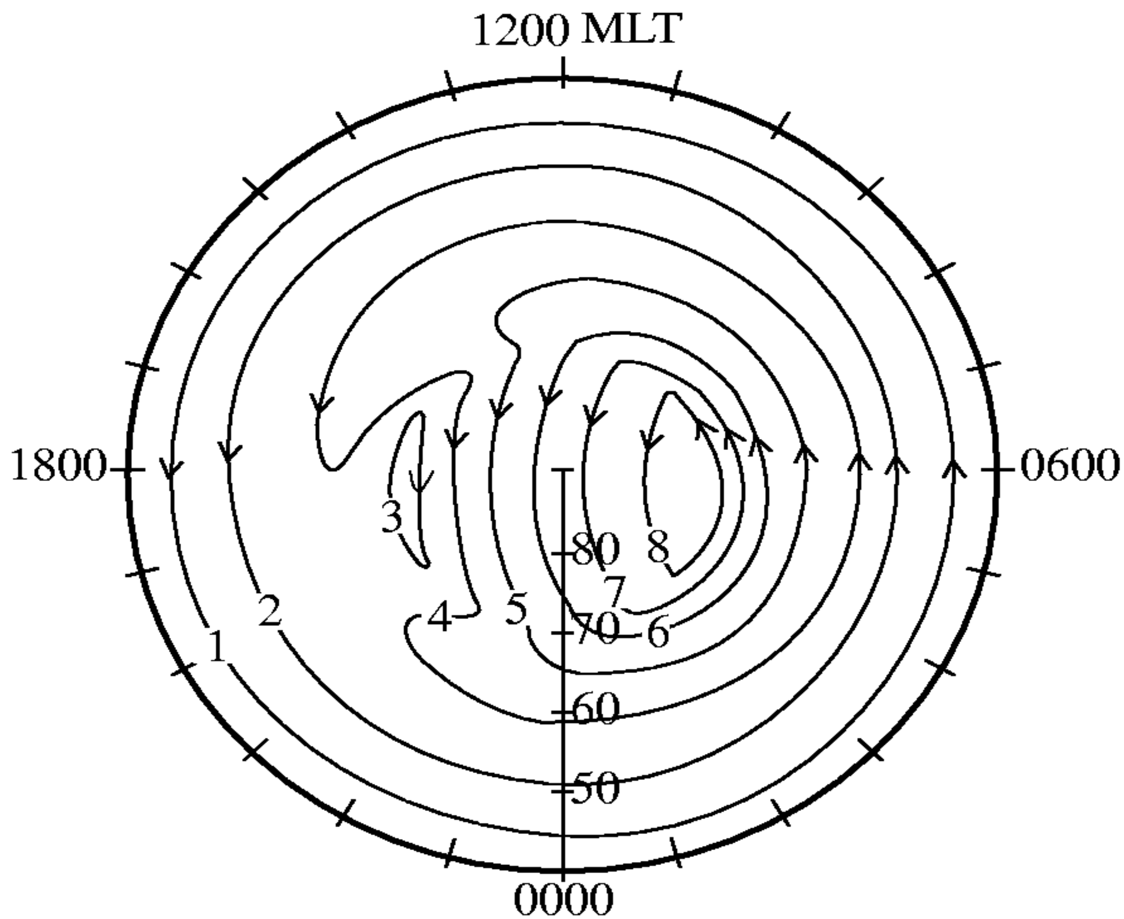
Schunk (1983)

Volland Model

2-cell Pattern, ΔΦ=40 kV, No Corotation



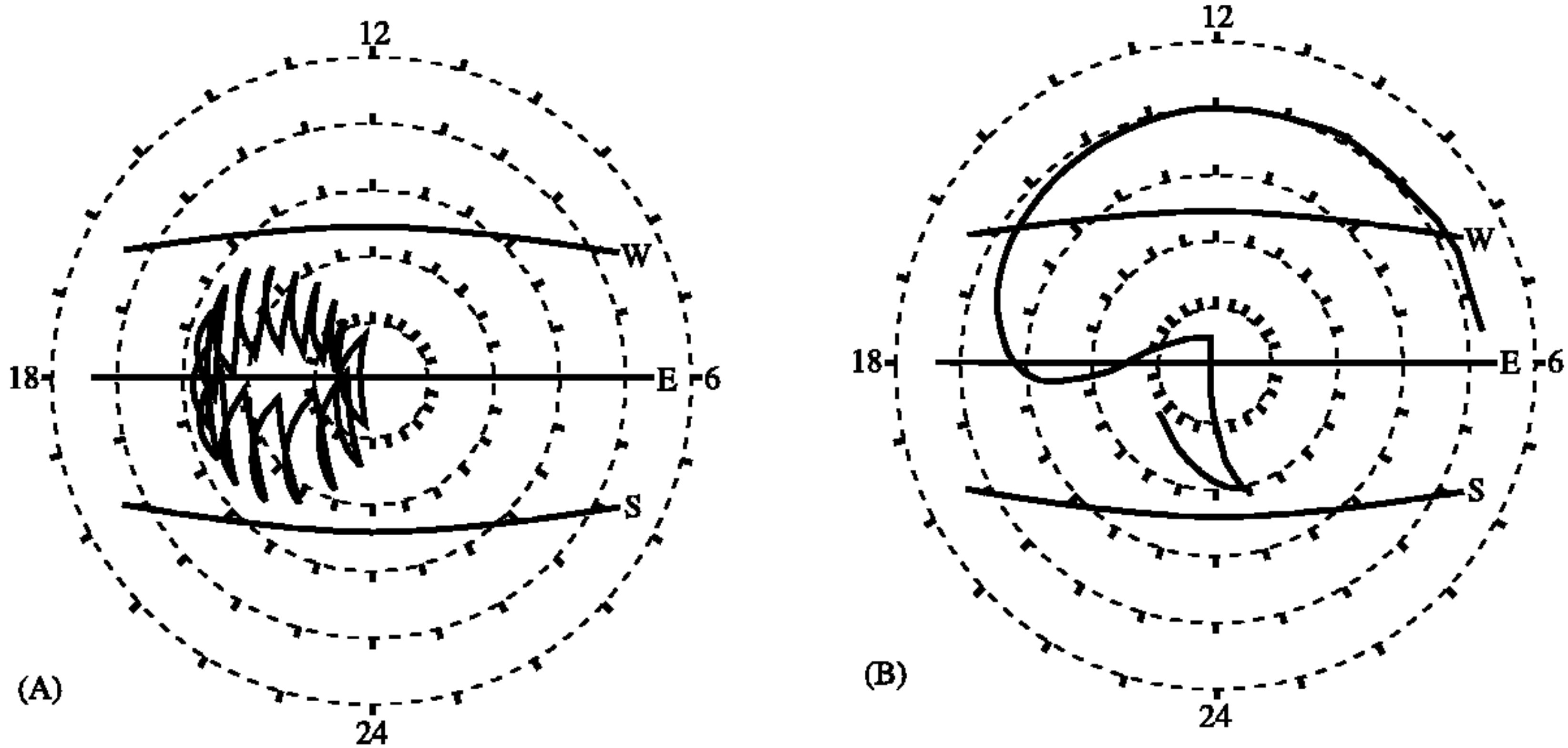




LABEL	1	2	3	4	5	6	7	8
CIRCULATION PERIOD (day)	1.00	1.01	0.10	1.34	0.50	0.31	0.18	0.11

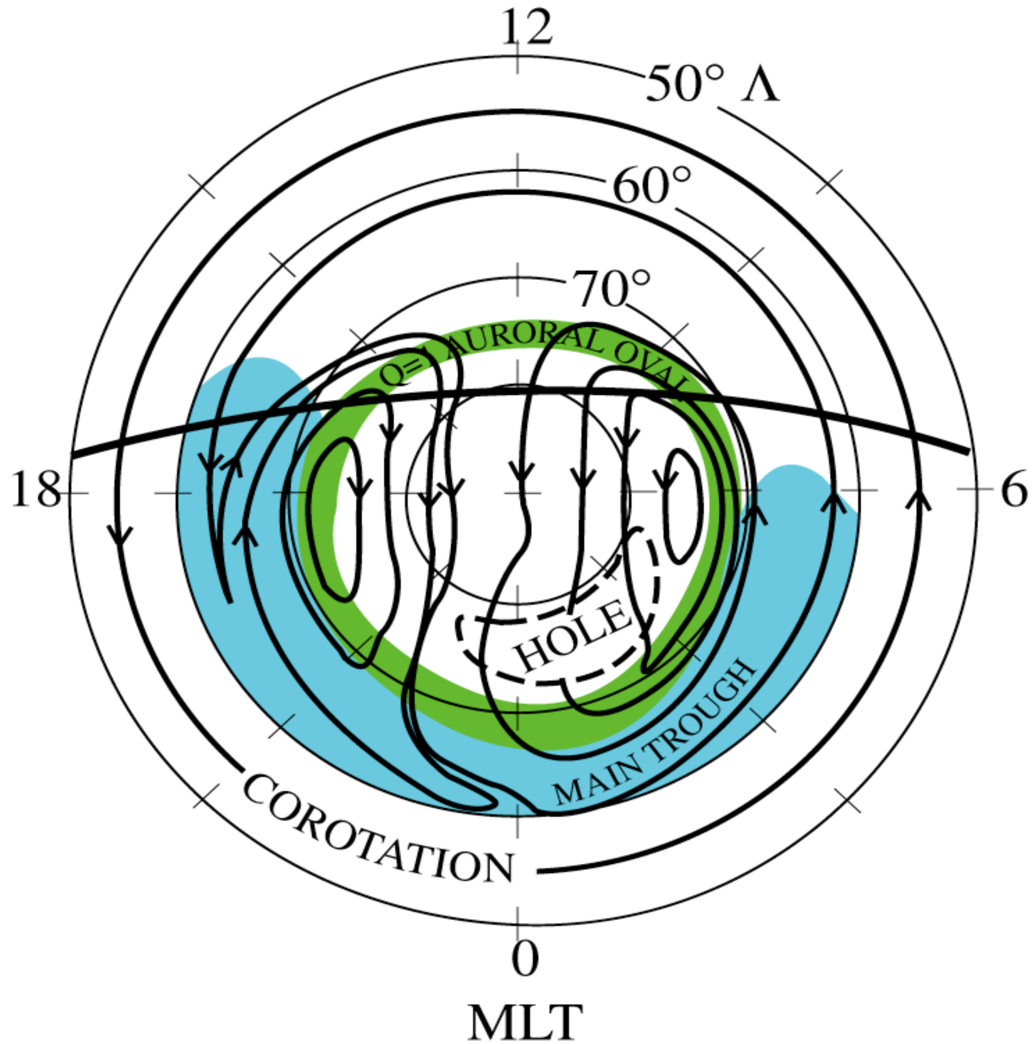
Sojka et al. (1979)

Geographic Inertial Frame



Sojka et al. (1979)

High Latitude Climatology



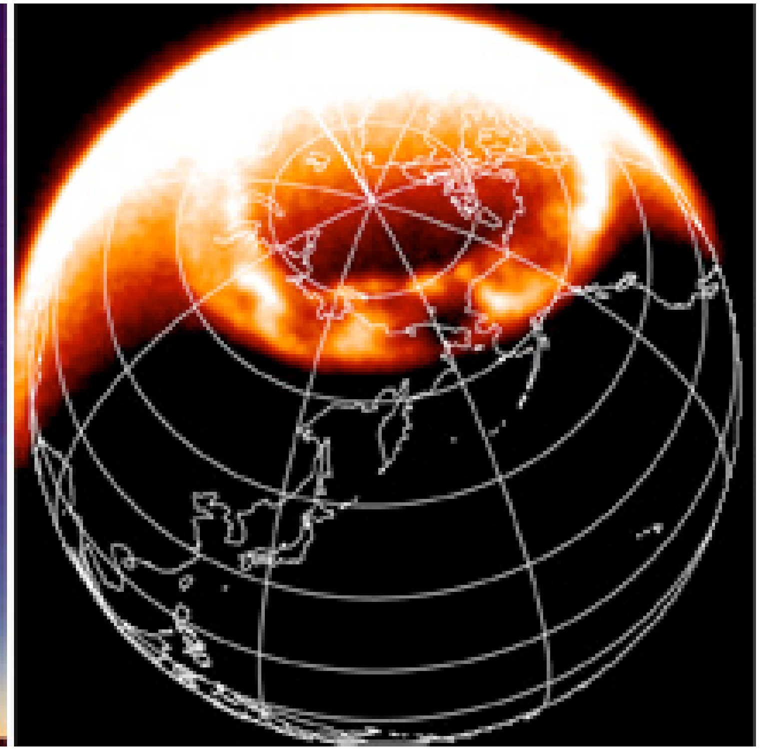
Brinton et al., 1978

Storms and Substorms

- Ionosphere
  - Increased Convection Speeds
  - Increased Joule and Particle Heating
  - $O^+ \rightarrow NO^+$
  - $T_i \rightarrow T_{i\parallel}, T_{i\perp}$

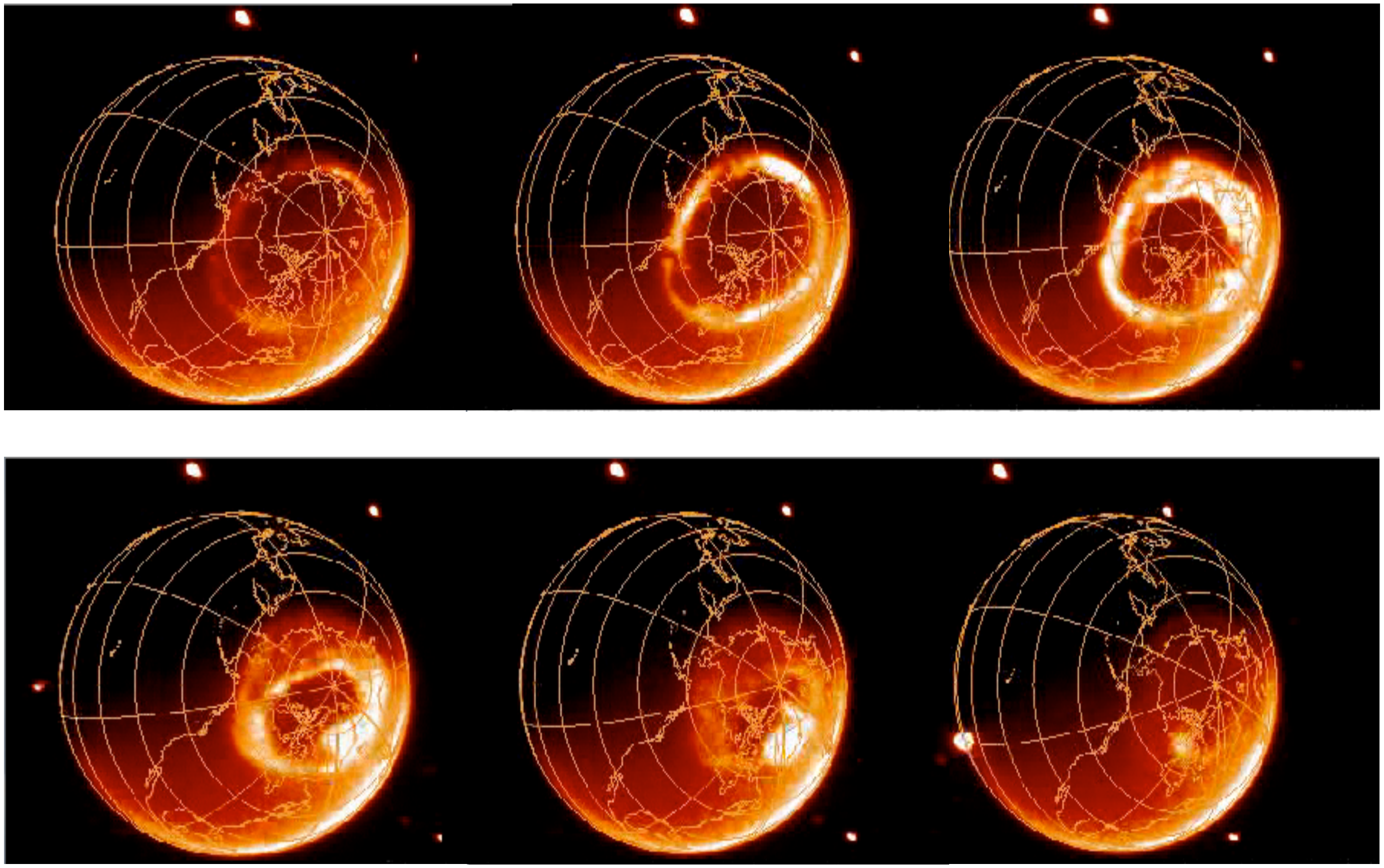
- Thermosphere
  - Gravity Waves
  - O/N_2 Changes
  - Enhanced Winds
  - Supersonic Winds
  - Anisotropic T_n

Satellite Images



- Ground Photograph by Jan Curtis.
- FUV Image from the IMAGE Satellite.

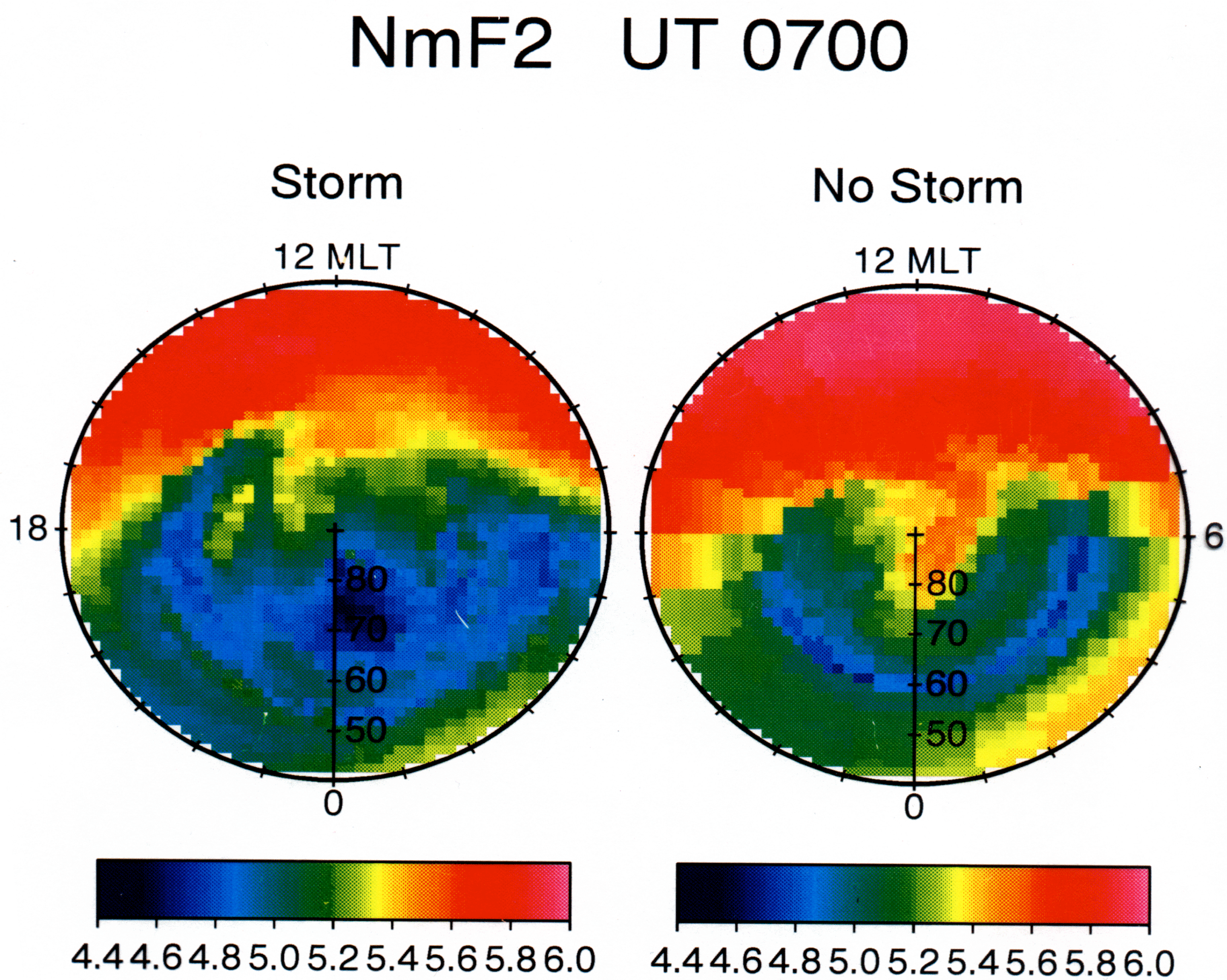
Satellite Images



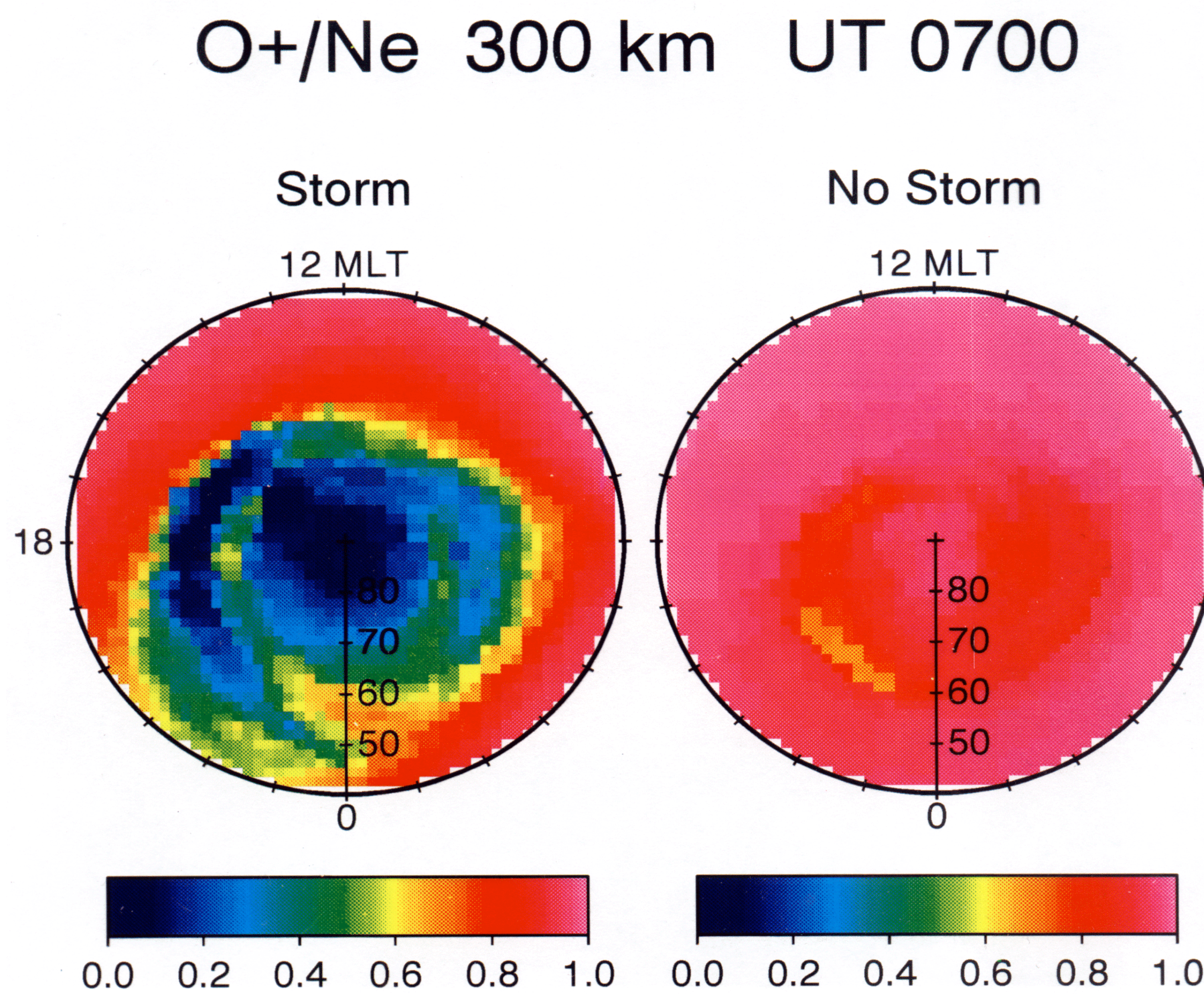
Burch, J. L., *Scientific American, 284*, 72-80, 2001

- Bastille Day Storm
- July 14-15, 2000
- Snapshots During a 1-Hour Period

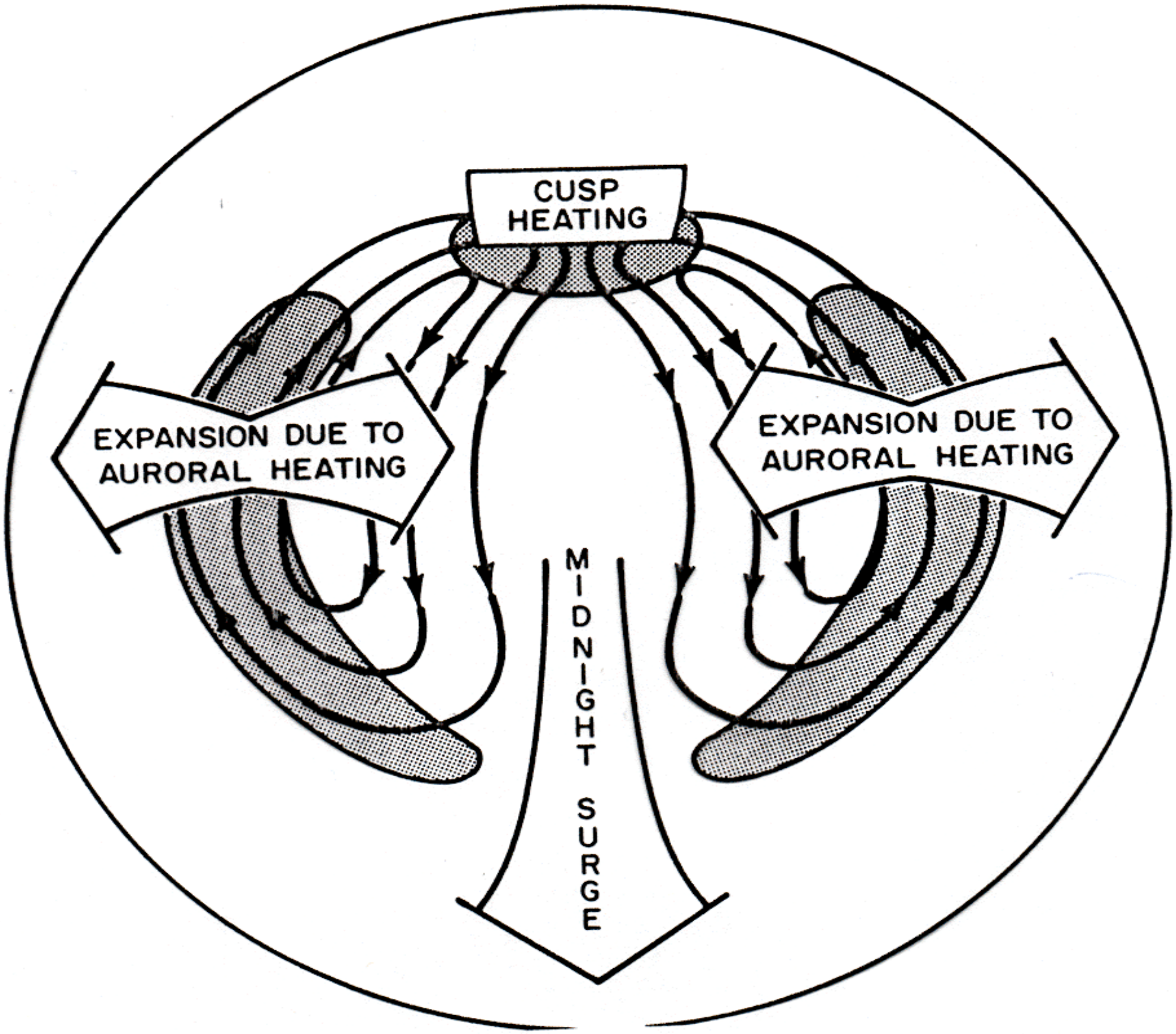
Ionosphere Forecast Model



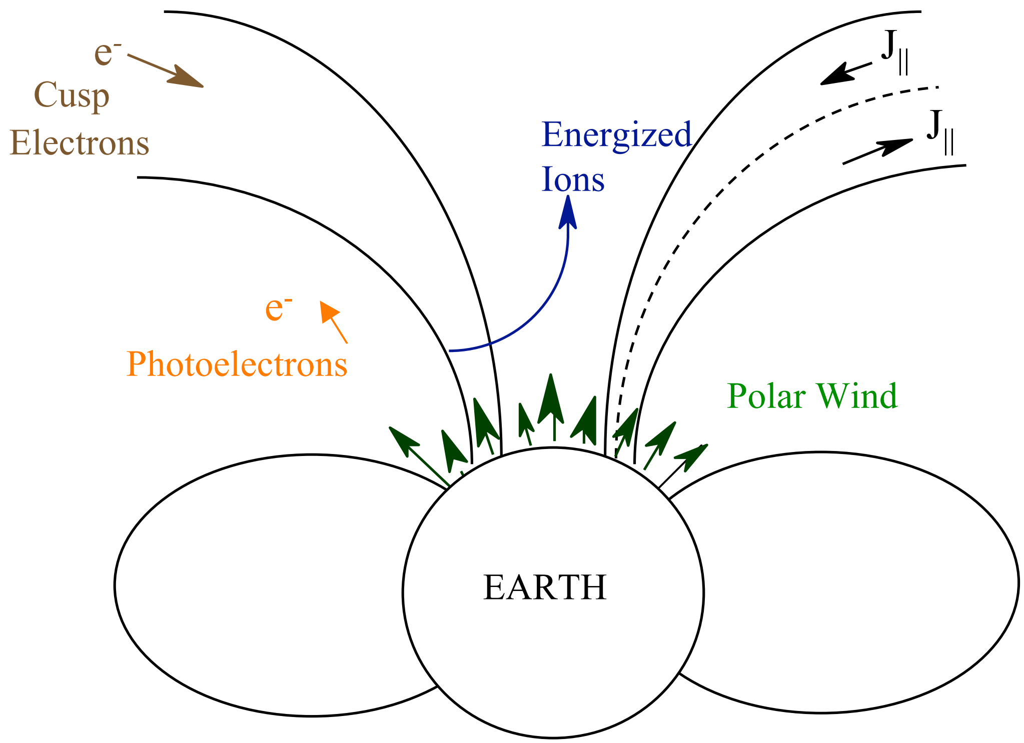
Ionosphere Forecast Model



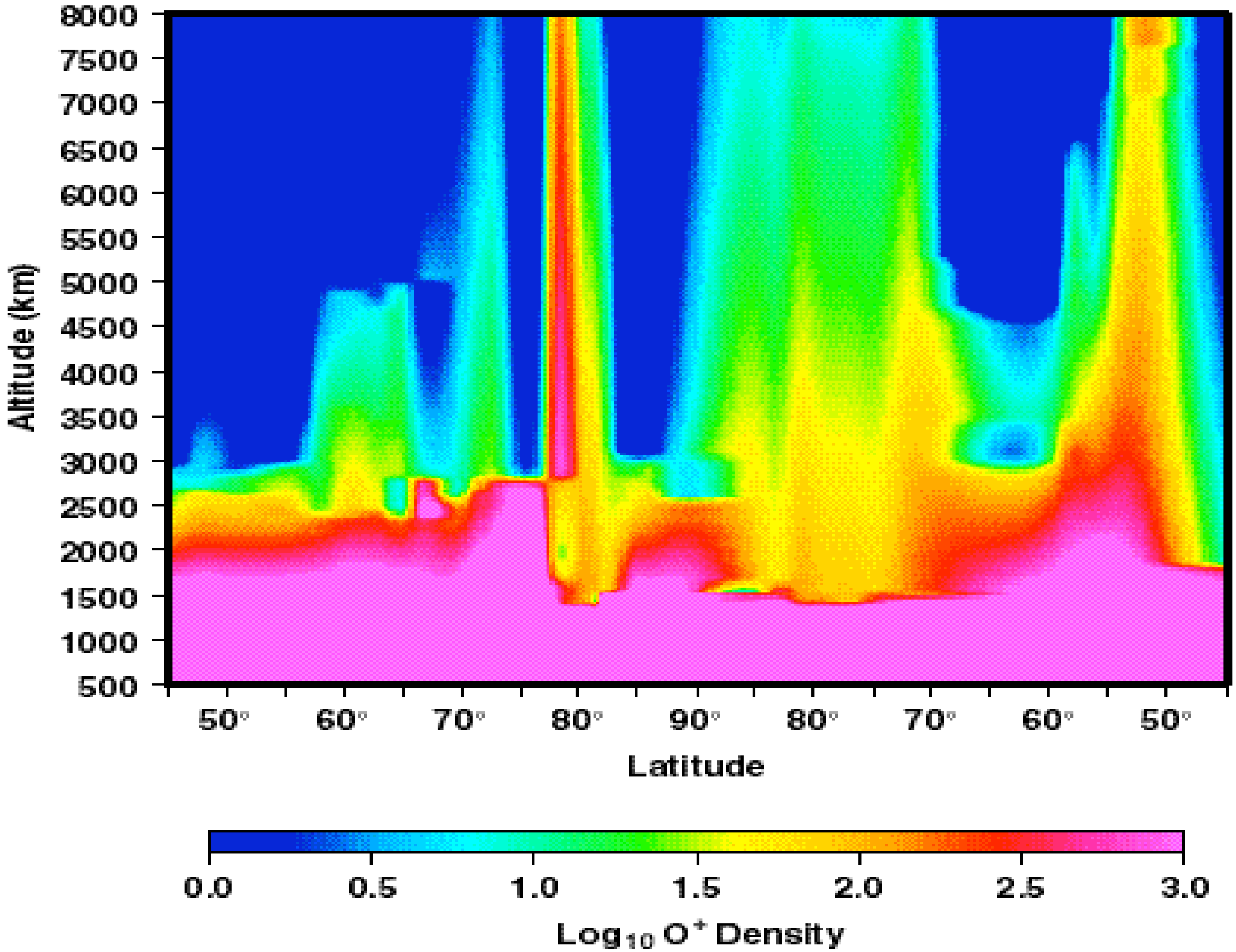
Neutral Gas Expansion



Ion Polar Wind

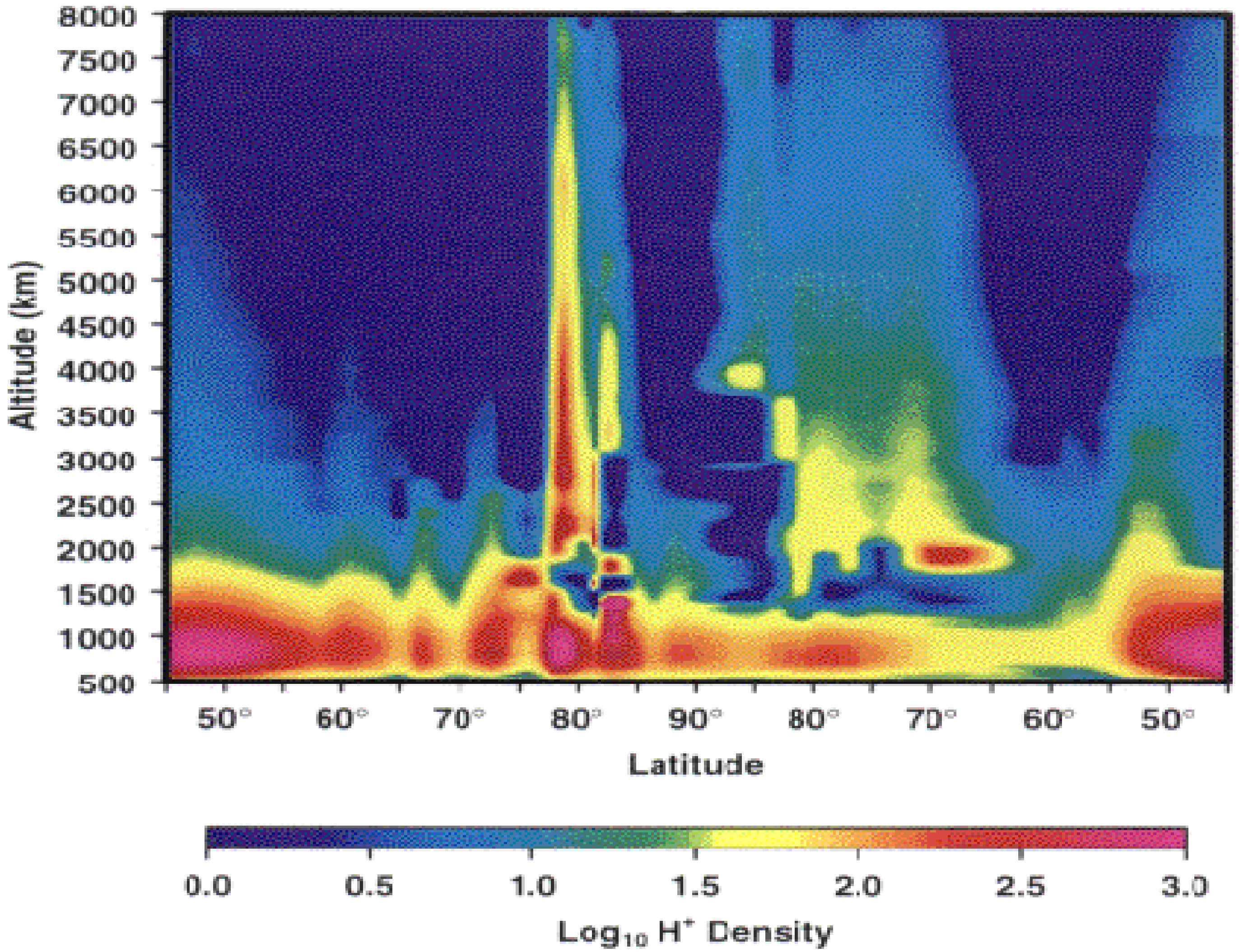


O^+ 6 UT



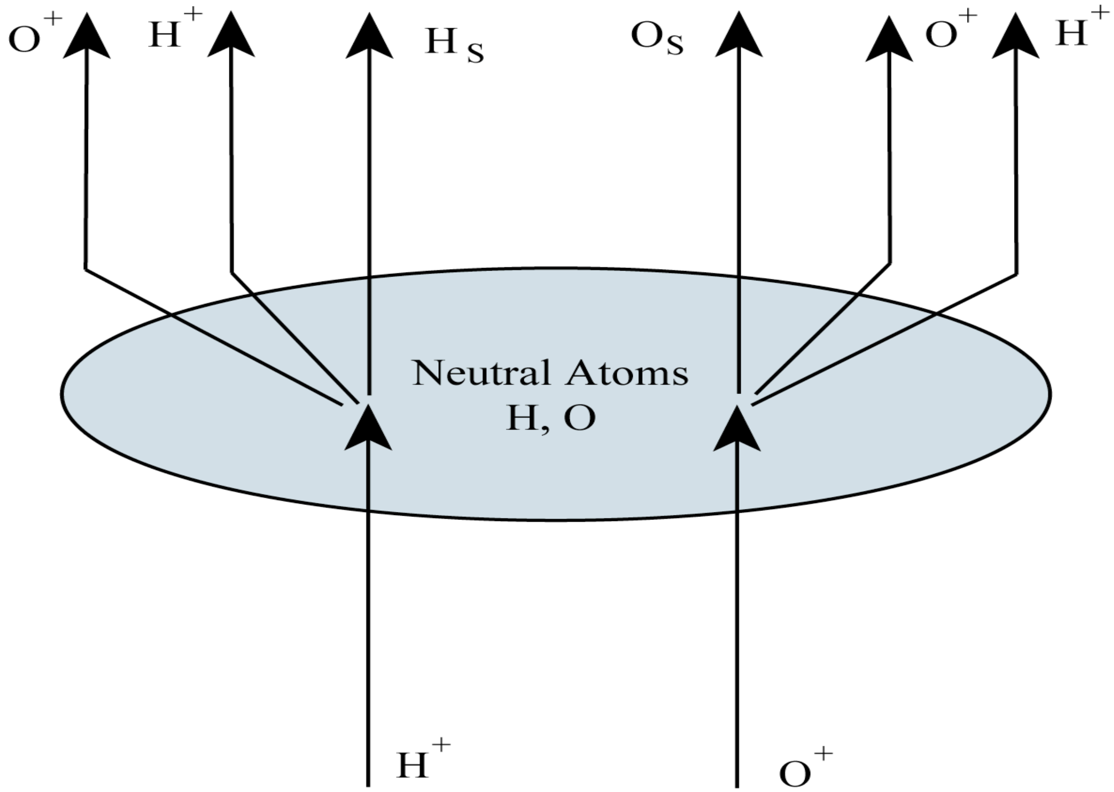
Demars and Schunk (2003)

H^+ 6 UT



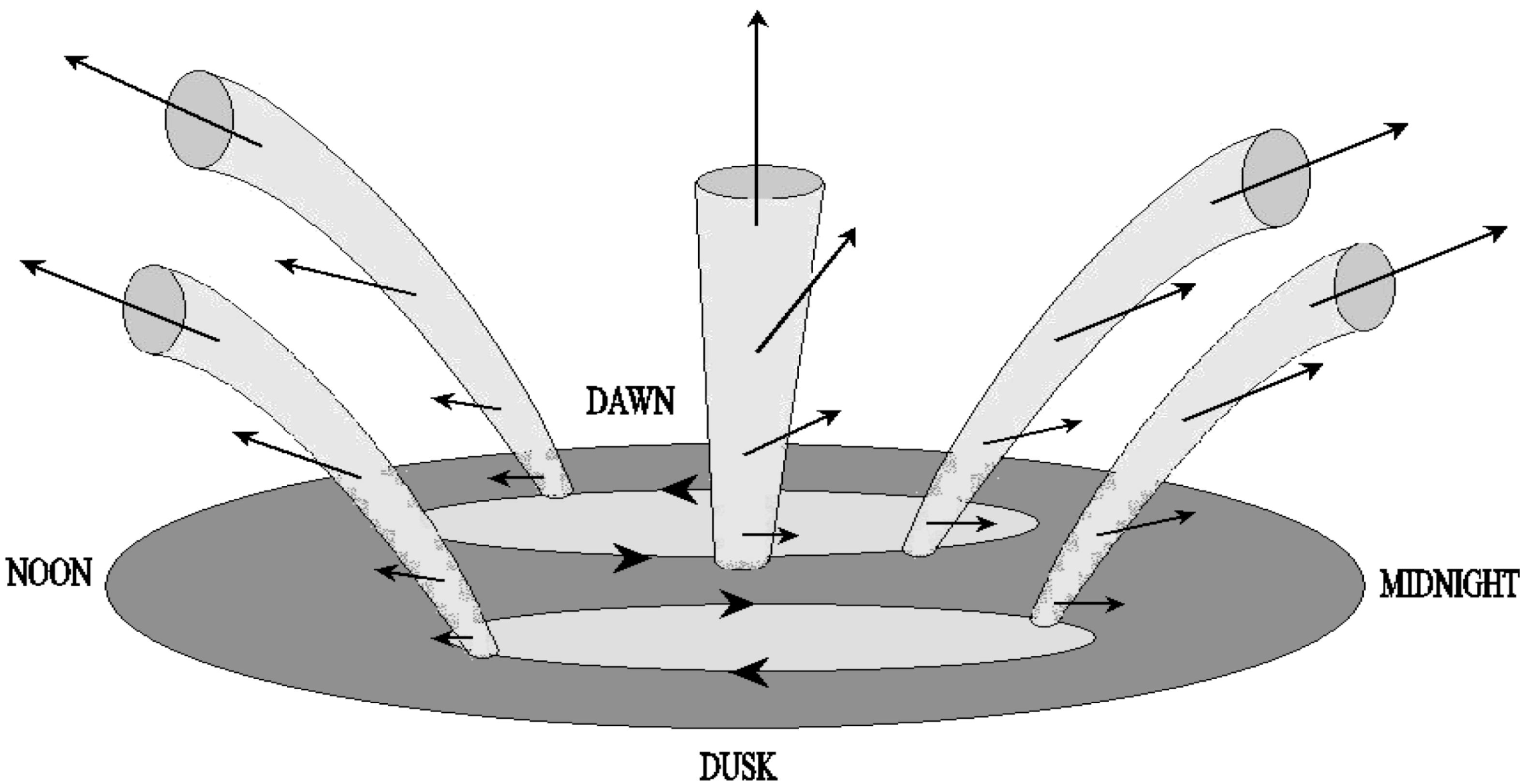
Demars and Schunk (2003)

Neutral Polar Wind



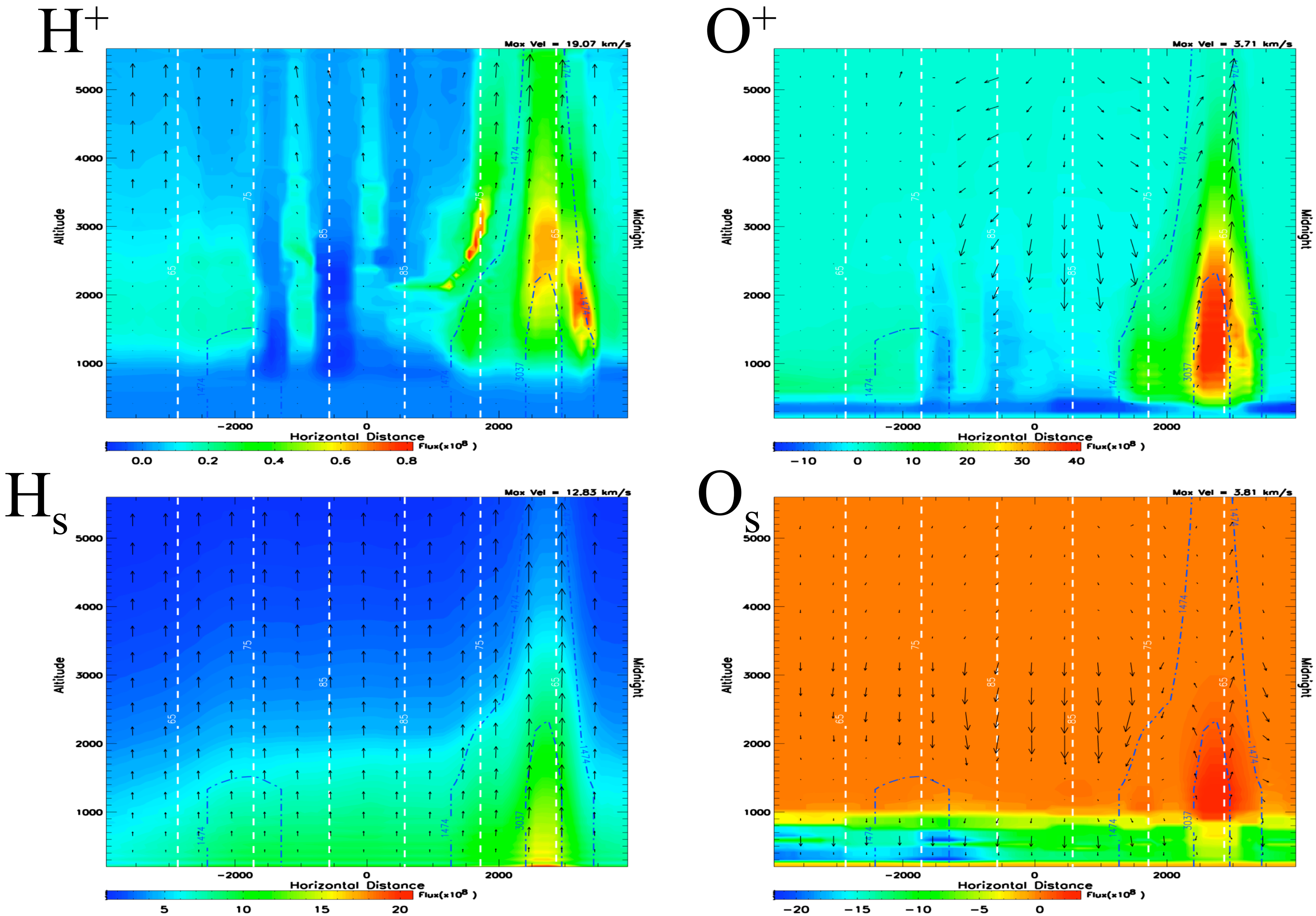
Gardner and Schunk (2004)

Neutral Polar Wind



Gardner and Schunk (2004)

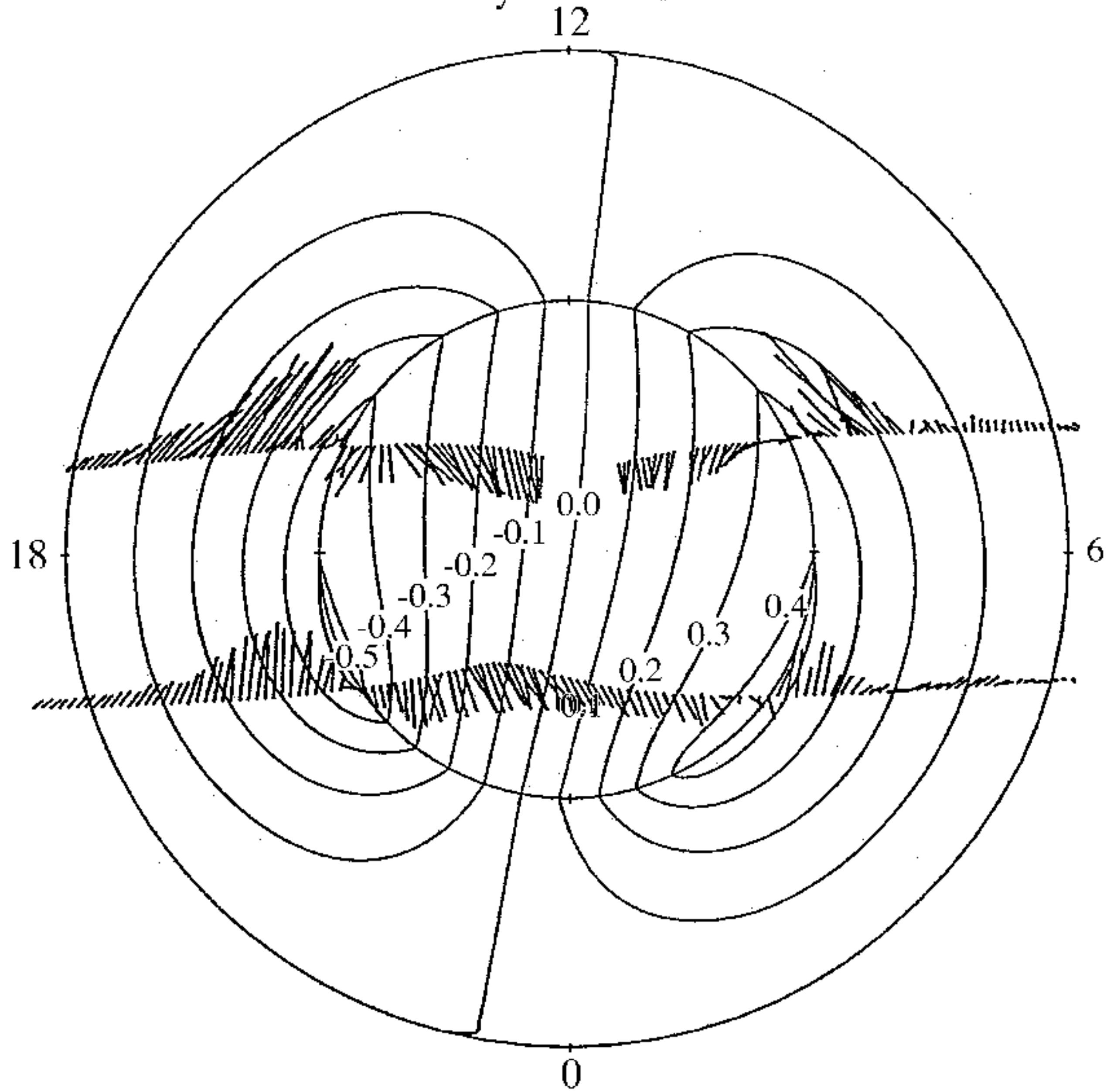
Noon-Midnight Meridian Flux 6:10 UT

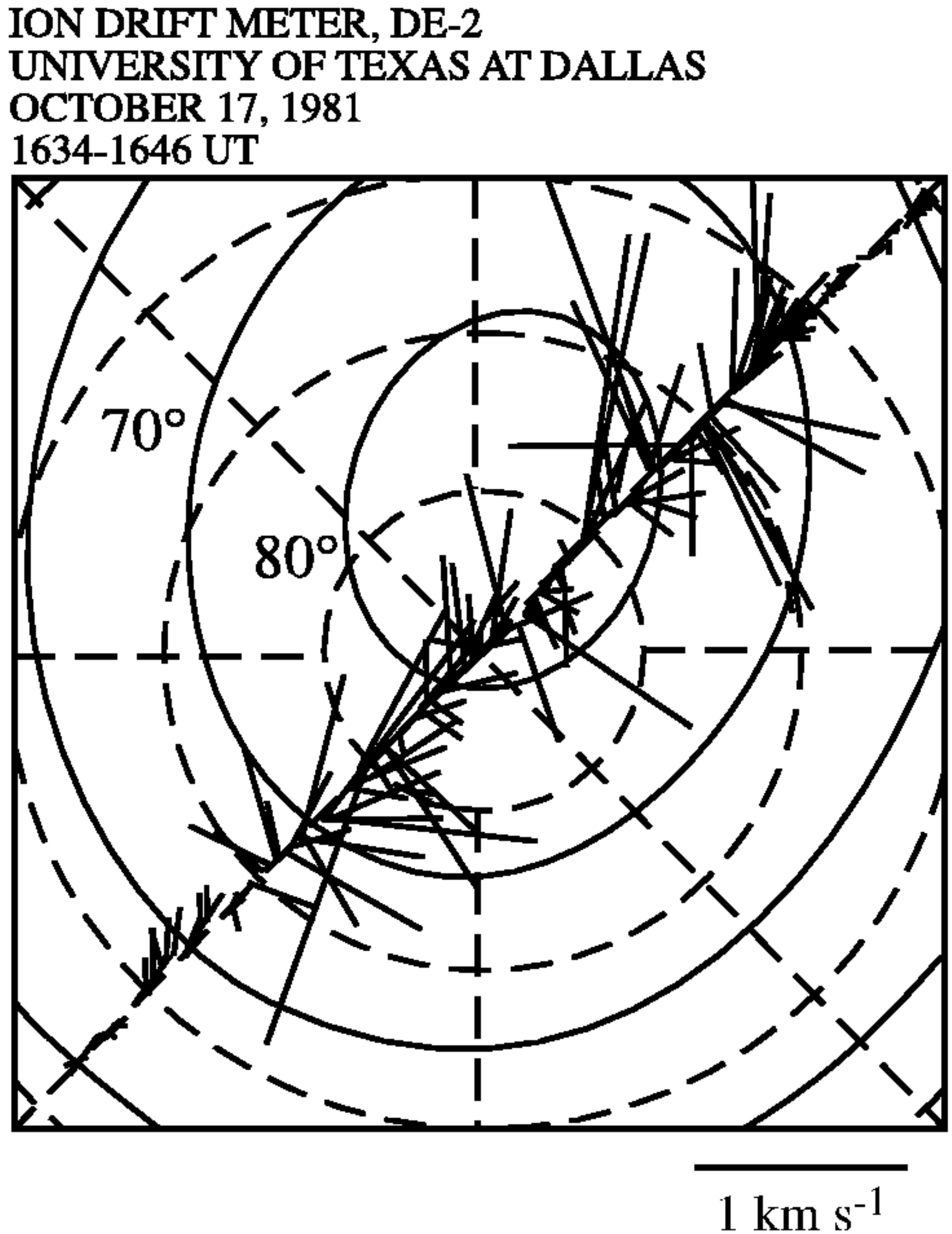


Causes of Plasma Structures

- Changes in the Solar Wind Drivers
- Structured Electric Fields
- Structured Particle Precipitation
- Time Variations in E-fields and Precipitation
- Time Delays and Feedback Mechanisms in the M-I-T System
- Plasma Instabilities

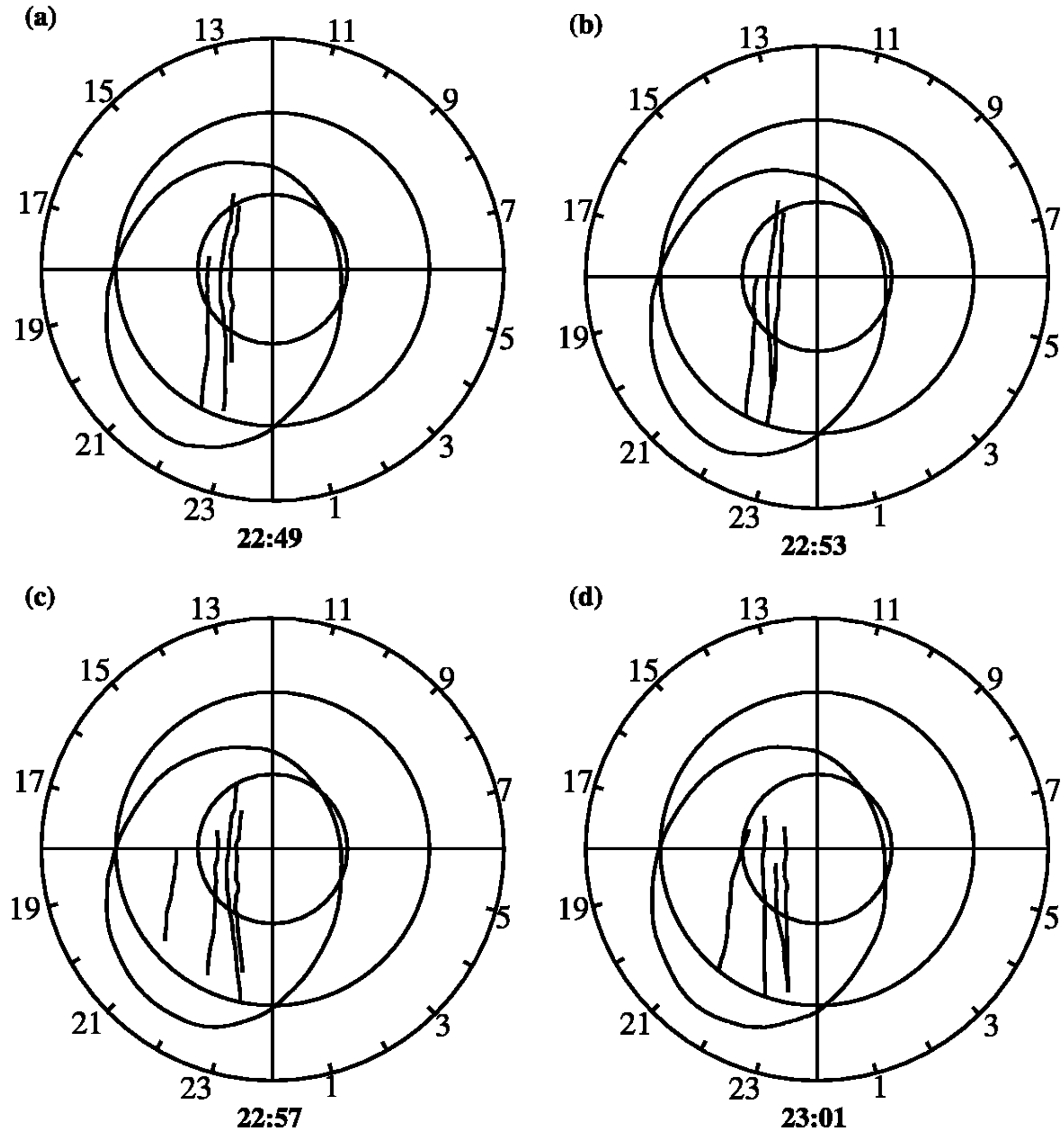
$-1 < B_y < +1;\ B_z < -1$



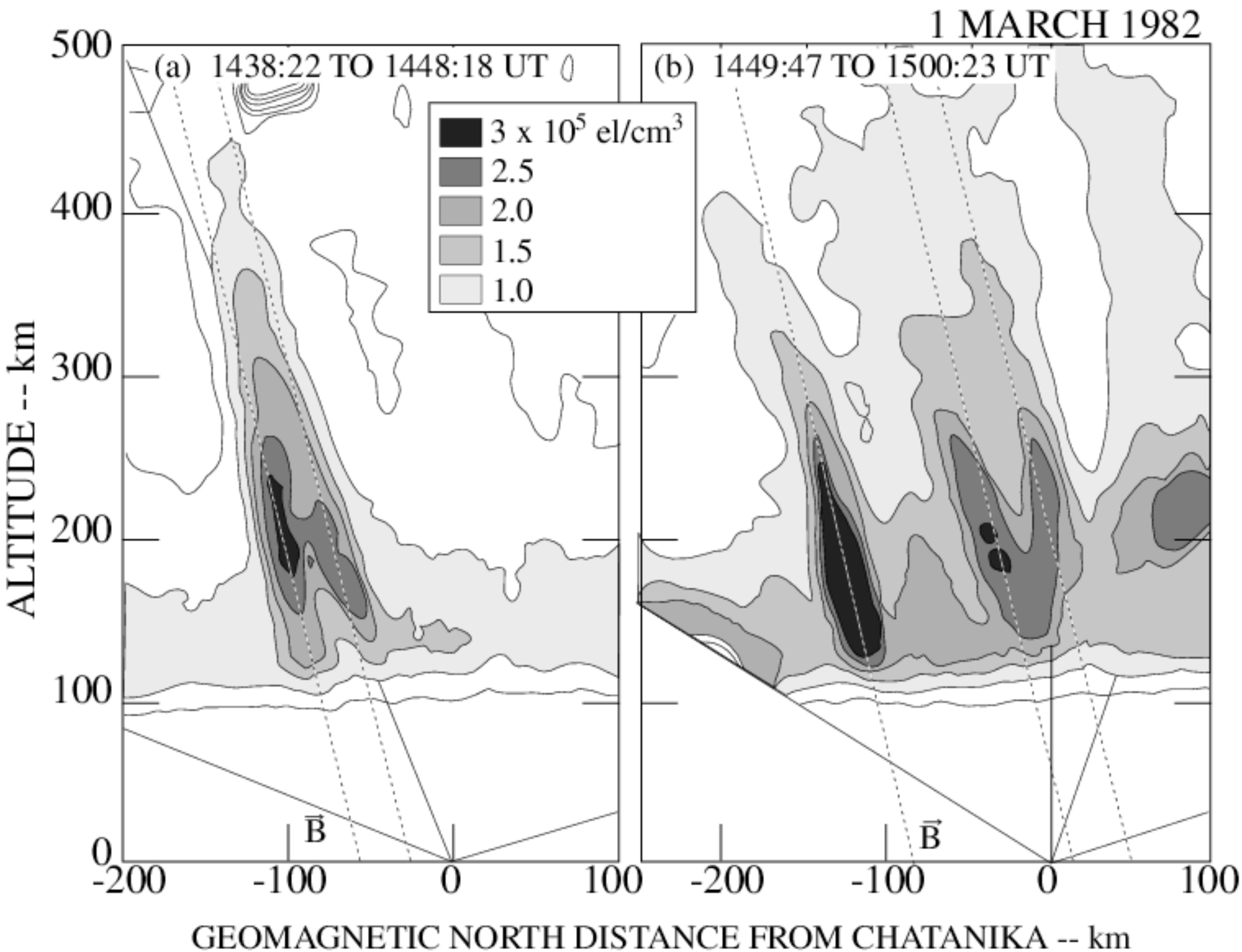

ION DRIFT METER, DE-2
UNIVERSITY OF TEXAS AT DALLAS
OCTOBER 17, 1981
1634-1646 UT
70°
80°
1 km s-1

Greenland

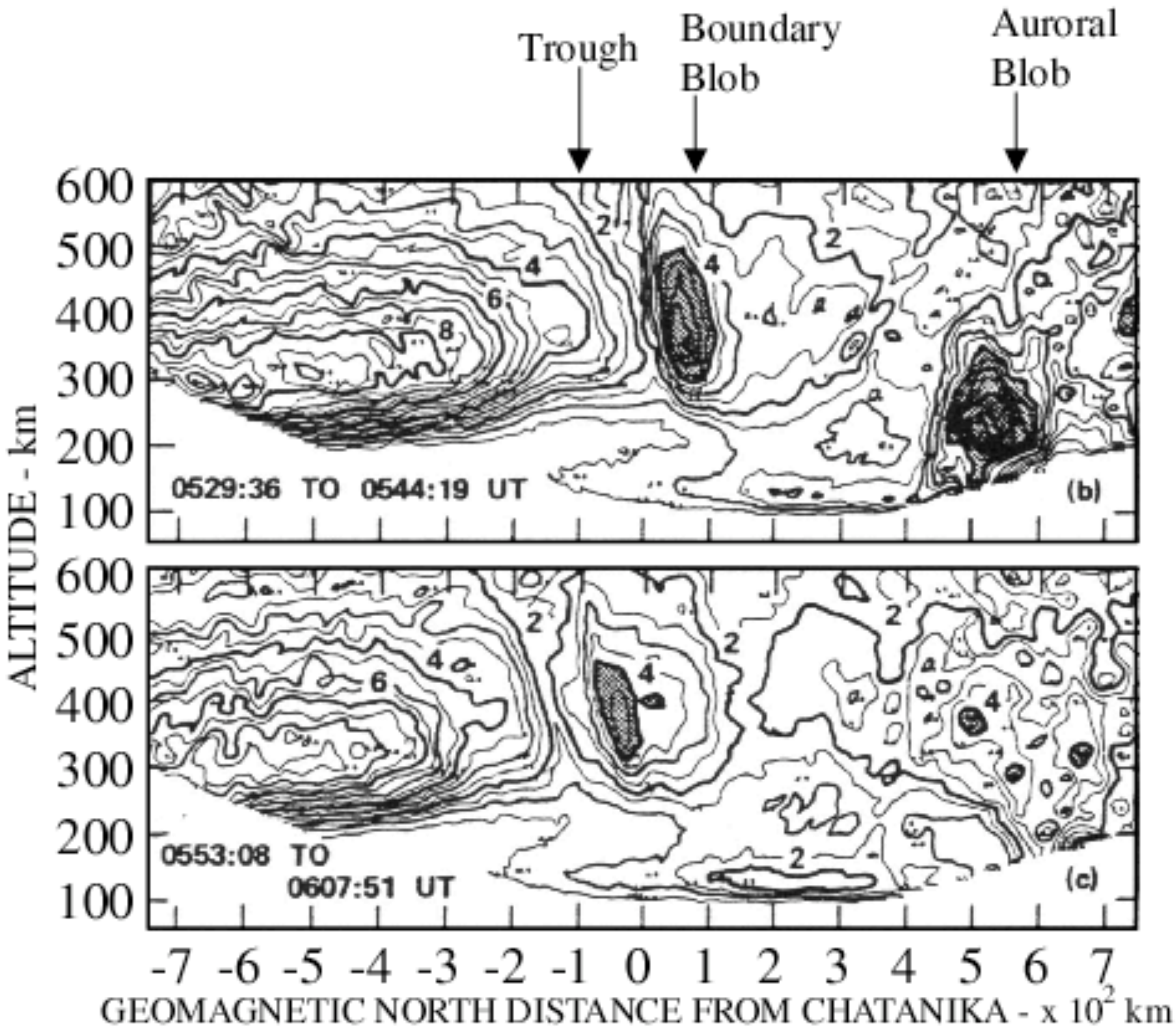
100-300 km
by
1000-3000 km



Valladares et al (1994)



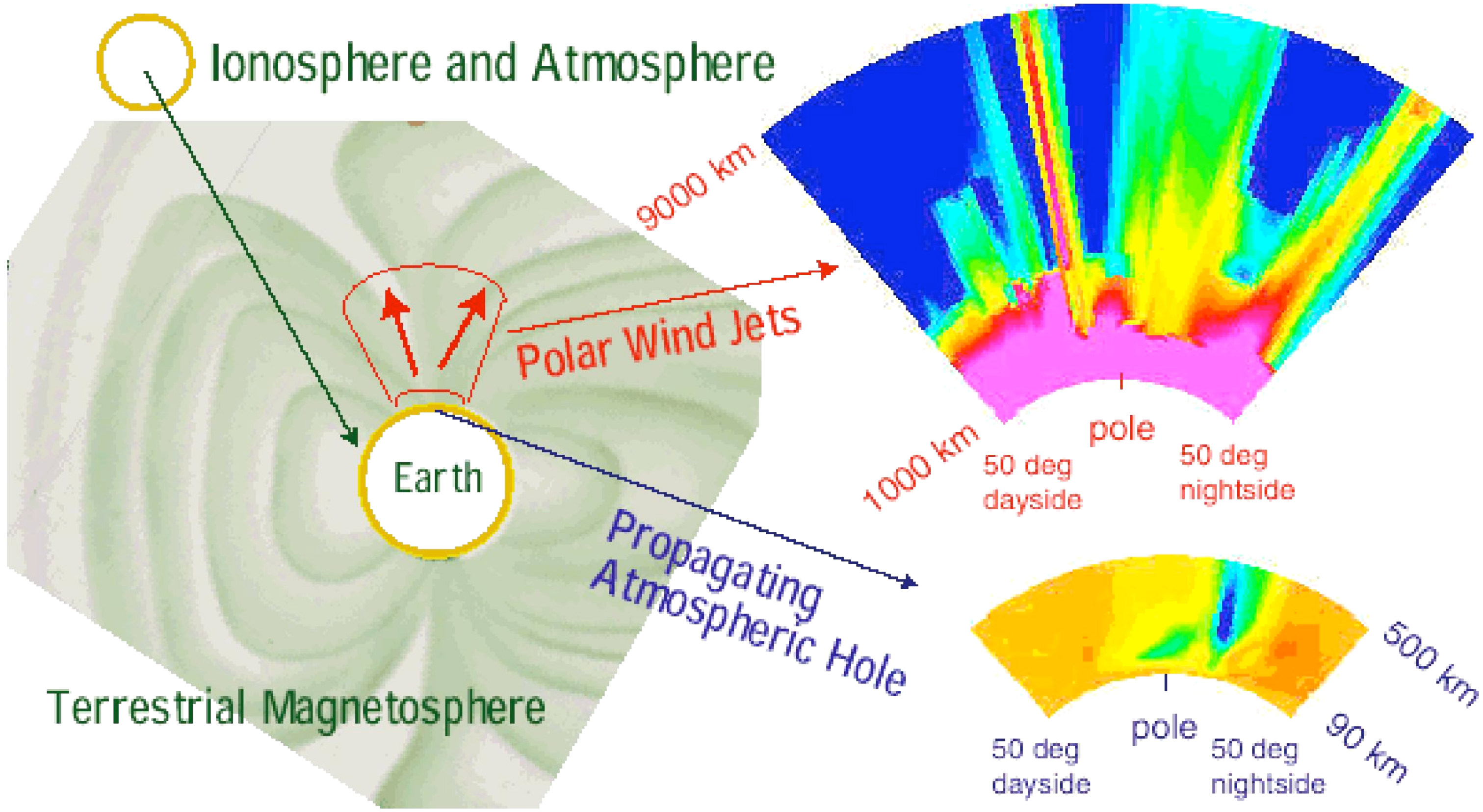
1 MARCH 1982
(a) 1438:22 TO 1448:18 UT
(b) 1449:47 TO 1500:23 UT
3 x 10^5 el/cm^3
2.5
2.0
1.5
1.0
ALTITUDE -- km
500
400
300
200
100
0
-200
-100
0
100
B
GEOMAGNETIC NORTH DISTANCE FROM CHATANIKA -- km



Trough
Boundary Blob
Auroral Blob
0529:36 TO 0544:19 UT
(b)
0553:08 TO 0607:51 UT
(c)
ALTITUDE - km
GEOMAGNETIC NORTH DISTANCE FROM CHATANIKA - x 10^2 km

Mesoscale Ionospheric Structures

- Propagating Plasma Patches
- Propagating Atmospheric Hole
- Propagating Polar Wind Jets
- Propagating Neutral Streams
- Sun-Aligned Polar Cap Arcs
- Theta Aurora
- Boundary and Auroral Blobs
- Stationary Polar Wind Jets
- Neutral Polar Wind Streams
- Sub-Auroral Ion Drift Events (SAID)
- Storm Enhanced Densities (SED) Ridges



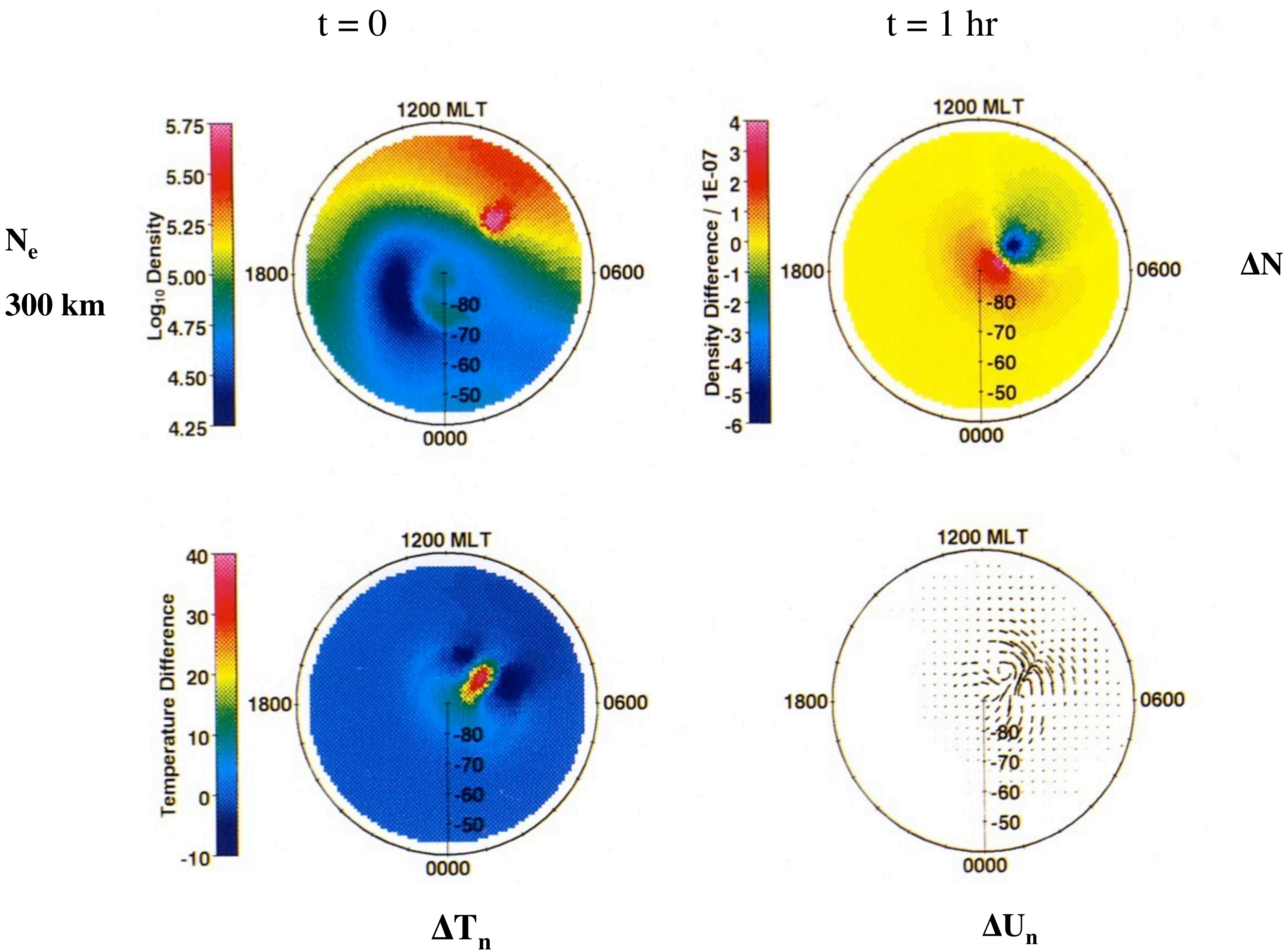
The near-Earth domain composed of the magnetosphere, polar wind, ionosphere and neutral atmosphere. Shown are propagating, supersonic, polar wind jets and propagating atmospheric holes.

Propagating Plasma Patches

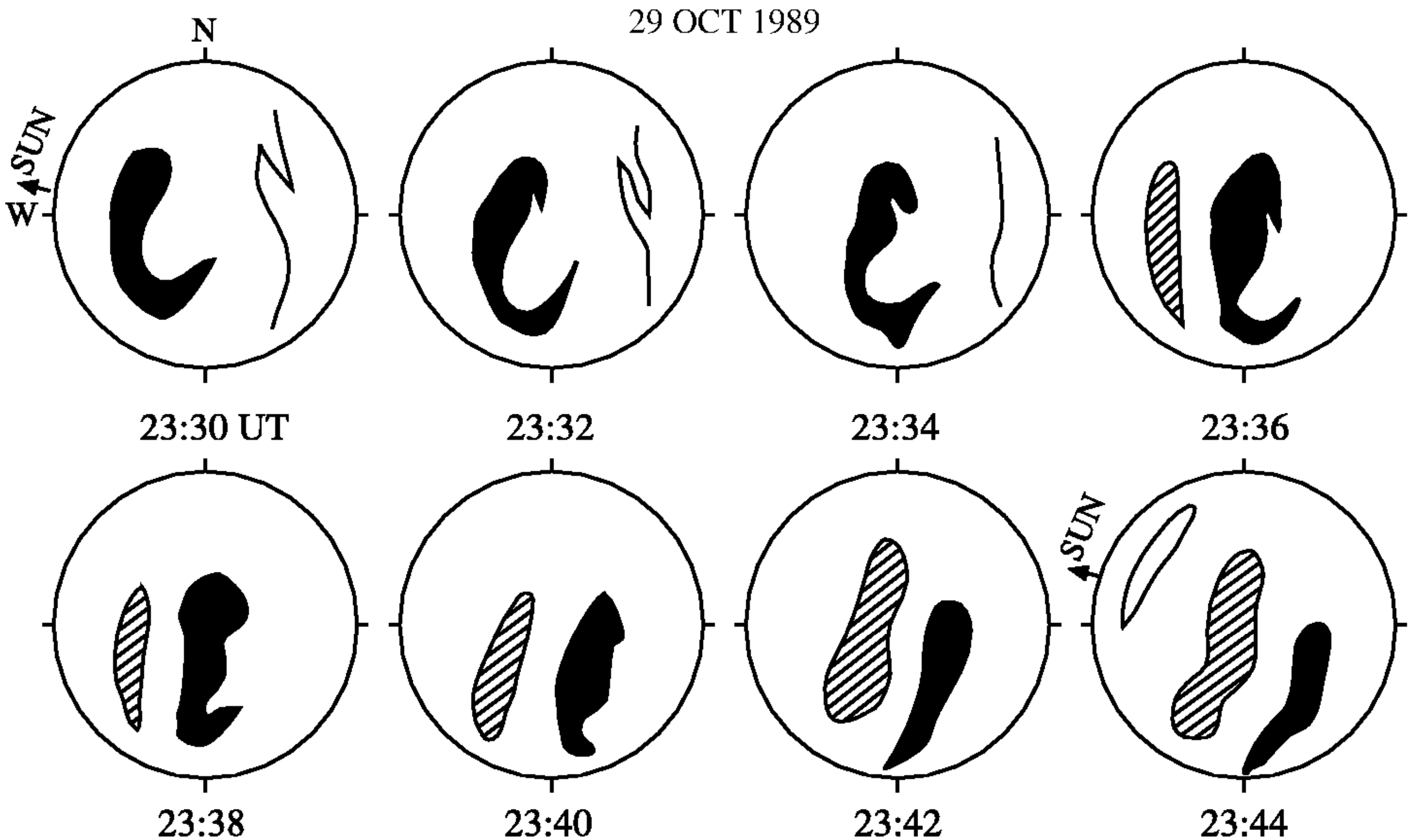
- Mesoscale Regions of Enhanced Plasma Density
- Created in or Equatorward of Noon Auroral Zone
- Antisunward Convection with Background Plasma
- Horizontal Extent of 200 - 1000 km
- Circular or Cigar-Shaped
- Single or Multiple Patches
- Density Enhancement of Few % to Factor 100
- Enhancement Extends Along **B**

Single, Circular, Propagating Plasma Patch

- Gaussian Patch Distribution - 1000 km
- Peak N_e Factor 5 Above Background
- F10.7 = 150, Winter Polar Region
- Quiet Conditions, then Southward IMF & 100 kV at Time Plasma Patch Imposed
- Collisional Snowplow
- N_n Depletion in and Behind Patch, Enhancement in Front
- Increased U_n in Patch
- Neutral Gas Upwelling and O/N_2 Changes
- Disturbance Moves Along with Patch



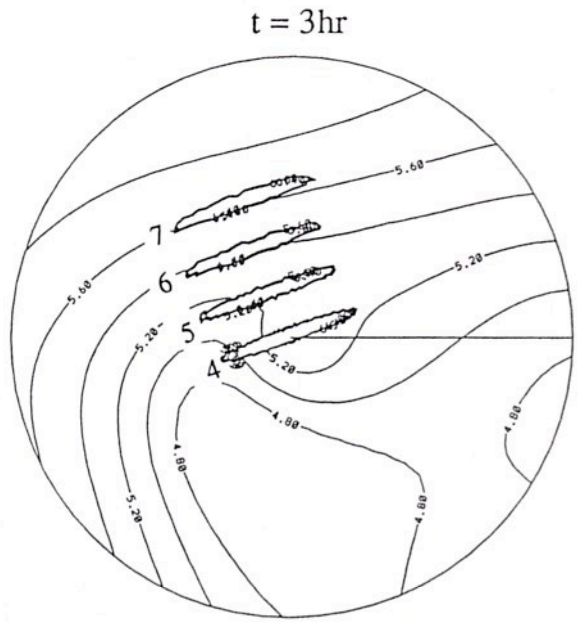
t = 0
t = 1 hr
N_e
300 km
ΔN
1200 MLT
1800
0600
0000
Log10 Density
5.75
5.50
5.25
5.00
4.75
4.50
4.25
-80
-70
-60
-50
Density Difference / 1E-07
4
3
2
1
0
-1
-2
-3
-4
-5
-6
Temperature Difference
40
30
20
10
0
-10
ΔT_n
ΔU_n

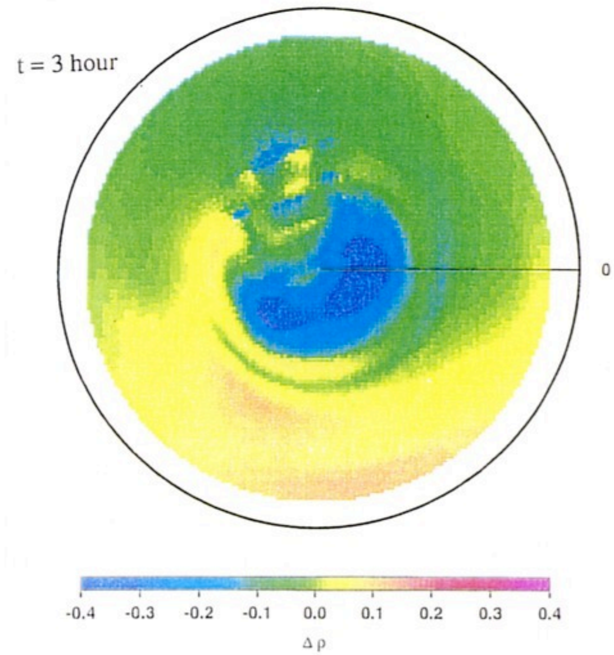


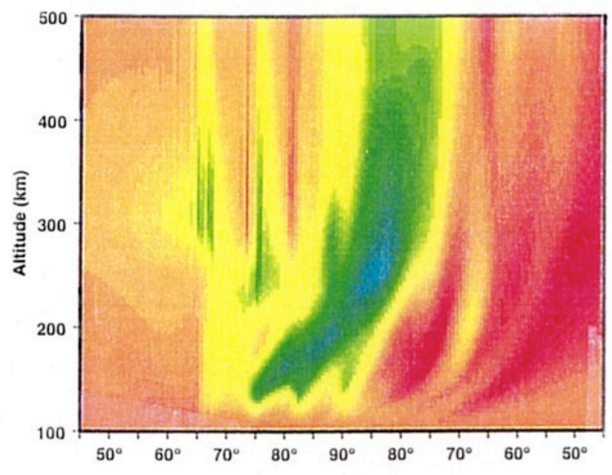
Qaanaaq, Greenland, October 29, 1989

All-Sky Images (630 nm)

2 - Minute Interval







Neutral Density Perturbation

Neutral Gas Perturbations
300 km

- Single, Circular, Propagating Plasma Patch
  - o $\rho_n \sim 30\text{-}35\ \%$
  - o $T_n \sim 100 - 300$ K
  - o $U_n \sim 100$ m/s
- Multiple, Cigar-Shaped, Propagating Plasma Patches
  - o $\rho_n \sim 30\ \%$
  - o $T_n \sim 100 - 400$ K
  - o $U_n \sim 150$ m/s
- Comparable to Day-Night Change in the Thermosphere at Mid-Latitudes

MSIS Thermosphere

Noon-Midnight Variation at 300 km
Mid-Latitudes

- Solar Minimum, Winter Solstice

  $\rho_n \sim 40\ \%$

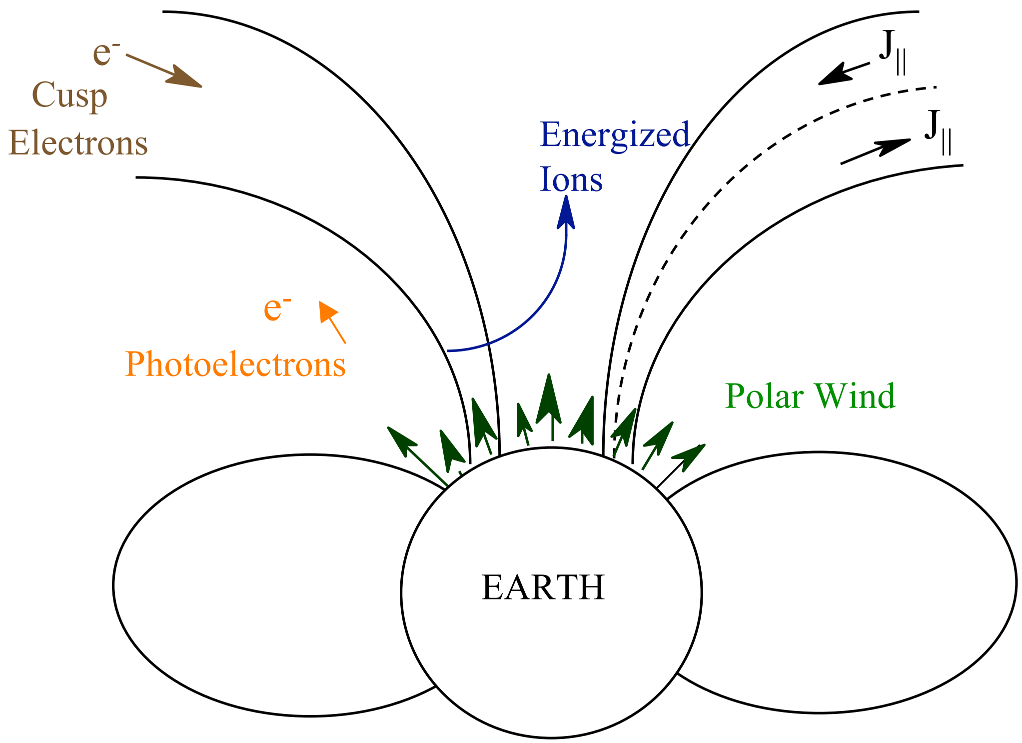
  $T_n \sim 45$ K

- Solar Maximum, Summer Solstice

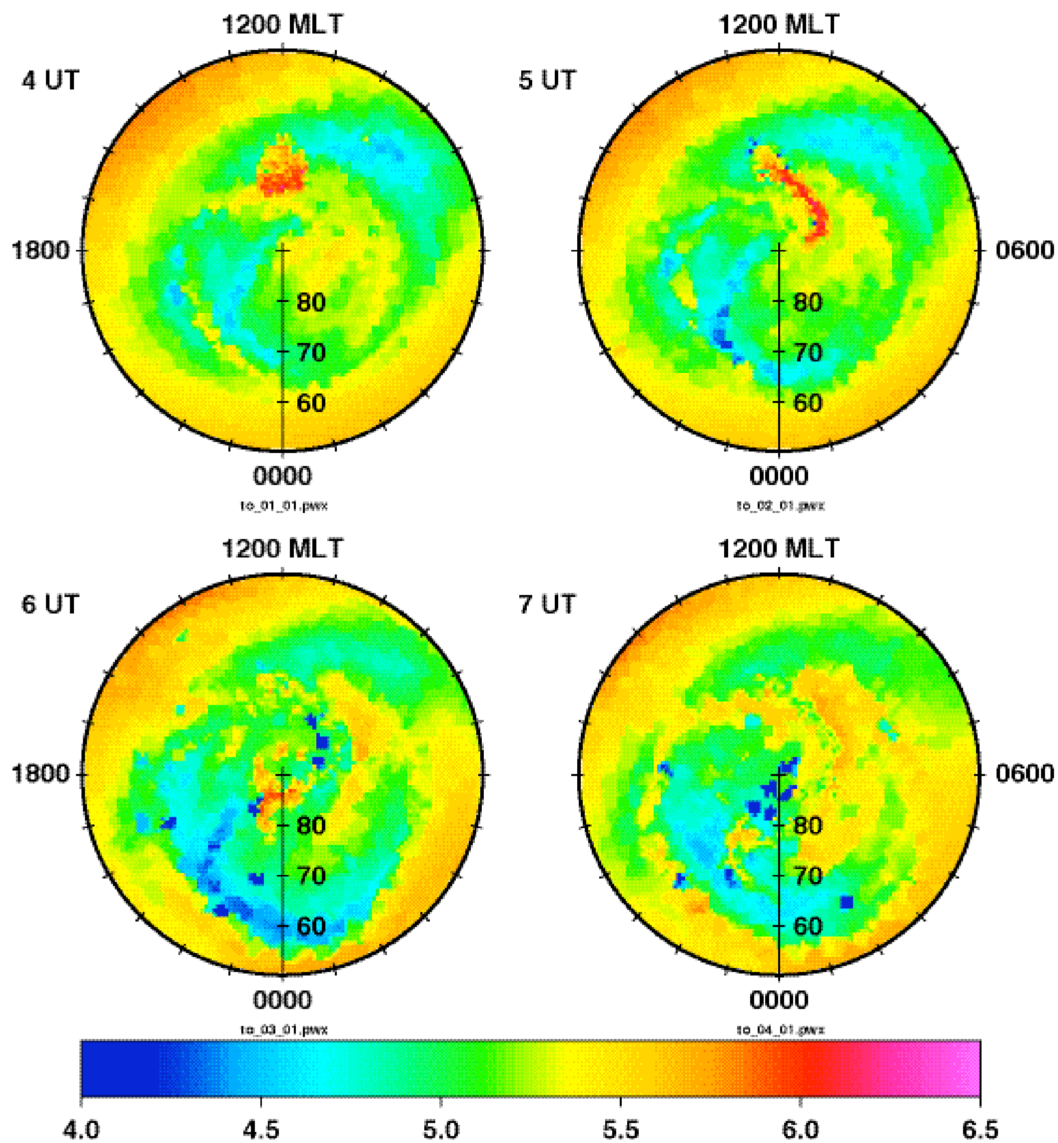
  $\rho_n \sim 50\ \%$

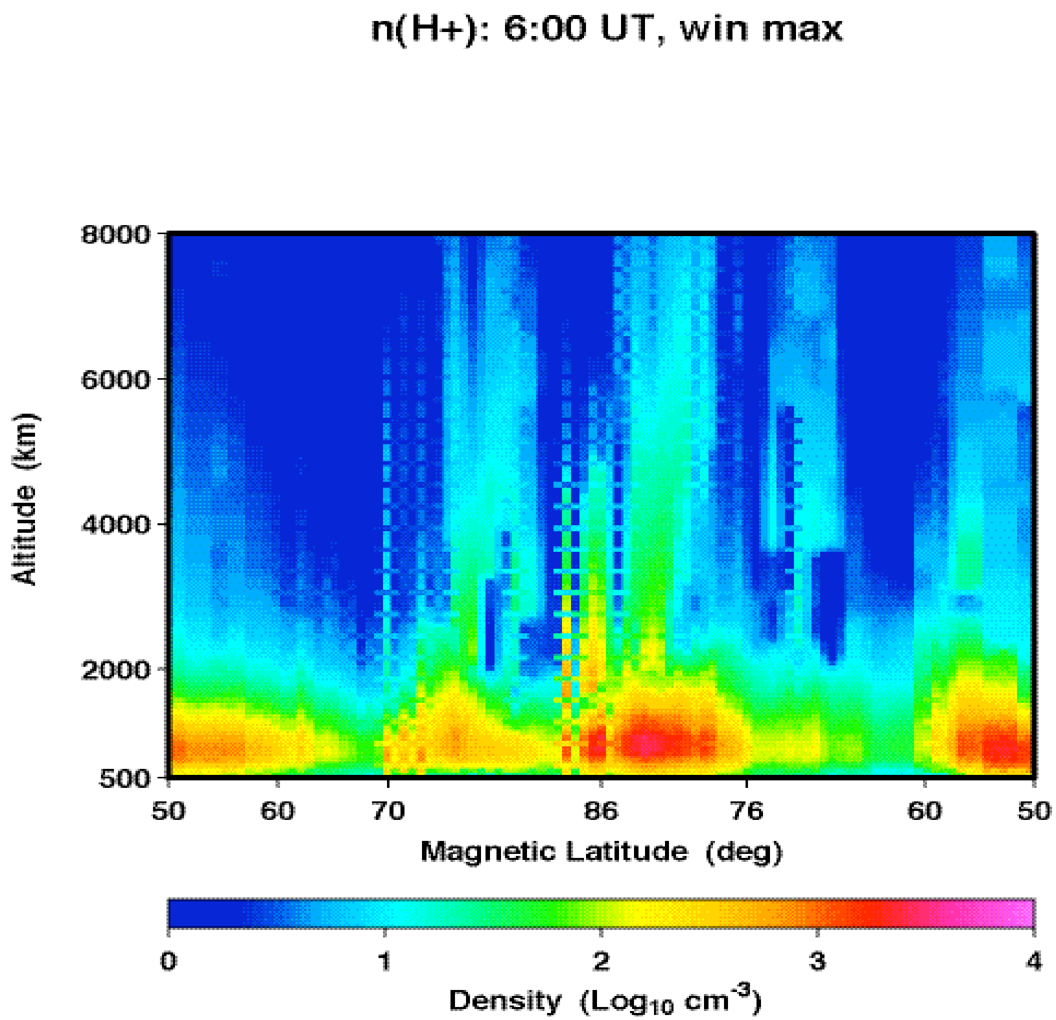
  $T_n \sim 250$ K

Propagating Polar Wind Jet



n(O+): 500 km, winter max

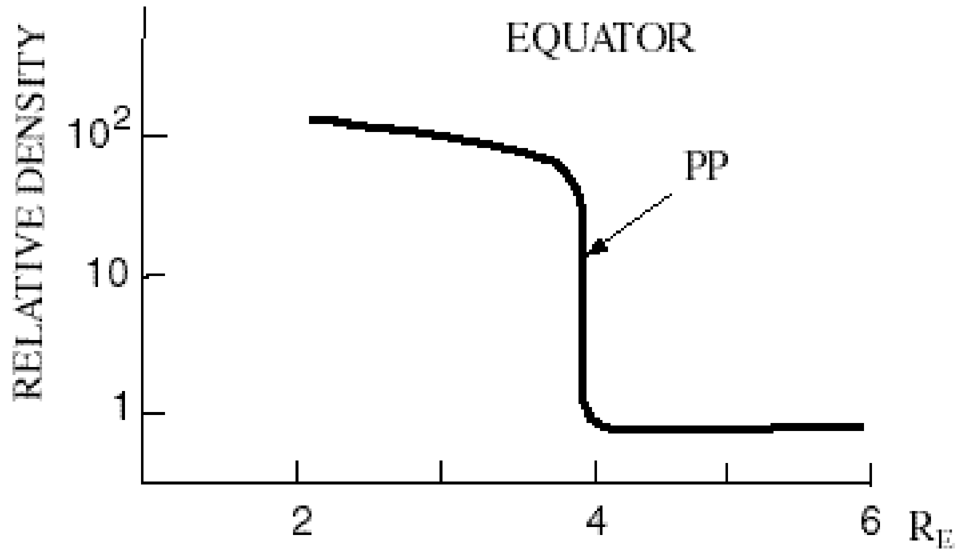


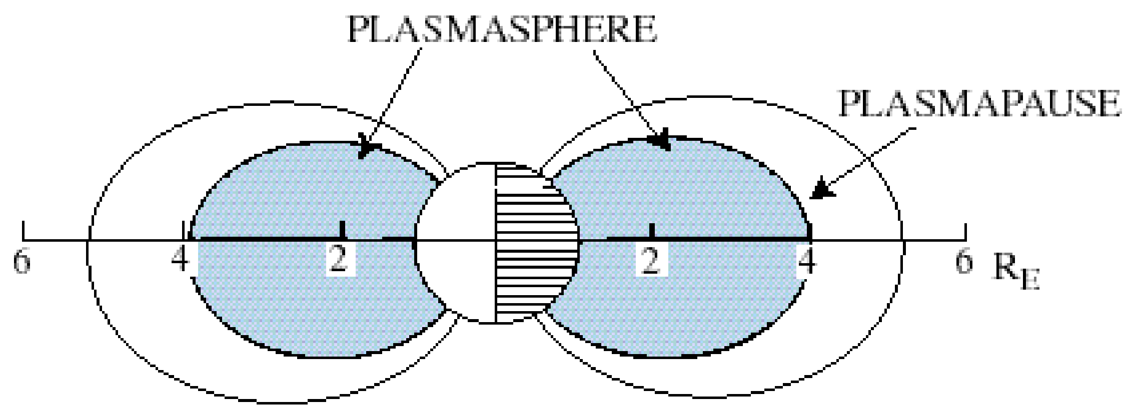


Schunk et al (2004)

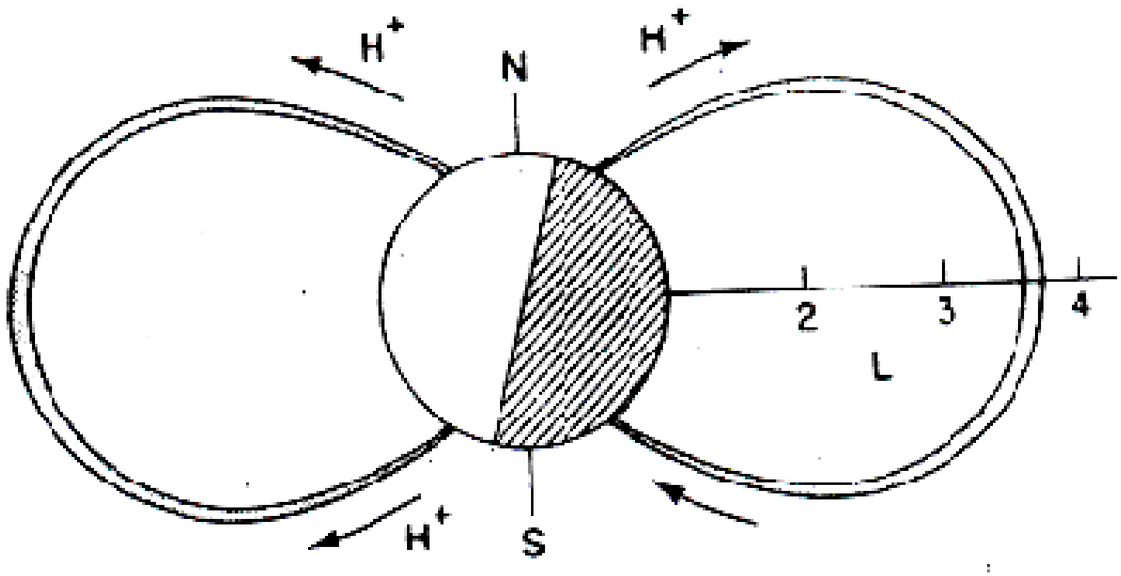
Figure 5

Mid-Latitudes


EQUATOR
RELATIVE DENSITY
10²
10
1
PP
2
4
6
R_E


PLASMASPHERE
PLASMAPAUSE
6
4
2
2
4
6
R_E

Interhemisphere Flow

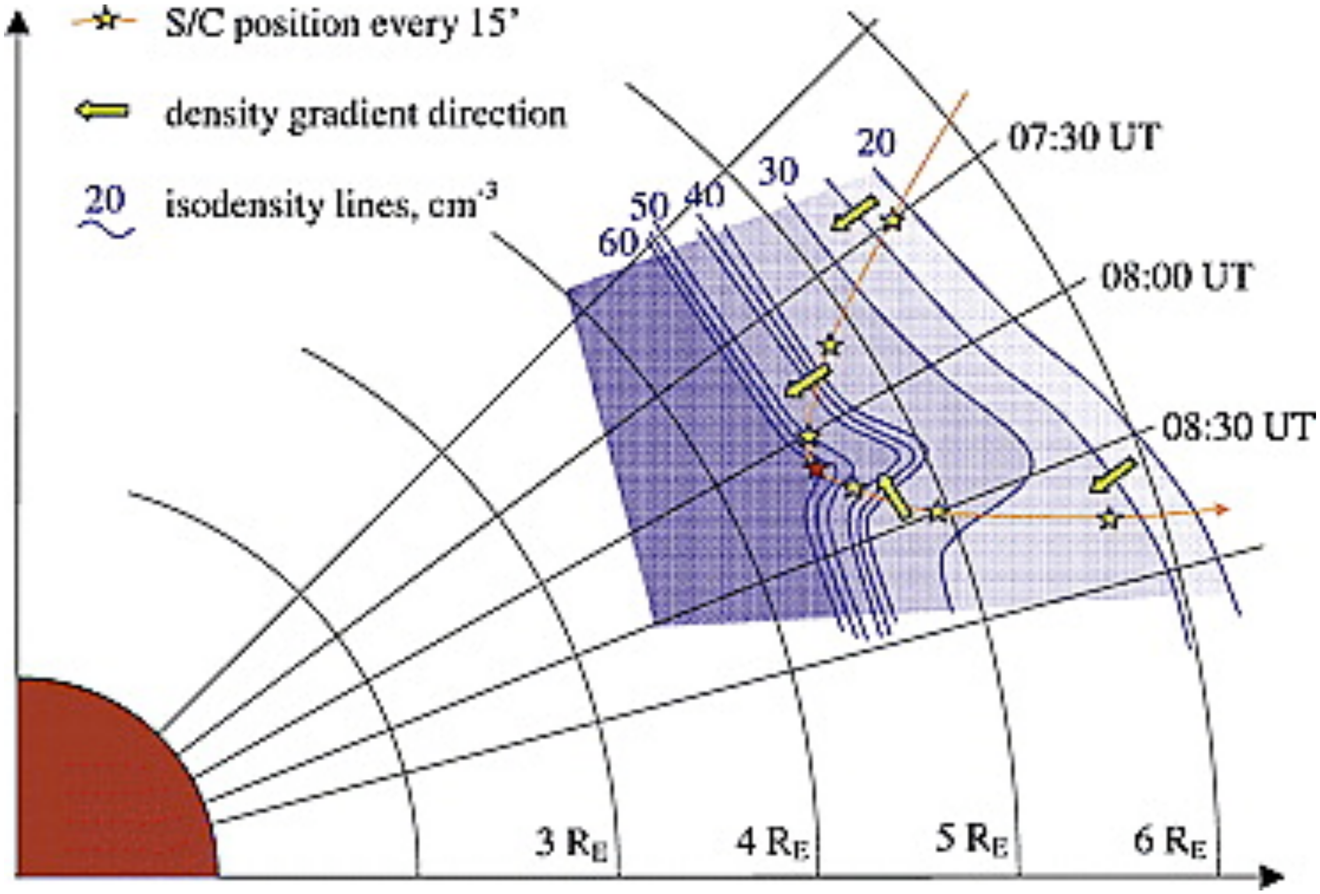


day night

Solstice

Evans and Holt (1978)

Darrouzet et al (2006)

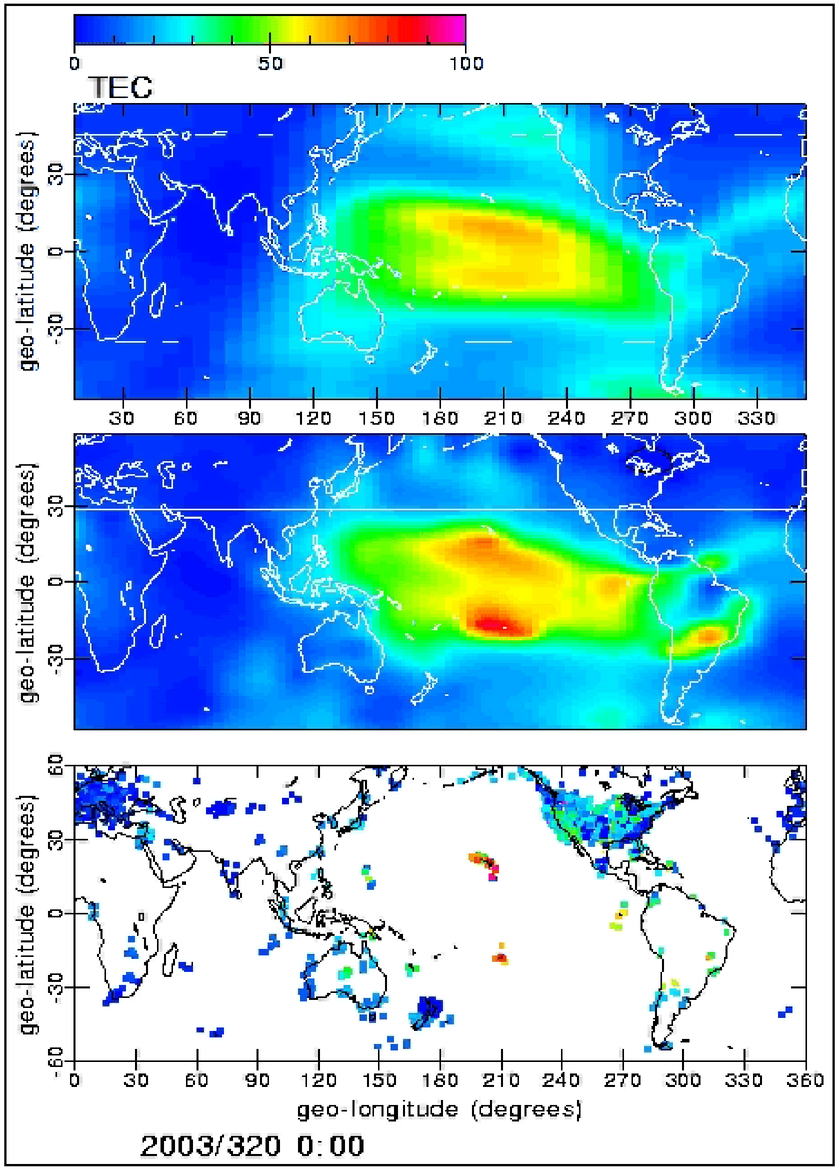


Cluster Mission
Plasma Density Structures
Transverse Equatorial Size 20-5000 km

Gauss-Markov Kalman Filter Example

- **November 16, 2003**
- **GPS Ground TEC measurements from more than 900 GPS Receivers (from SOPAC Data Archive)**
- **Includes Receivers from:**
  - ➔ **IGS**
  - ➔ **CORS**
  - ➔ **EUREF**
  - ➔ **and others**

Gauss-Markov Kalman Filter Reconstruction



Climate

Kalman Filter

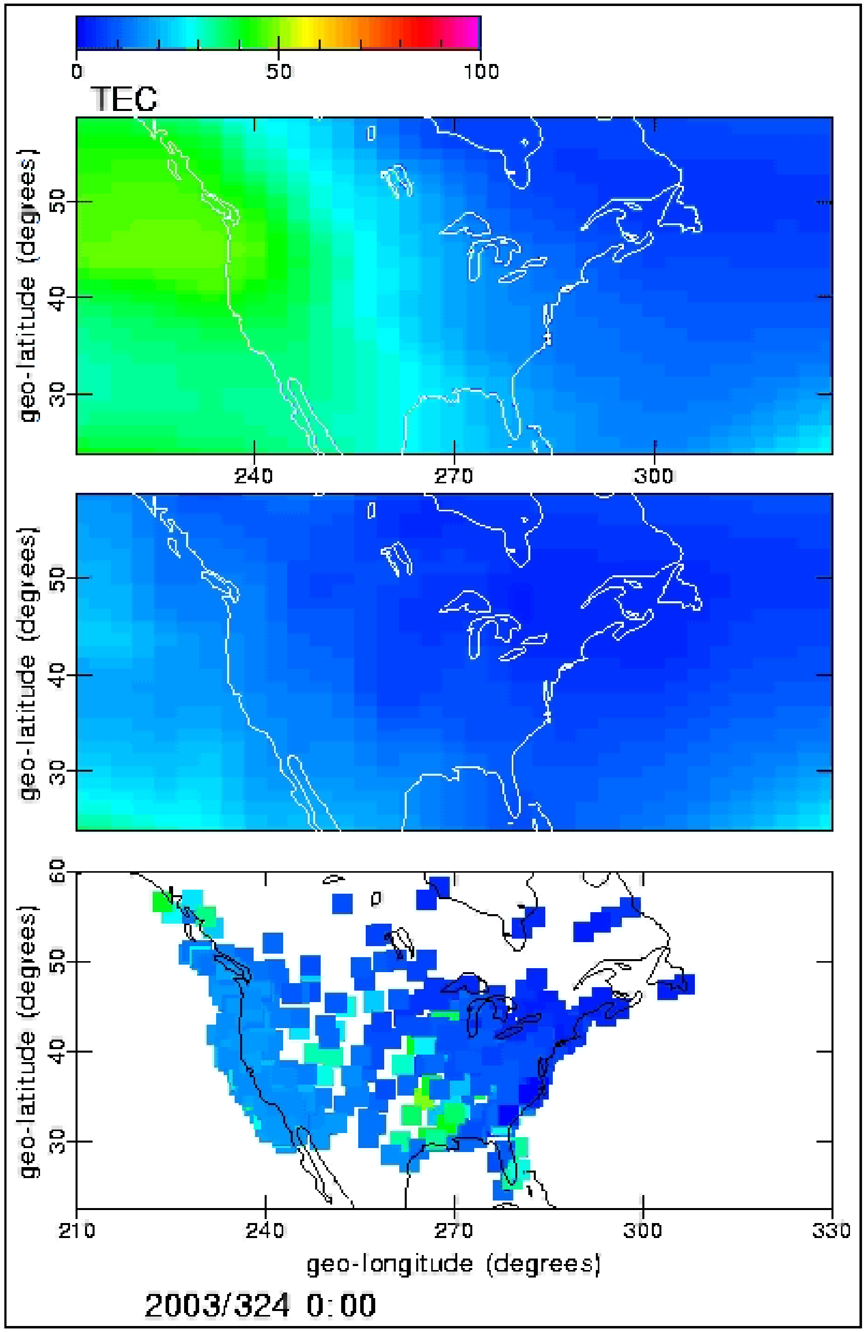
More than 3000
Slant
TEC Measurements
are assimilated every
15 minutes.

GAIM
"Bringing the pieces together"
Global Assimilation of Ionospheric Measurements
Utah State University, (435)797-2962, schunk@cc.usu.edu;
Universities of Colorado (Boulder), Texas (Dallas), and Washington

Gauss-Markov Kalman Filter Example
Regional Mode

- **3-D Ionospheric N_e Reconstruction over North America**
- **Large Geomagnetic Storm on November 20-21, 2003**
- **GPS Ground TEC Measurements from more than 300 GPS Receivers (CORS GPS Network + other) over the continental US and Canada**
- **2 Ionosondes at Dyess and Eglin**

→ **Observe large TEC Enhancements over the Great Lakes during November 20, 2003 @ 2000 UT.**



Climate

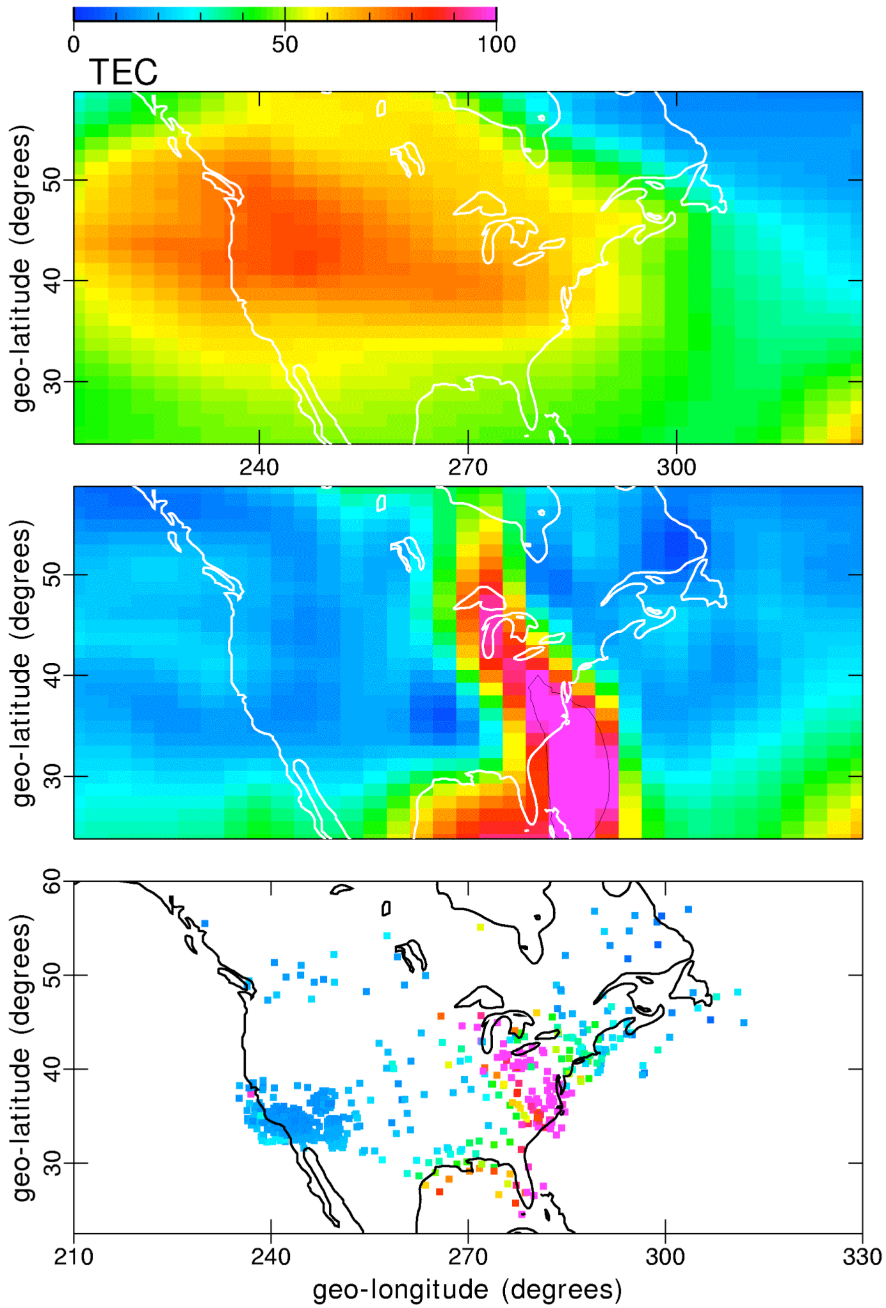
Kalman Filter

About 2000 Slant TEC Values are Assimilated every 15 min

GAIM
"Bringing the pieces together"

Global Assimilation of Ionospheric Measurements

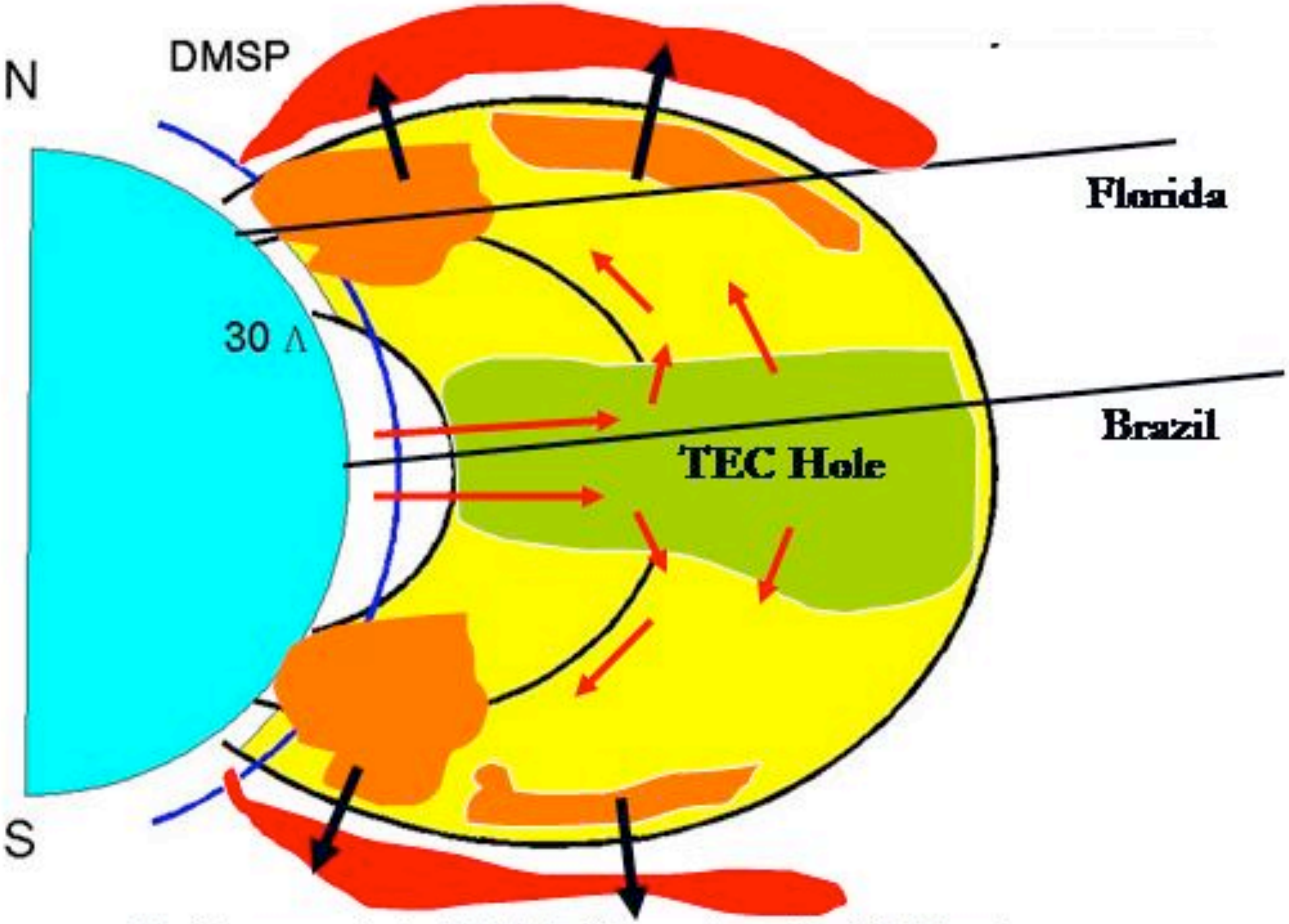
Utah State University, (435)797-2962, schunk@cc.usu.edu;
Universities of Colorado (Boulder), Texas (Dallas), and Washington



2003/324 20:00

Schunk et al. (2005)

Eastward Electric Field Uplifts Equatorial Ionosphere



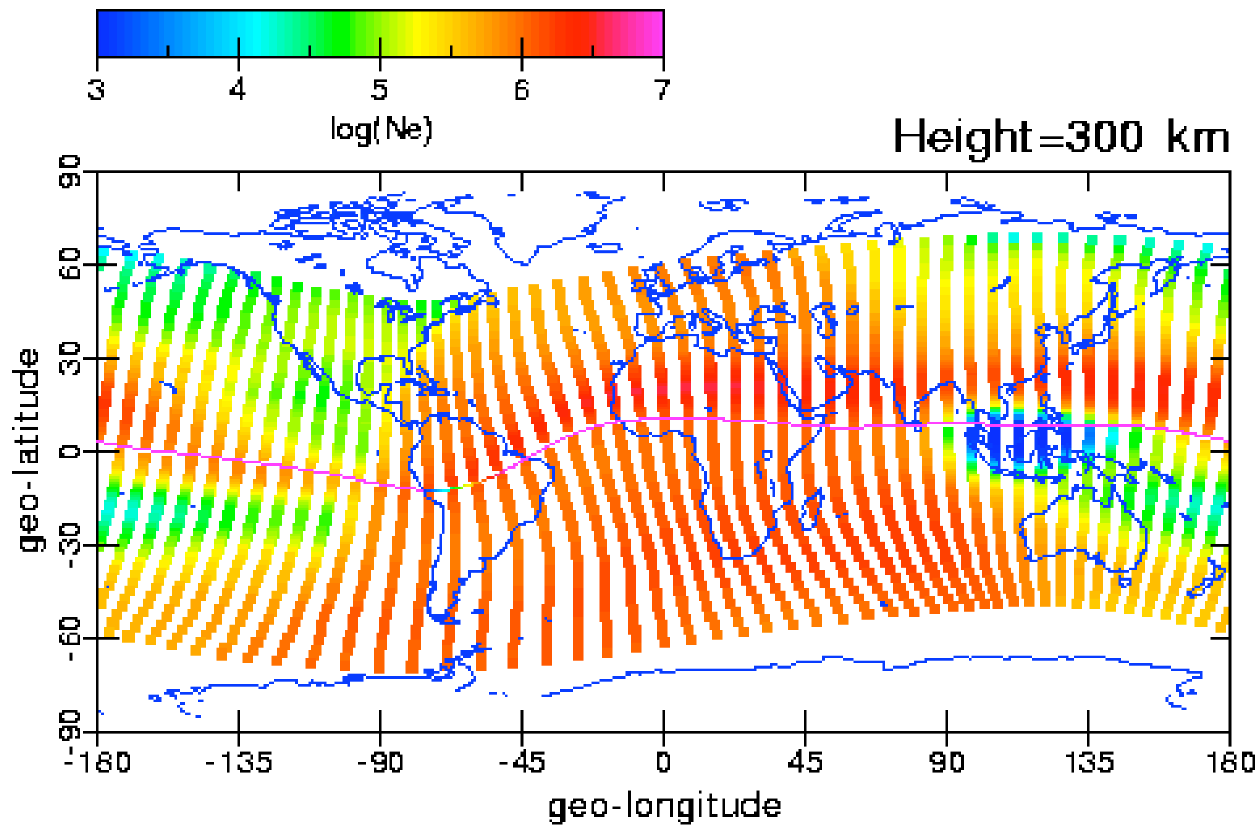
Poleward SAPS Electric Field Strips Away Outer Layers of Plasmasphere

Foster et al (2004)

Low-Latitude Ionosphere

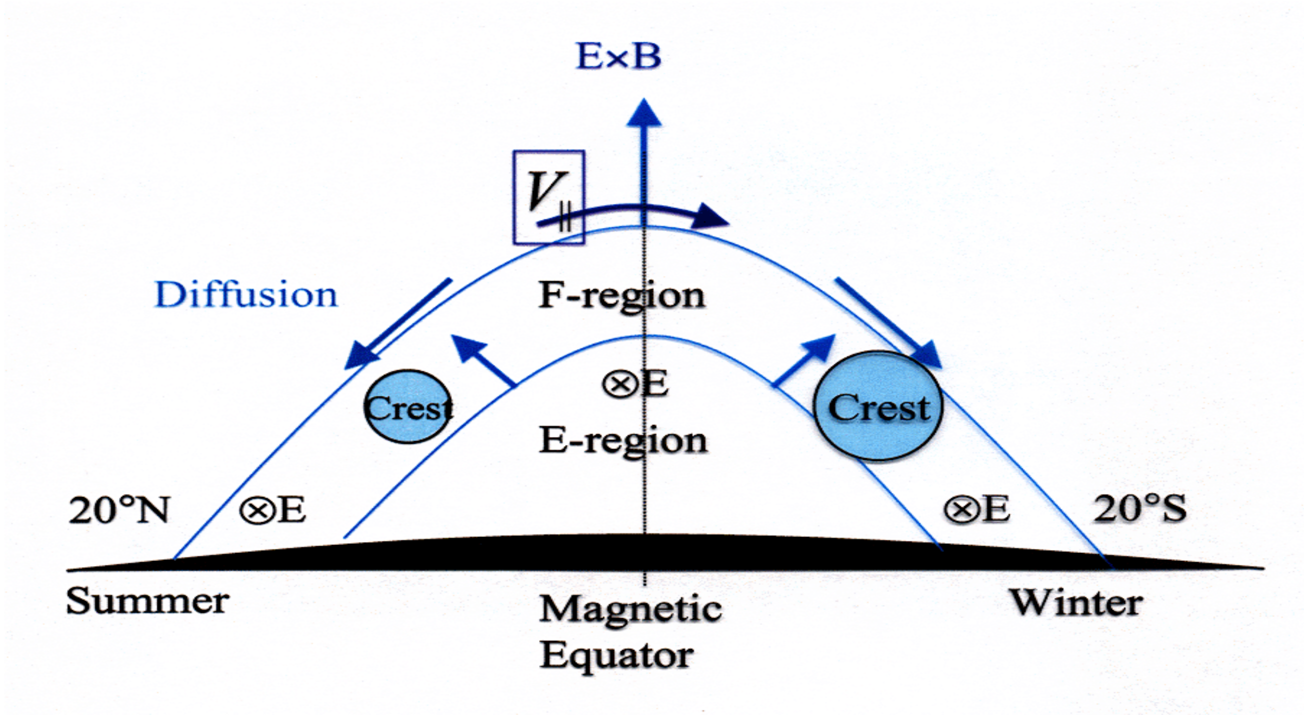
- Equatorial Anomaly
- N_e Variability
- Spread-F/Plasma Bubbles
- Rayleigh-Taylor Instability

IGRF Magnetic Field



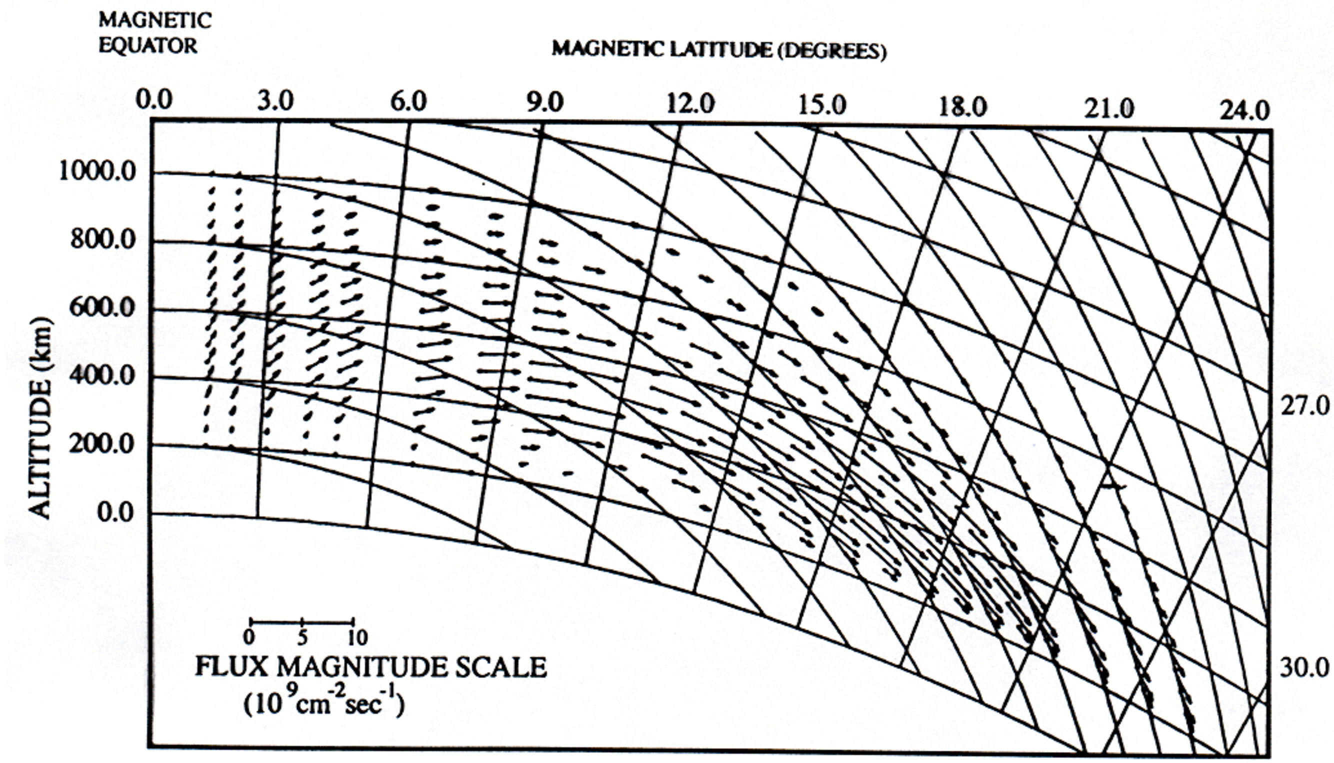
Snapshot of modeled electron densities at 300 km and 12 UT displayed in a geographic coordinate system. The electron densities were calculated from the Ionosphere-Plasmasphere Model (IPM) and are shown along geomagnetic field lines.

Effects of Diffusion, Electric Fields, and Winds on the Low-Latitude Ionosphere



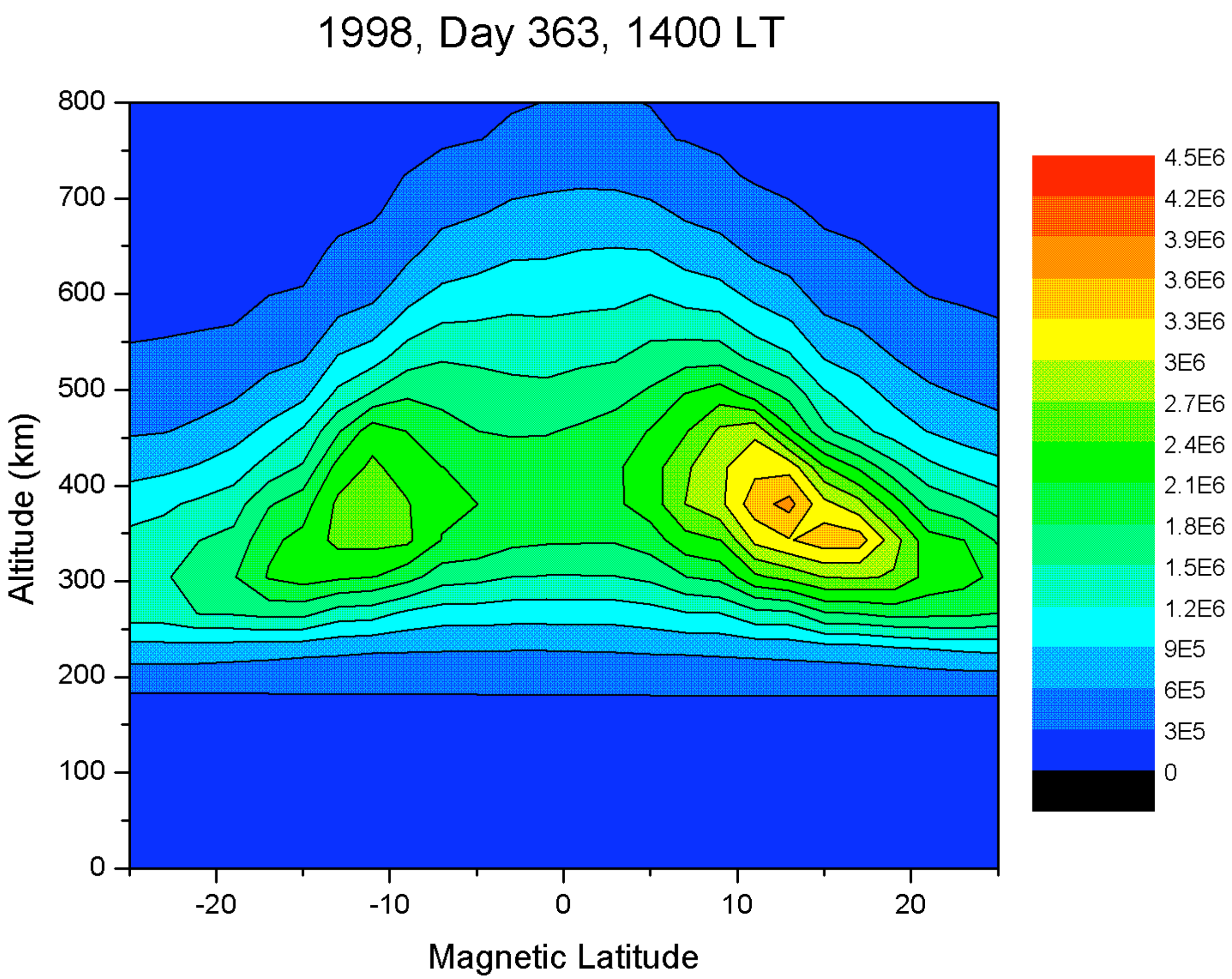
F-region Ionization Transport Process With the Transequatorial Wind

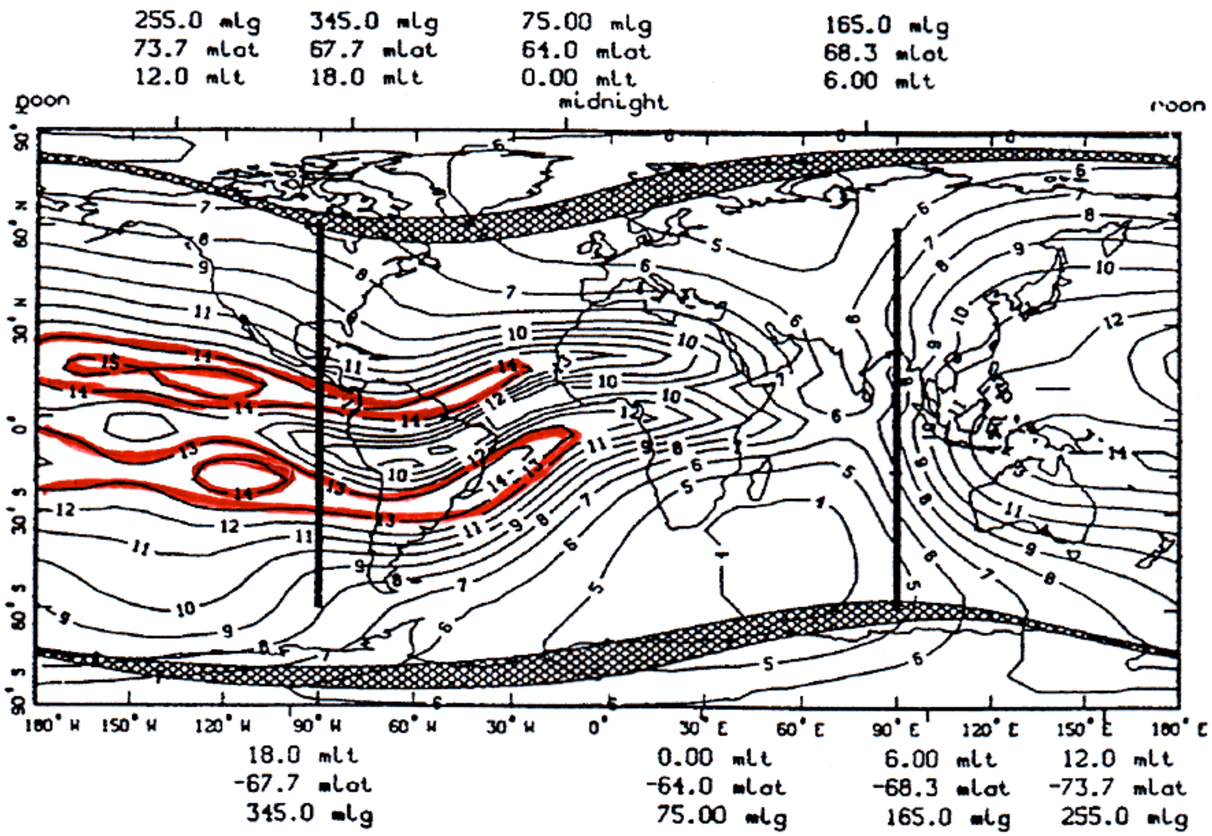
Equatorial Fountain



Hanson and Moffett (1966)

Low Latitude Climatology





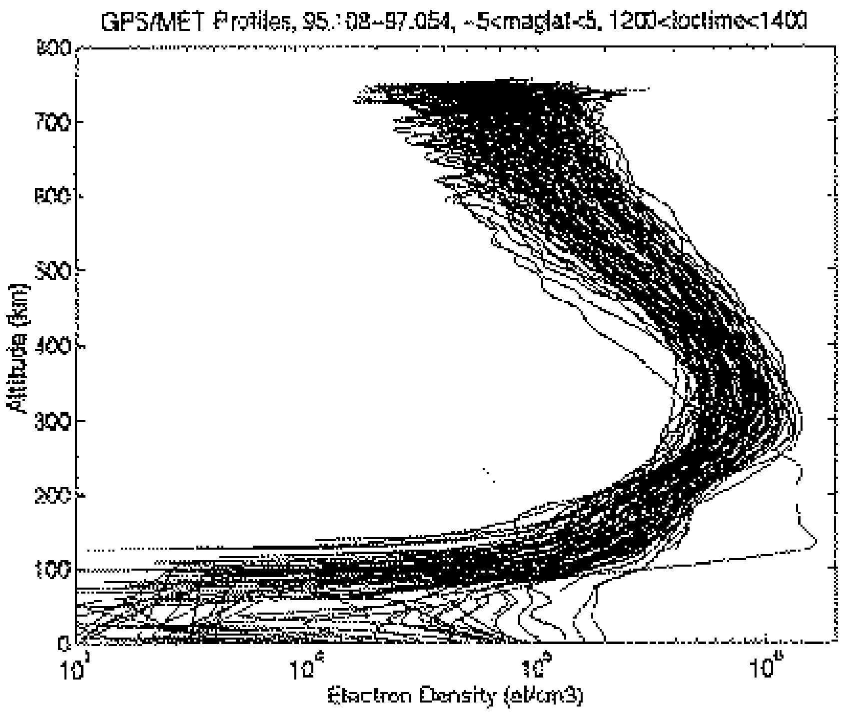
Bilitza et al. (1993)

- International Reference Ionosphere (IRI)
- f_oF_2 for solar Maximum, Equinox and UT=0

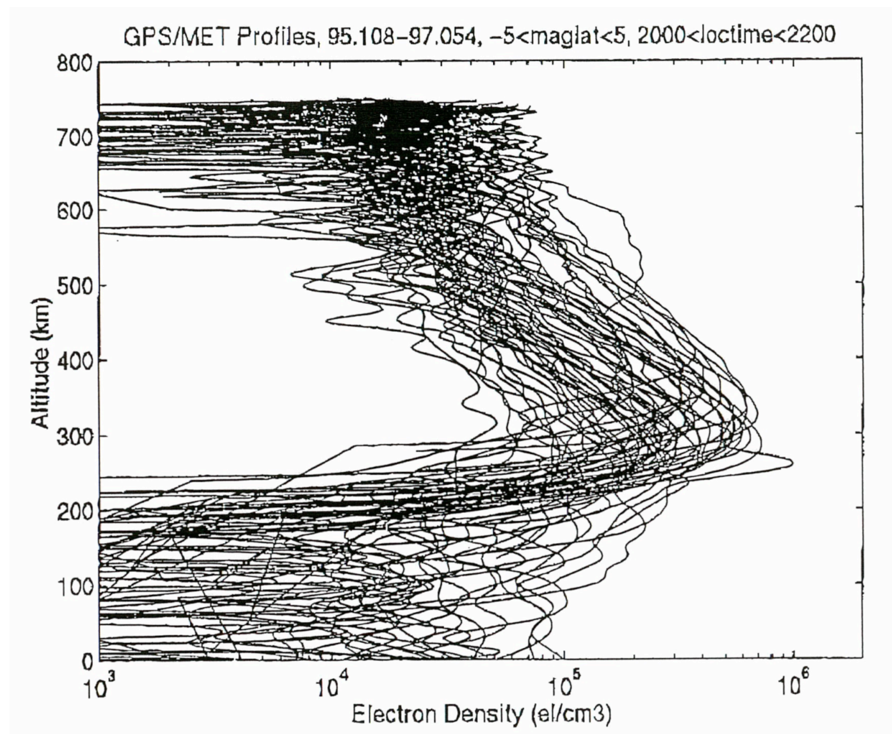
GPS/MET Satellite

Equatorial Profiles

$-5° \leq \theta \leq 5°$
1200 < local time < 1400



$-5° \leq \theta \leq 5°$
2000 < local time < 2200

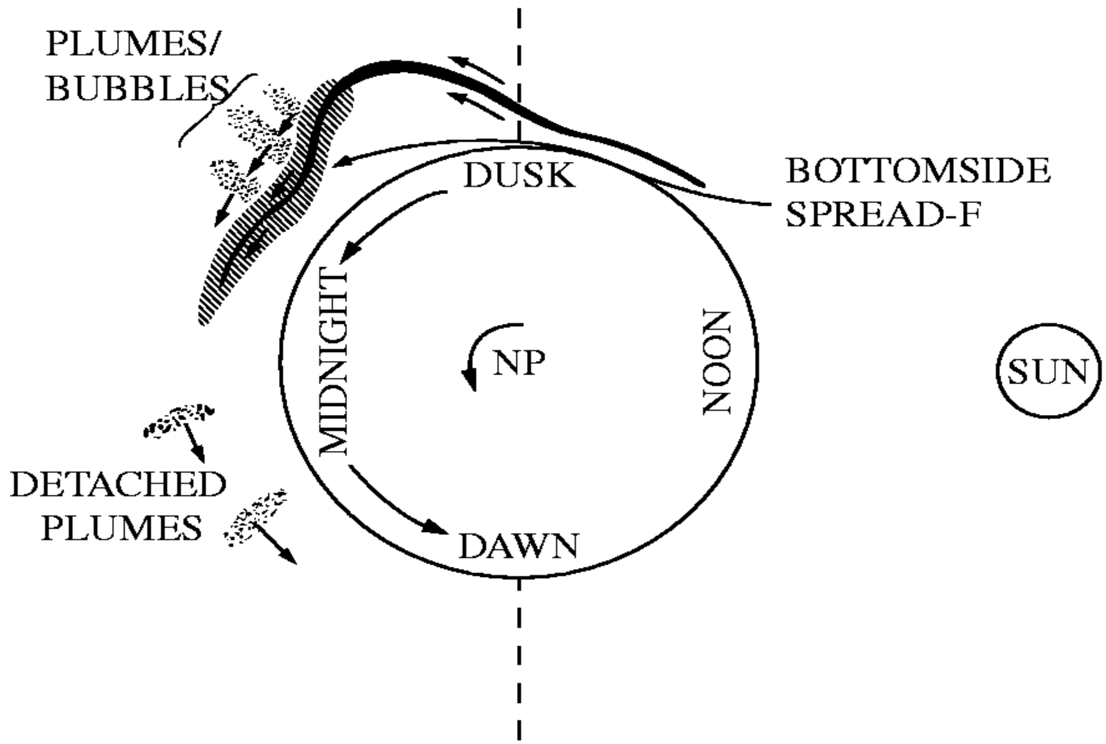


Equatorial Plasma Bubbles

- Vertically Elongated Wedges of Depleted Plasma
- Entire North - South Extent of **B** Depleted
- Up to Factor 1000 Depletion
- Bubble Apex Altitudes Between 500 - 1500 km
- Typical Bubbles: 100-500 m/s up
- Fast Bubbles: 500 m/s - 5 km/s up

  1 km/s horizontal

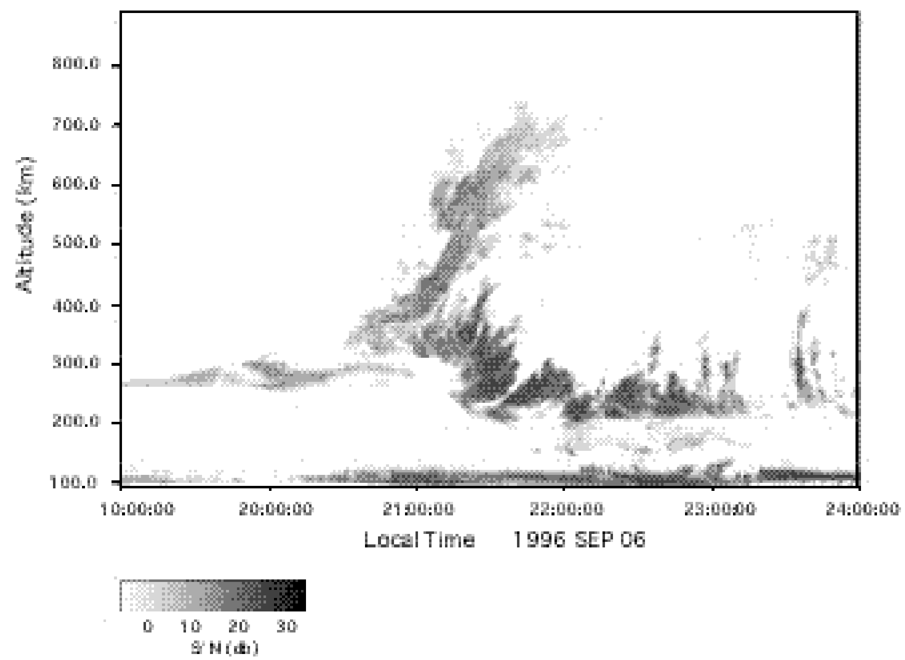
Spread F/Equatorial Bubbles



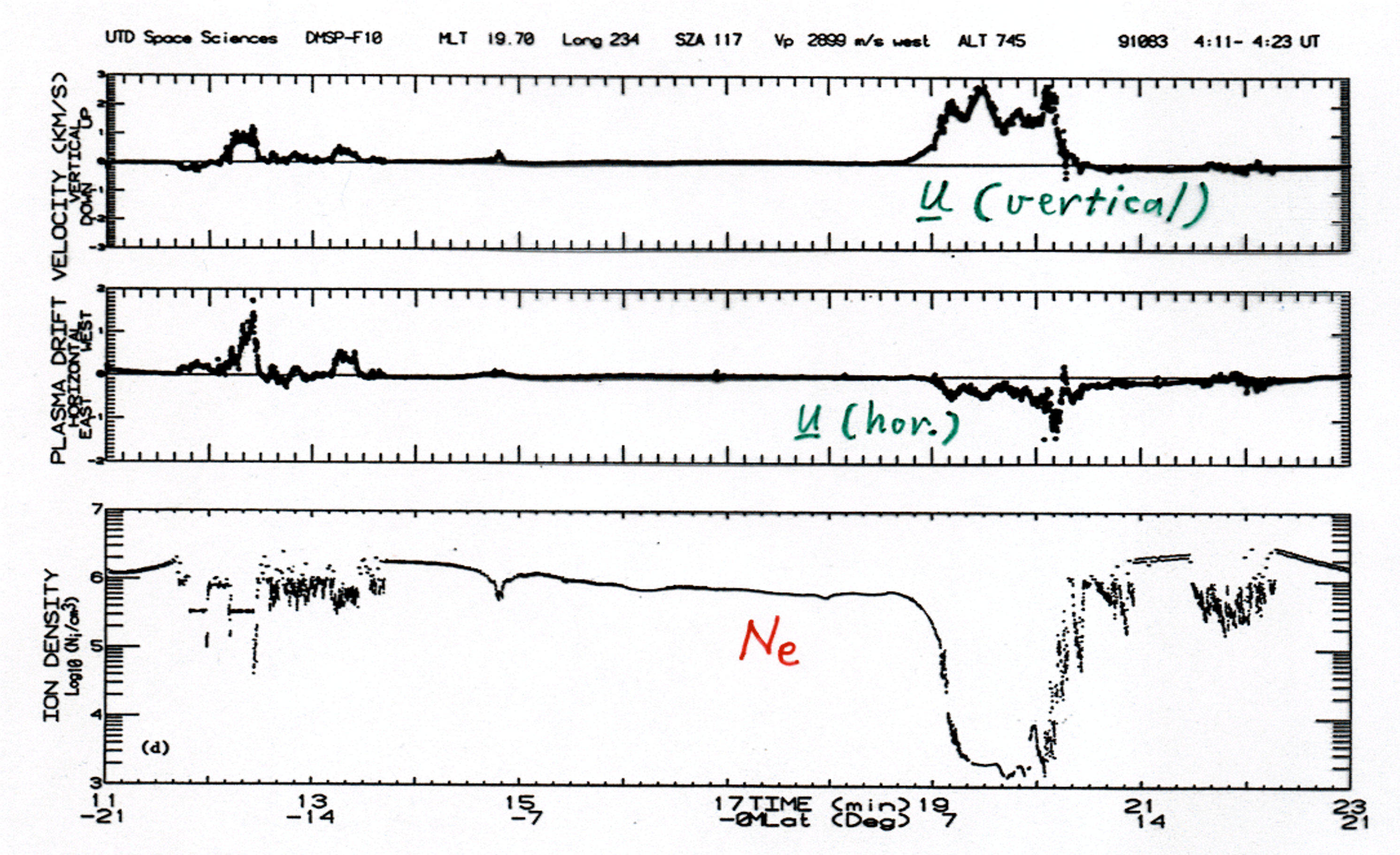
Argo and Kelley (1986)

Equatorial Spread-F and Bubbles

JULIA Coherent Scatter Radar



Hysell and Burcham (1998)

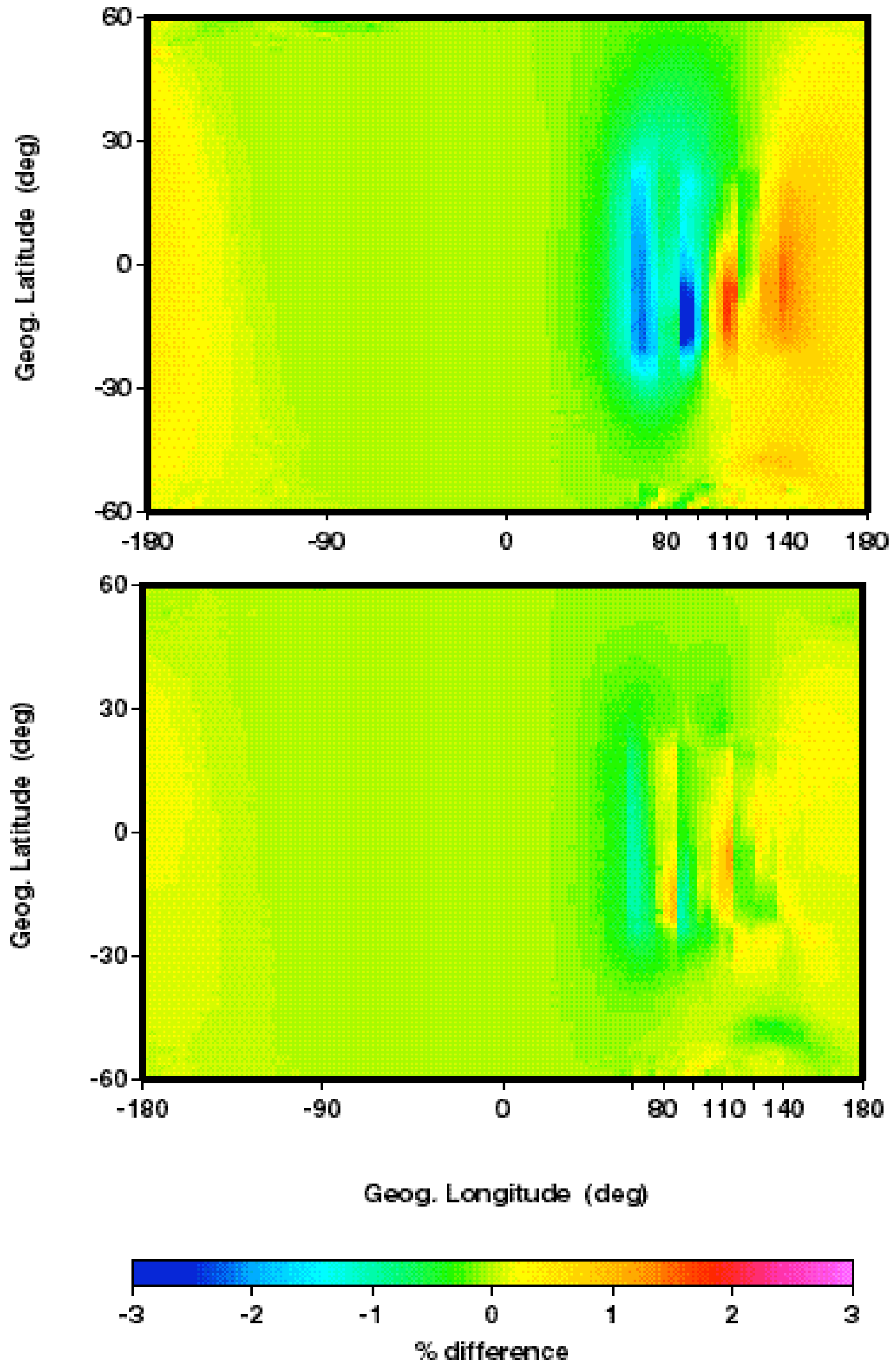


- DMSP F10 Satellite
- 234 E Longitude, 19.7 MLT, 117 SZA, 750 km Orbit
- Typical Bubbles: 100-500 m/s up
- Fast Bubbles: 500 m/s - 5 km/s up

  1 km/s horizontal

Neutral Density (top) and Temperature (bottom) Perturbations due to 4 Plasma Bubbles

300 km



Golden Age of Aeronomy

- Large Amount of Data Available
- Access via Virtual Observatories
- Data Assimilation Models
- Coupled Physics-Based Geospace Models
- Community Coordinated Modeling Center (CCMC)
- Elucidating Mass, Momentum, and Energy Coupling in the M-I-T System at Global, Regional, and Local Scales will be Possible
- Rigorous Inclusion of Instabilities in Global Models will be Possible