Thermal Ion Escape as a Source of Magnetospheric Plasma

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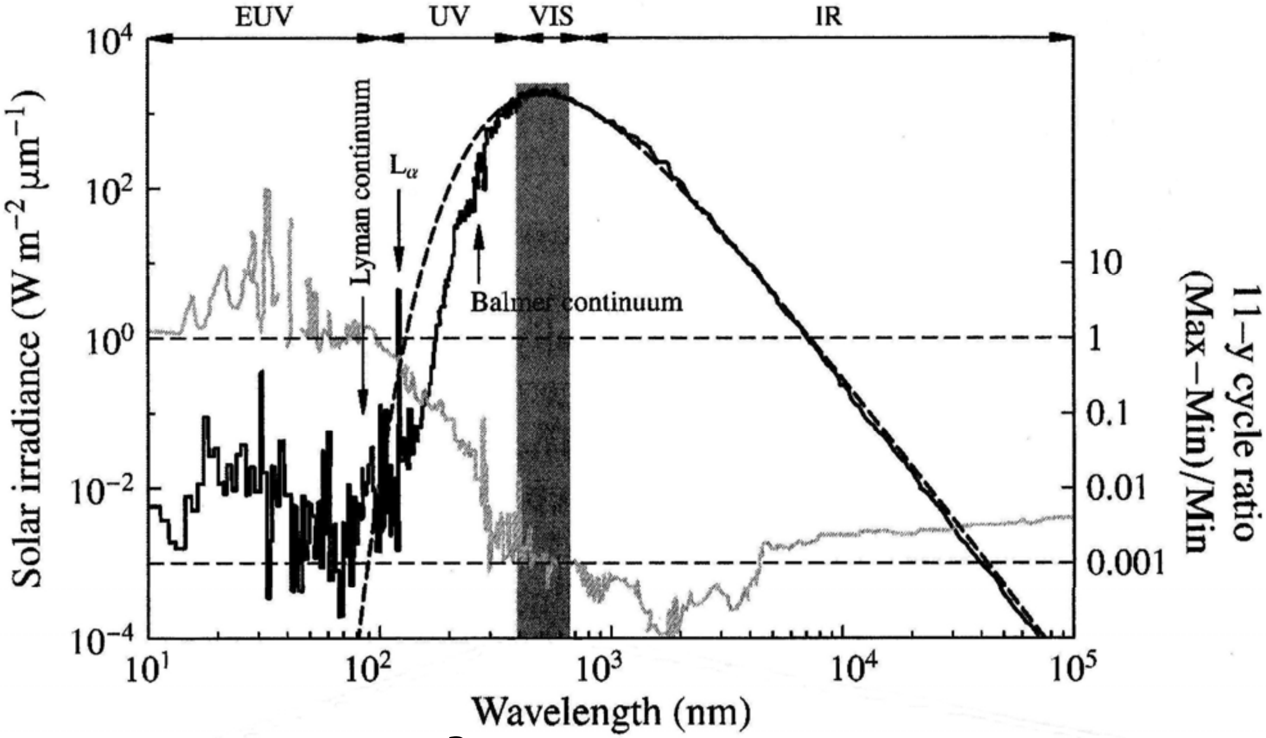
Solar Radiation

HINODE/XRT (0.6nm～20nm)

EUV: Extreme UltraViolet



Planck's law $$I(\lambda) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{k\lambda T}} - 1}$$

Stefan–Boltzmann law $$F = \int_0^{\infty} I(\lambda) d\lambda = \sigma T^4$$

$$C_s = 1.37\mathrm{kW/m^2}$$

Solar Constant

Photochemistry in the Upper Atmosphere

Photoionization by EUV

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

$$O_2 + h\nu \rightarrow O_2^+ + e$$

$$N_2 + h\nu \rightarrow N_2^+ + e$$

$$He + h\nu \rightarrow He^+ + e$$

Electron-Ion Recombination

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

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

$$N_2^+ + e \rightarrow N + N$$

Radiative Recombination

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

$$He^+ + e \rightarrow He + h\nu$$

$$H^+ + e \rightarrow H + h\nu$$

Ion-Molecule reactions

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

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

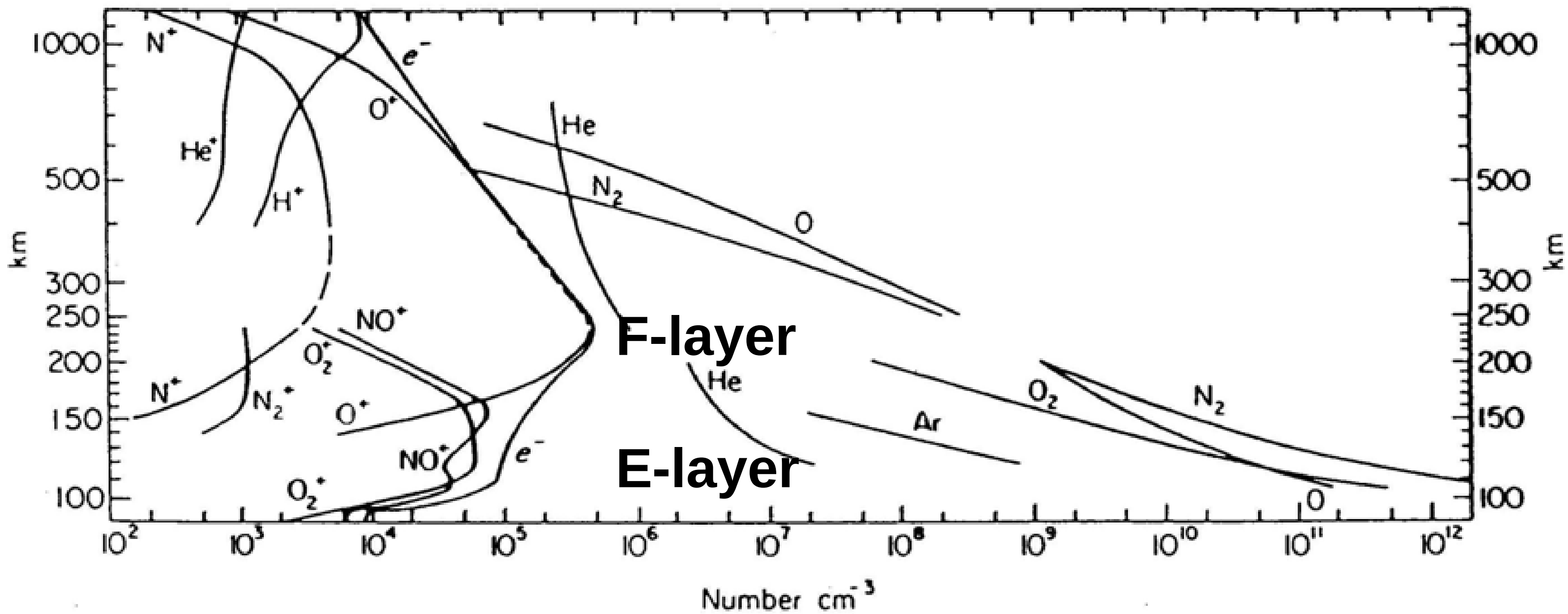
$$O_2^+ + NO \rightarrow O_2 + NO^+$$

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

$$N_2^+ + O_2 \rightarrow N_2 + O_2^+$$

$$H^+ + O \rightarrow H + O^+$$

Ionosphere and Thermosphere



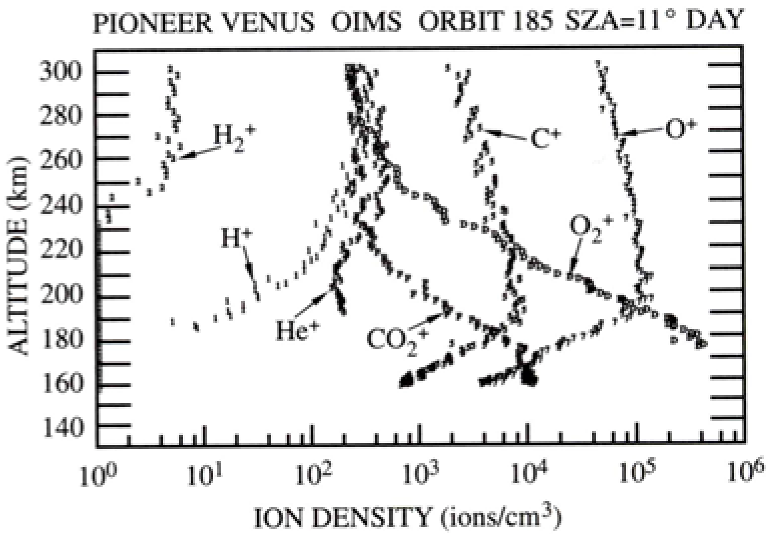
Ionosphere **Thermosphere**

***Ionization rate is <10^{-4} in F-region.**

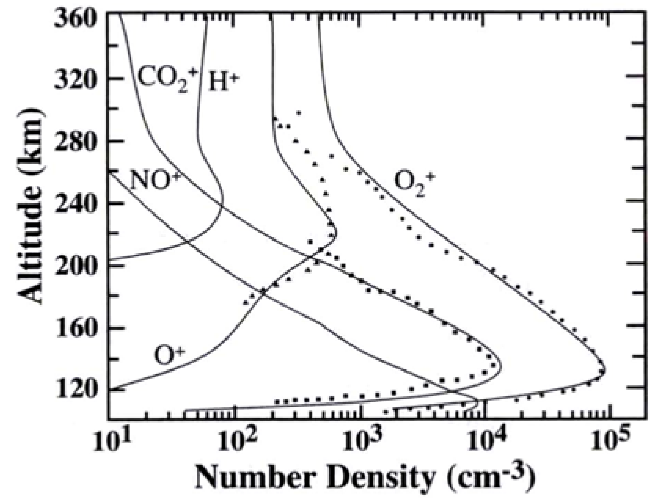
***Coupling between Atmosphere and Plasma is important for the dynamics and photochemistry in the ionosphere/thermosphere.**

Planetary Ionosphere

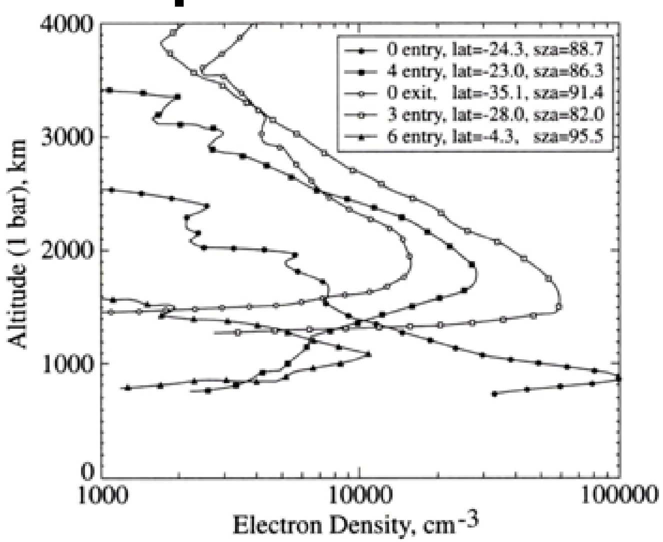
Venus



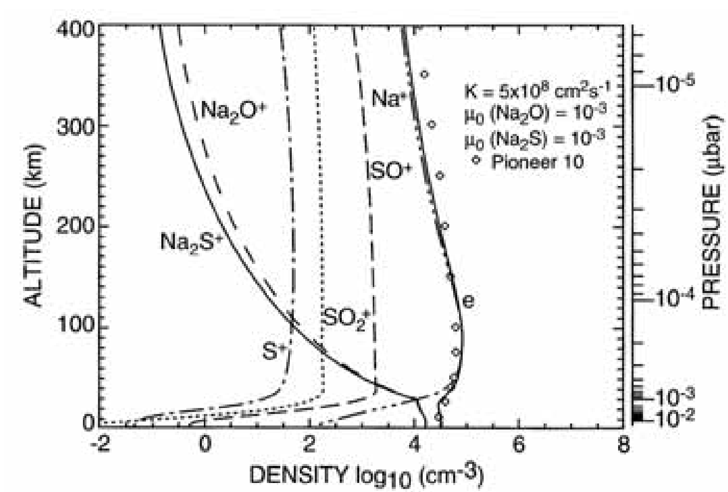
Mars



Jupiter



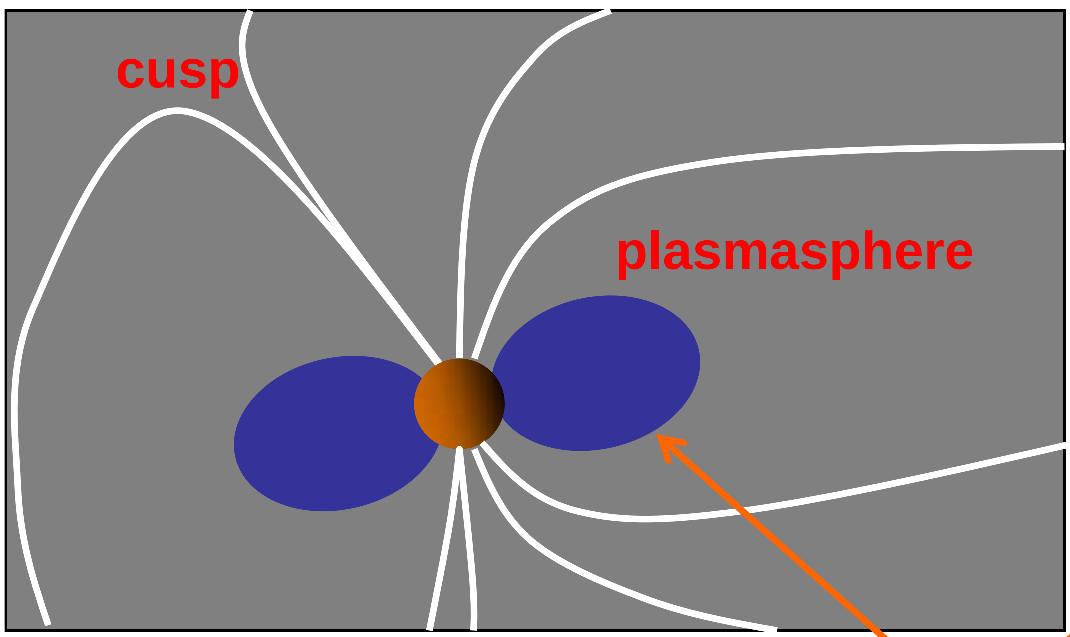
Io



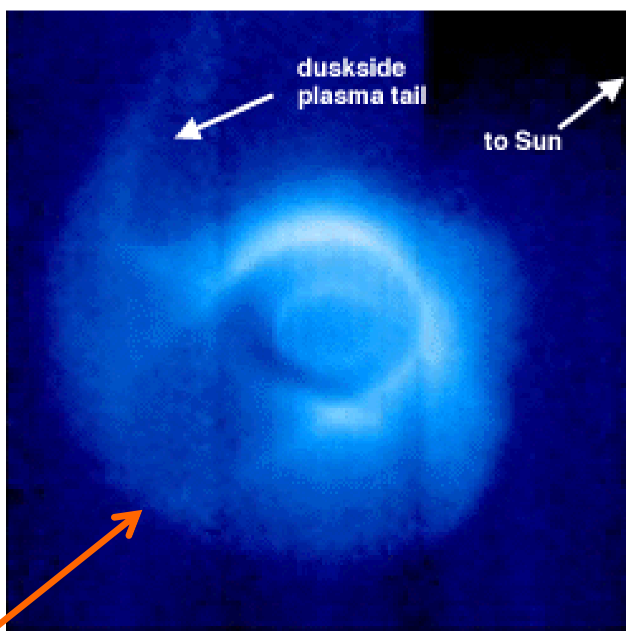
Plasmasphere

The Earth's plasmasphere is a torus of cold (~1eV) and dense (~10^3cm^{-3}) plasma in the region of the inner magnetosphere. H^+ is the principal ion with ~20% He^+.

From dusk



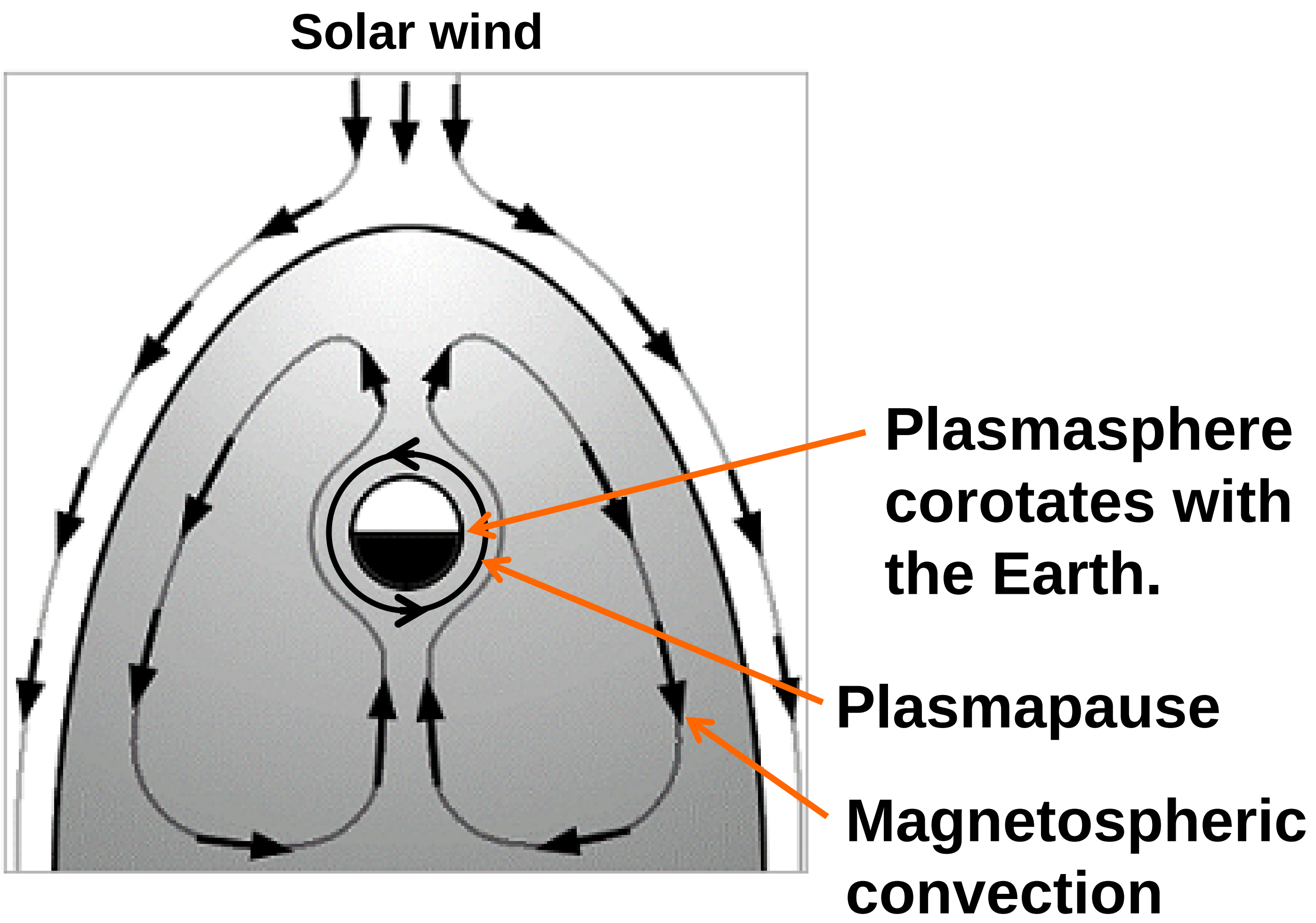
From north



plasmapause

IMAGE He+ (30.4 nm)

Magnetospheric Convection

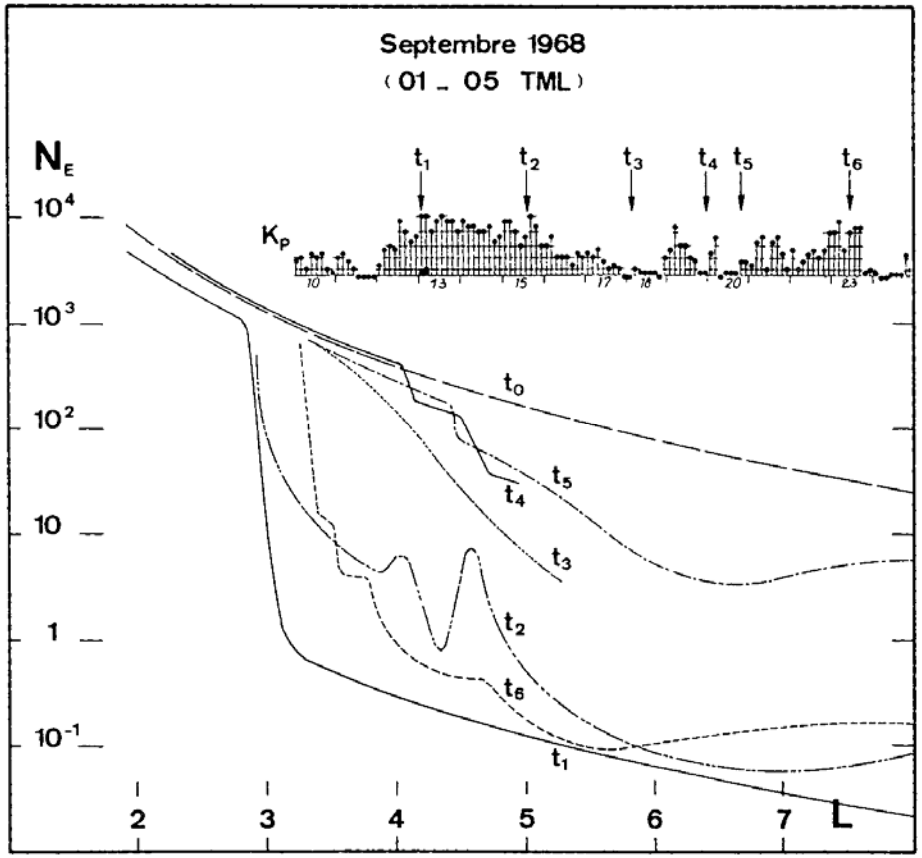


Plasmaspheric erosion (plasma tail) is the result of enhanced magnetospheric convection.

Plasmapause

Corcuff et al., 1972

Ne (cm^{-3})



Plasmasphere **Plasmapause**

Carpenter and Park, 1973

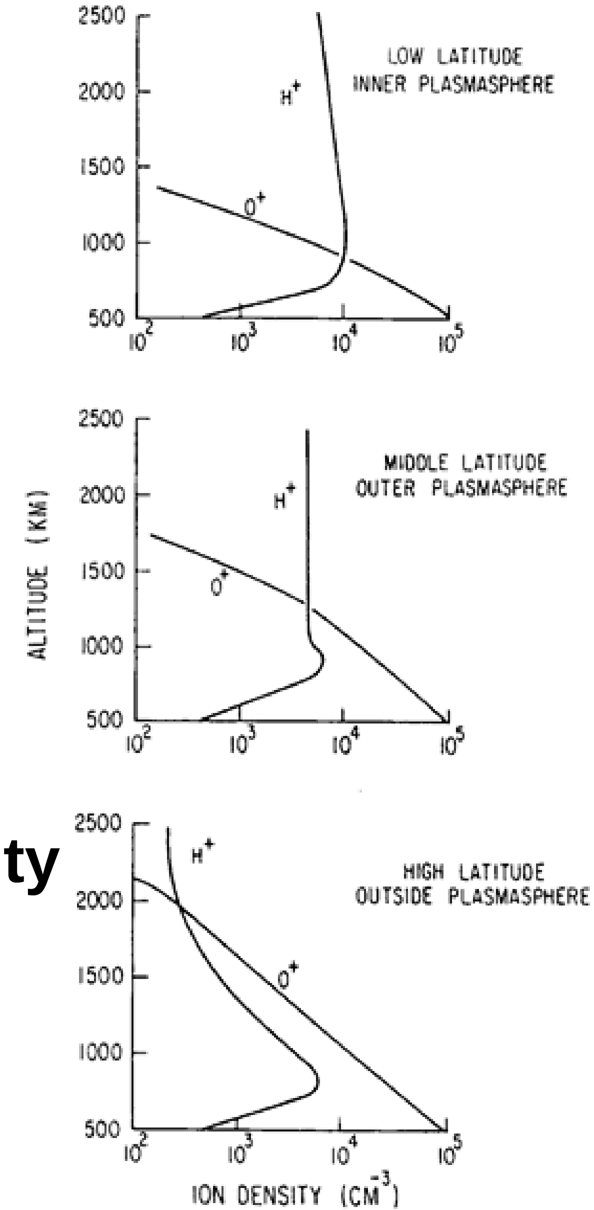
$$L_{pp} = 5.7 - 0.47 K_p$$

The location of the plasmapause depends on the magnetospheric disturbance.

Wave-like irregularity in the plasmapause results from transient, localized processes associated with substorms.

Plasma is supplied continuously from ionosphere. (Refilling)

Topside Ionosphere



Low latitude

Middle latitude

High latitude
(outside plasmasphere)

Why is low H+ density at high latitudes?

Banks et al., 1976

Momentum Equation in Ionosphere

Momentum Equation for Ion and Electron

$$\rho_i \frac{\partial \mathbf{v}_{//i}}{\partial t} + \rho_i \left(\mathbf{v}_{//i} \cdot \nabla_{//} \right) \mathbf{v}_{//i} = -\nabla_{//} p_i + e n_i \mathbf{E}_{//} - \rho_i \mathbf{g}_{//} - \rho_i \nu_{ie} \left(\mathbf{v}_{//i} - \mathbf{v}_{//e} \right)$$

Charge Neutrality **Ambipolar Electric Field**

$$m_e << m_i \,, \qquad \left| n_i - n_e \right| << n_i , n_e , \qquad \mathbf{E}_{//} = -\frac{\nabla_{//} p_e}{e n_e}$$

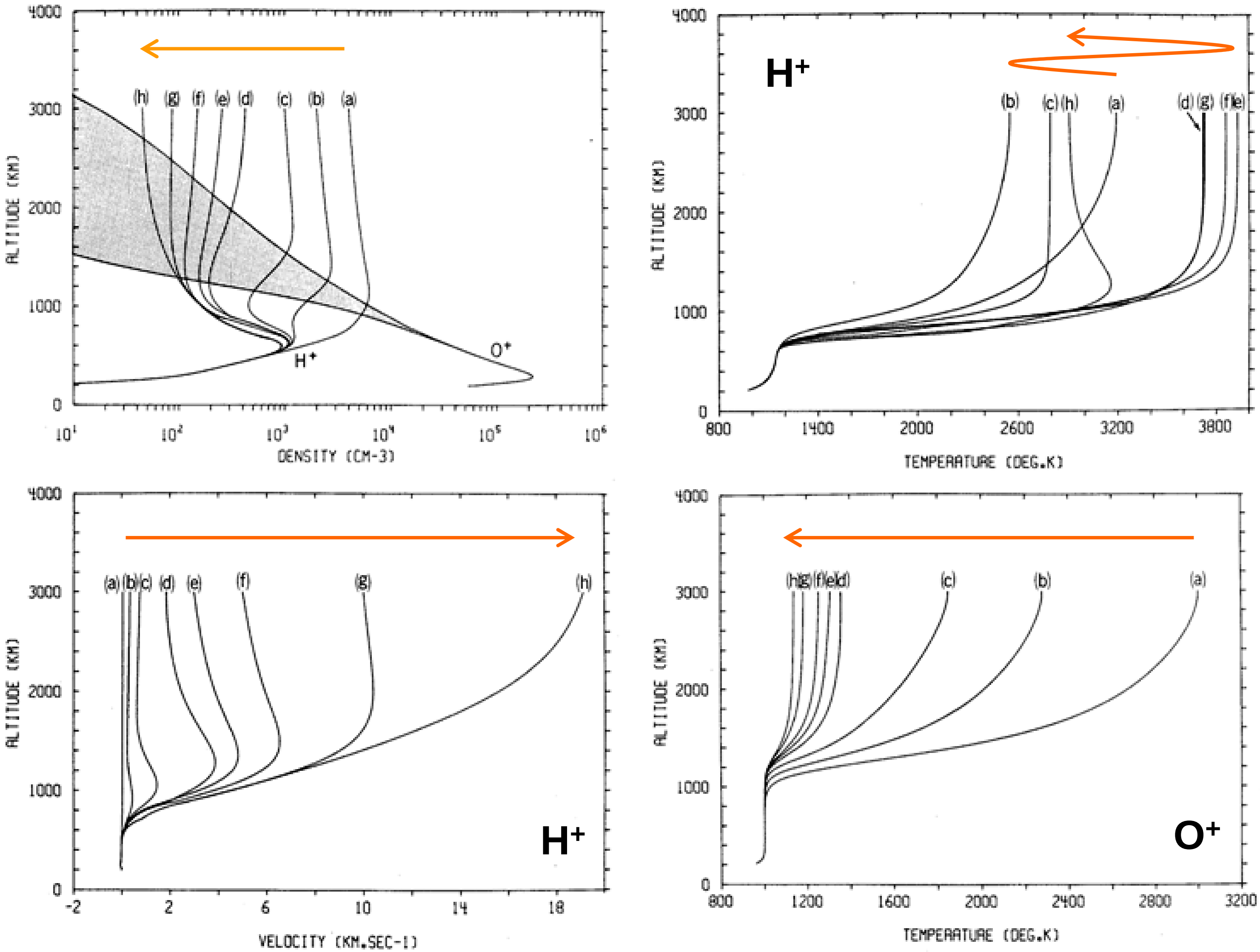
$$\rho_i \frac{\partial \mathbf{V}_{//}}{\partial t} + \rho_i \left(\mathbf{V}_{//} \cdot \nabla_{//} \right) \mathbf{V}_{//} = -\nabla_{//} p - \rho_i \mathbf{g}_{//} , \qquad p = p_i + p_e$$

Force along Open Magnetic Field Line
or Closed Magnetic Field Line during Refilling.

- **Pressure Gradient**
- **Ambipolar Electric Field** ←

Modeling of Topside Ionosphere

Boundary Condition: H+ density at 3000km altitude.



Collisional Coupling

H+ - O+

H+ - e

Te: 1000k at 200km
4650k at 3000km

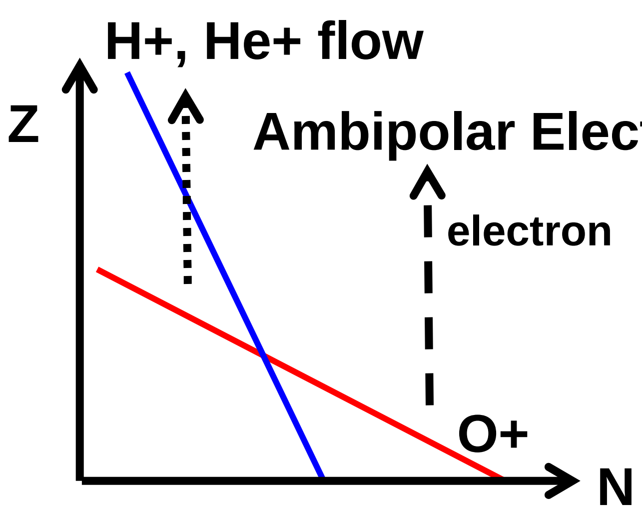
Raitt et al., 1975

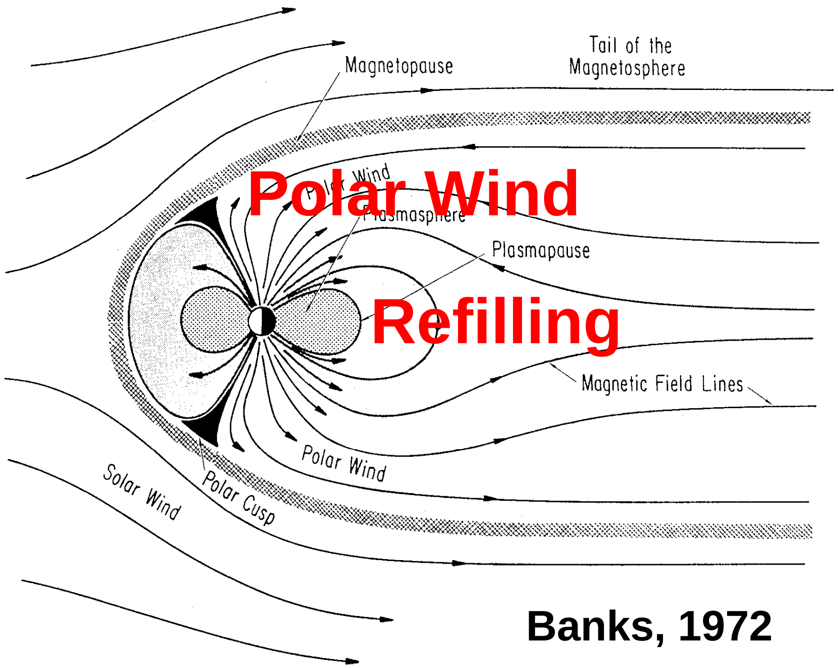
Polar Wind

Axford [1968] pointed out that the lighter ions must escape from the earth by the flux of escaping photo-electrons with energies greater than 2.4 eV, and suggested the ion escape speed of ~10 km/sec.

This phenomenon is called 'Polar Wind'.

The polar wind is important as a source of magnetospheric plasma [Shelley et al., 1982; Moore et al., 1986; Chappell et al., 1987].

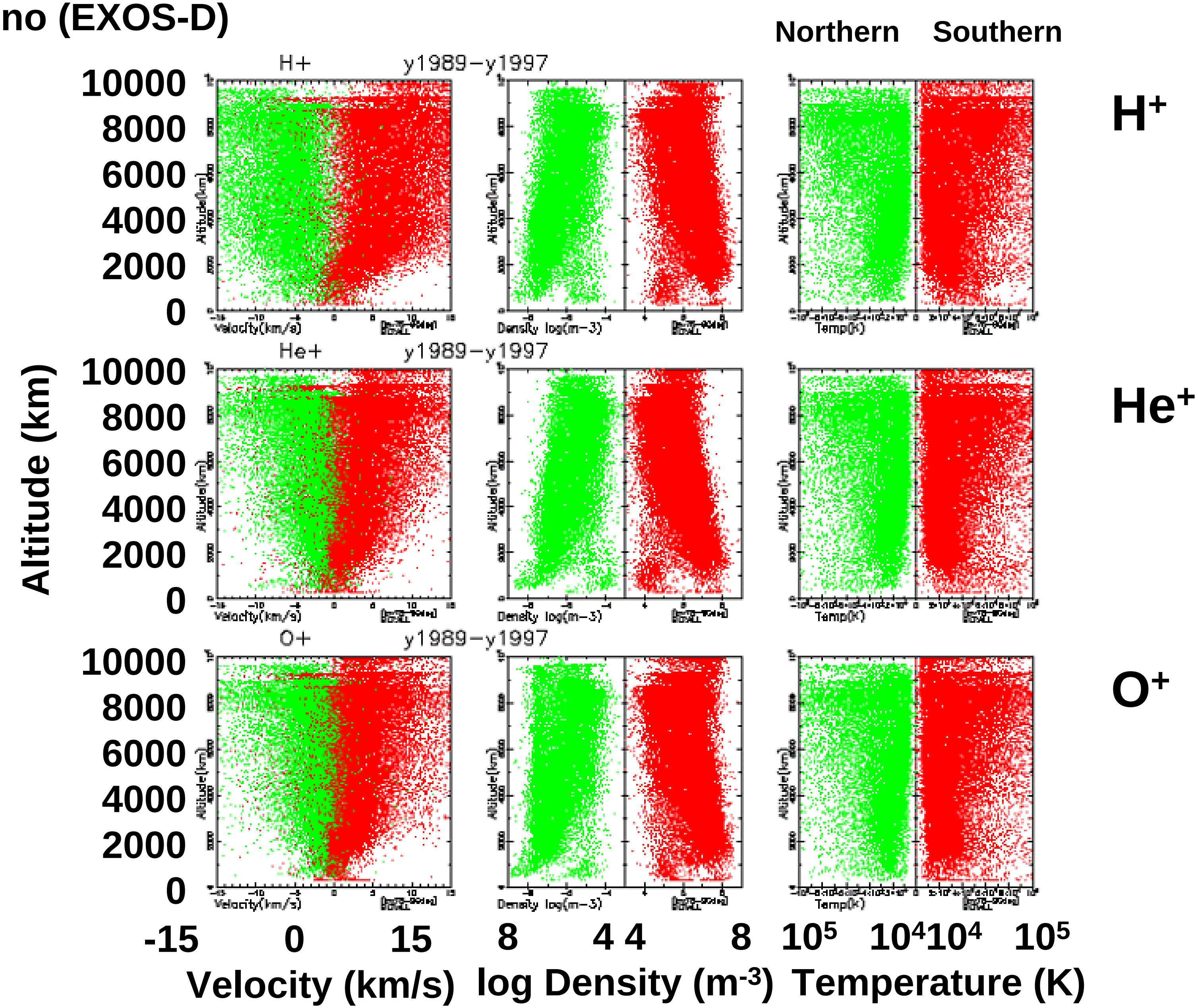




Banks, 1972

Topside Polar Ionosphere

Akebono (EXOS-D)



Thermal Ion Outflow

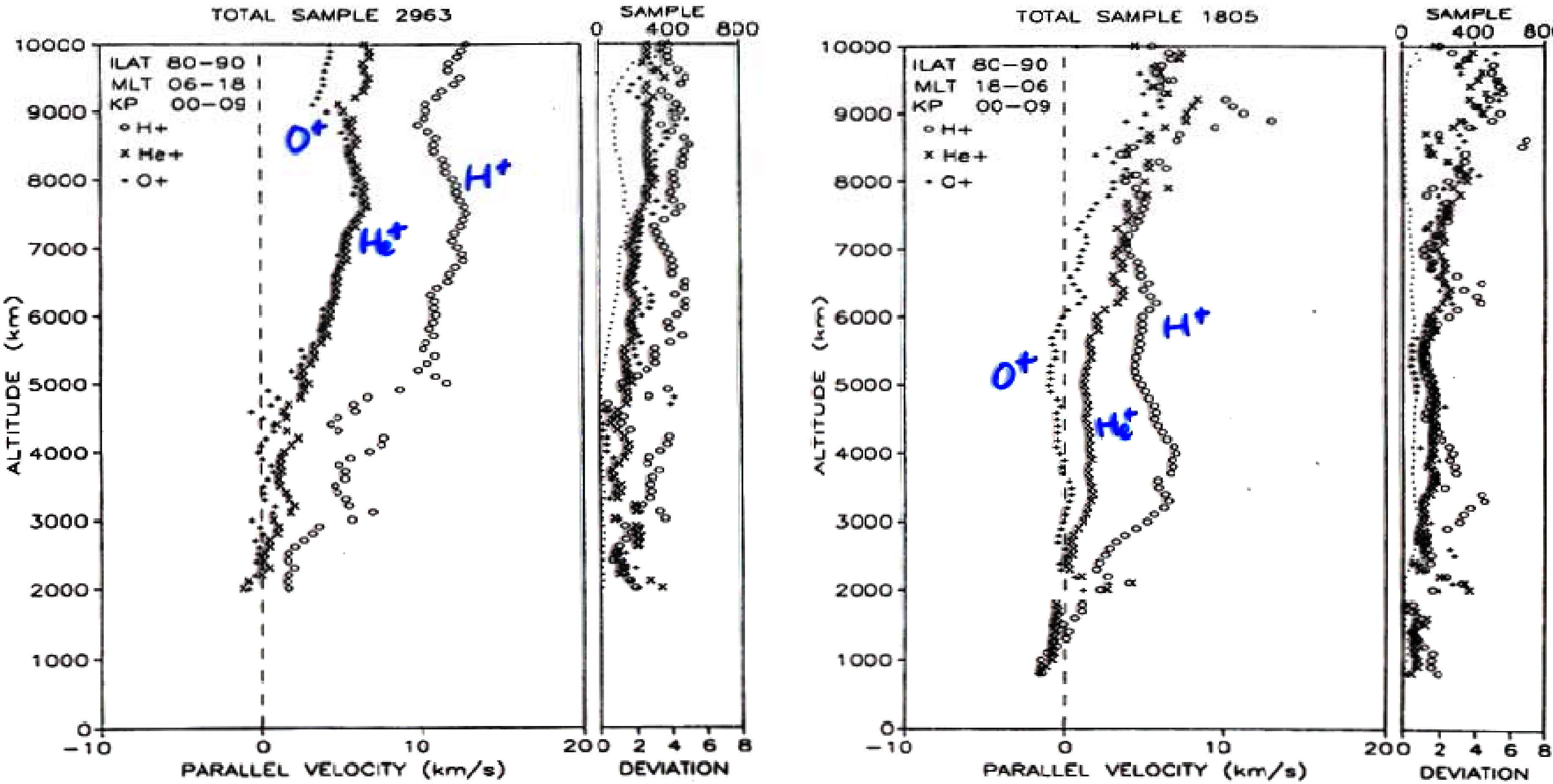


Fig. 4. Parallel ion velocity of the polar wind in the dayside (06-18 MLT) as a function of altitude, averaged over all *Kp* levels and all invariant latitudes above 80°. See Figure 3 caption for explanation.

Fig. 5. Parallel ion velocity of the polar wind in the nightside (18-06 MLT) as a function of altitude, averaged over all *Kp* levels and all invariant latitudes above 80°. See Figure 3 caption for explanation.

Akebono/SMS

Near magnetic pole,
all ionospheric ions are flowing to Magnetosphere.

Thermal Ion Heating

ANDRÉ ET AL.: ANDRÉ ET AL.: AURORAL ION ENERGIZATION

O+
H+
e
E
B
n
B
j

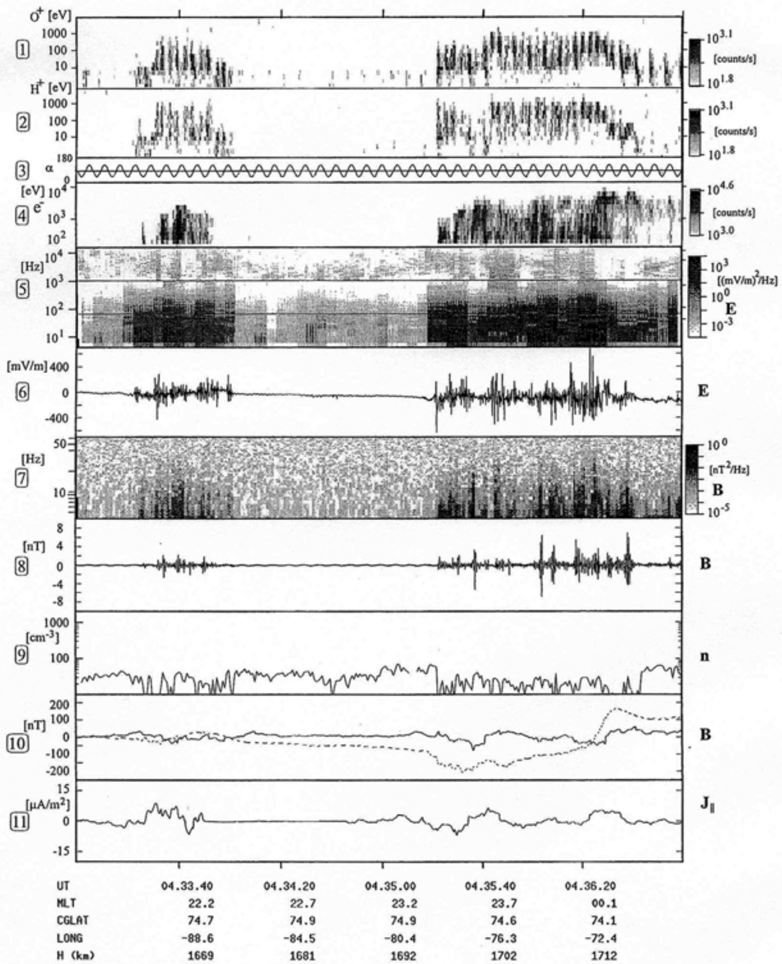


Figure 1. Freja data from orbit 5972 (January 1, 1994) where the satellite passed an ion heating region near midnight (event 1). Panel 1 and 2 show the count rates of O^+ and H^+, while panel 3 displays the corresponding pitch angles. Panel 4 displays count rates of downgoing electrons. Panel 5 shows the electric field spectral density up to about 10 kHz, while panel 6 displays a time series of the perpendicular electric field. Panel 7 shows the magnetic field spectral density up to 60 Hz, while panel 8 displays a time series of the magnetic field. Panel 9 shows an estimate of the density. Panel 10 displays magnetic perturbations in the geographic northward (solid) and eastward (dashed) directions. Panel 11 contains the field-aligned current intensity calculated using the magnetic perturbations shown in Panel 10. A positive field-aligned intensity represents an upward current. Transversely heated O^+ ions can be seen in panel 1 between 0433:30 and 0433:50 UT and also between 0435:20 and 0436:30 UT. There is a good correlation between waves in panels 5 and 7 and ion energization in panel 1, as is further discussed in the text. See also Figures 2 and 3.

In Cusp/Aurora regions, ions are heated perpendicular to the local magnetic field line.

This is called TAI. (Transversely Accelerated Ion)

There is good correlation between TAI and Electric/Magnetic field variations. (Low frequency waves)

Freja

Transversely Accelerated Ion

Akebono (EXOS-D)

Thermal H+

O+

Energetic Ele.

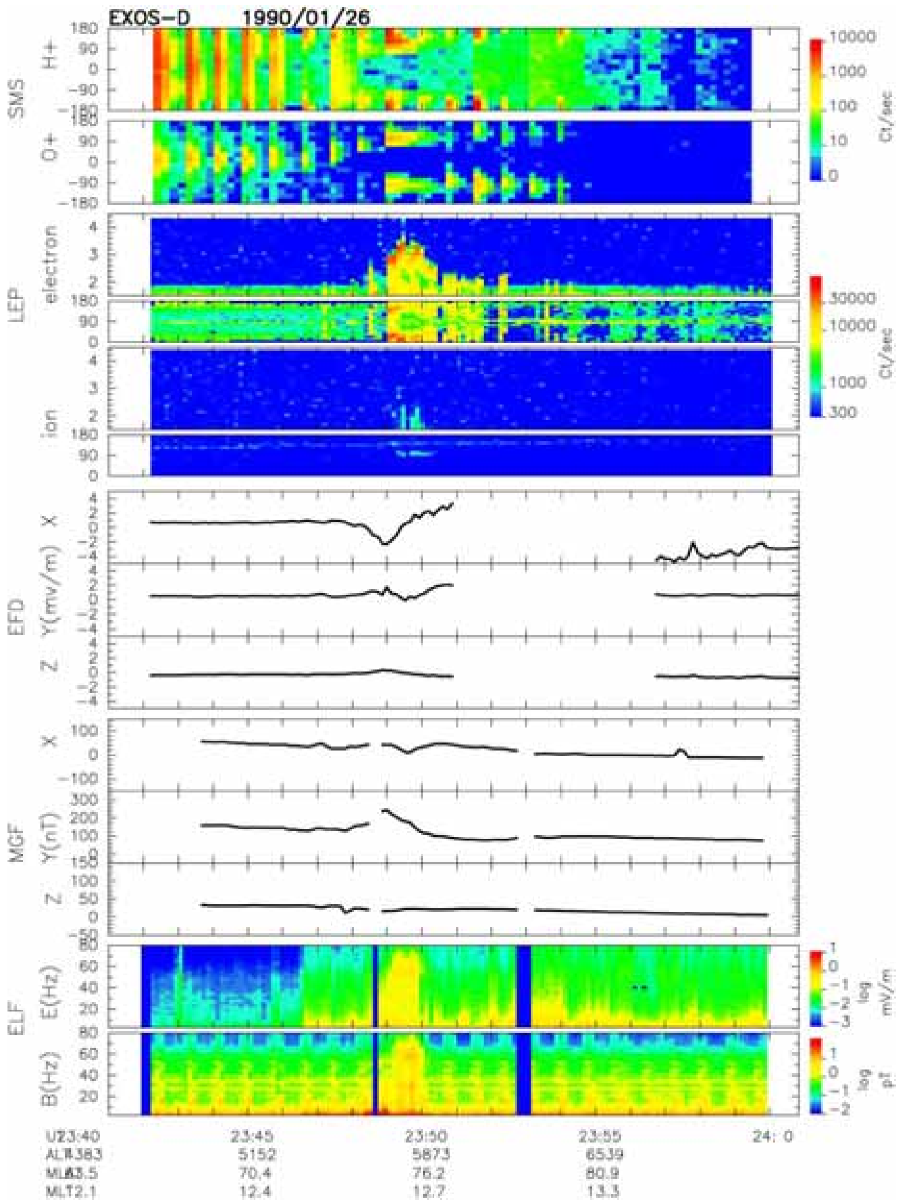
Ion

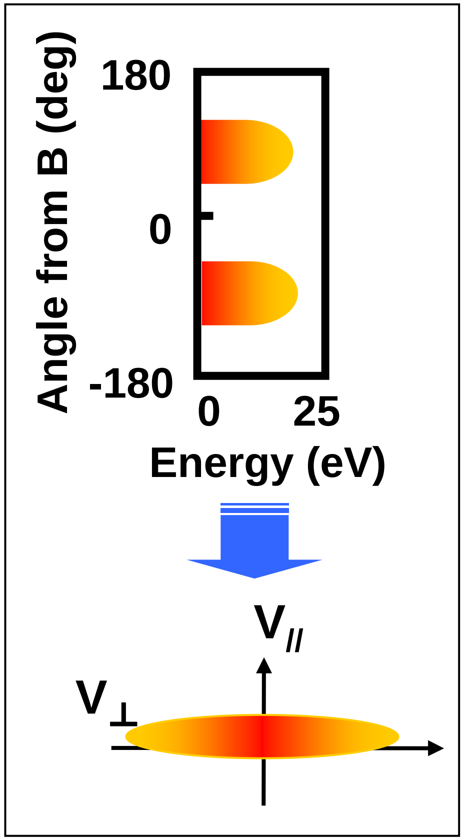
Electric Field

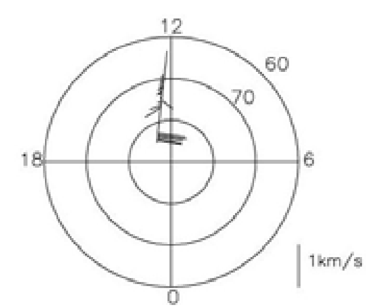
Magnetic Field

ELF wave E

B





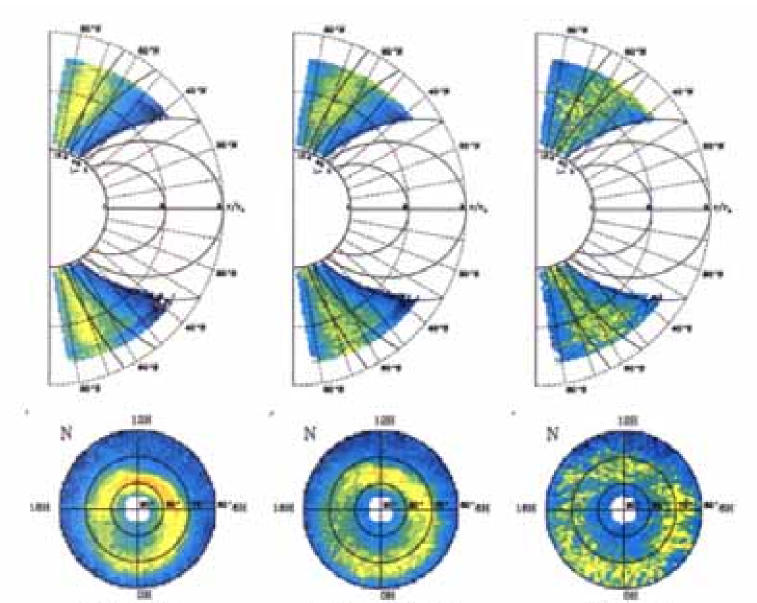


Outflow and Plasma wave

Akebono (EXOS-D)

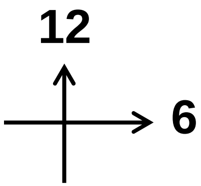
Kasahara et al., 2000

Broadband Noise



(a) $K_p \le 2+$ (b) $3- \le K_p \le 4+$ (c) $5- \le K_p$

Plate 6. (a-c) Kp dependence of the broadband noise at 5 Hz.

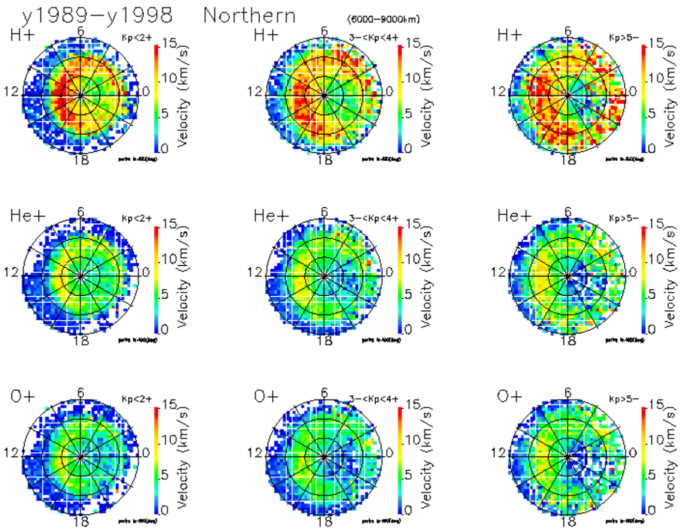


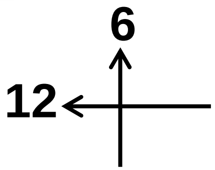
Velocity

H^+

He^+

O^+

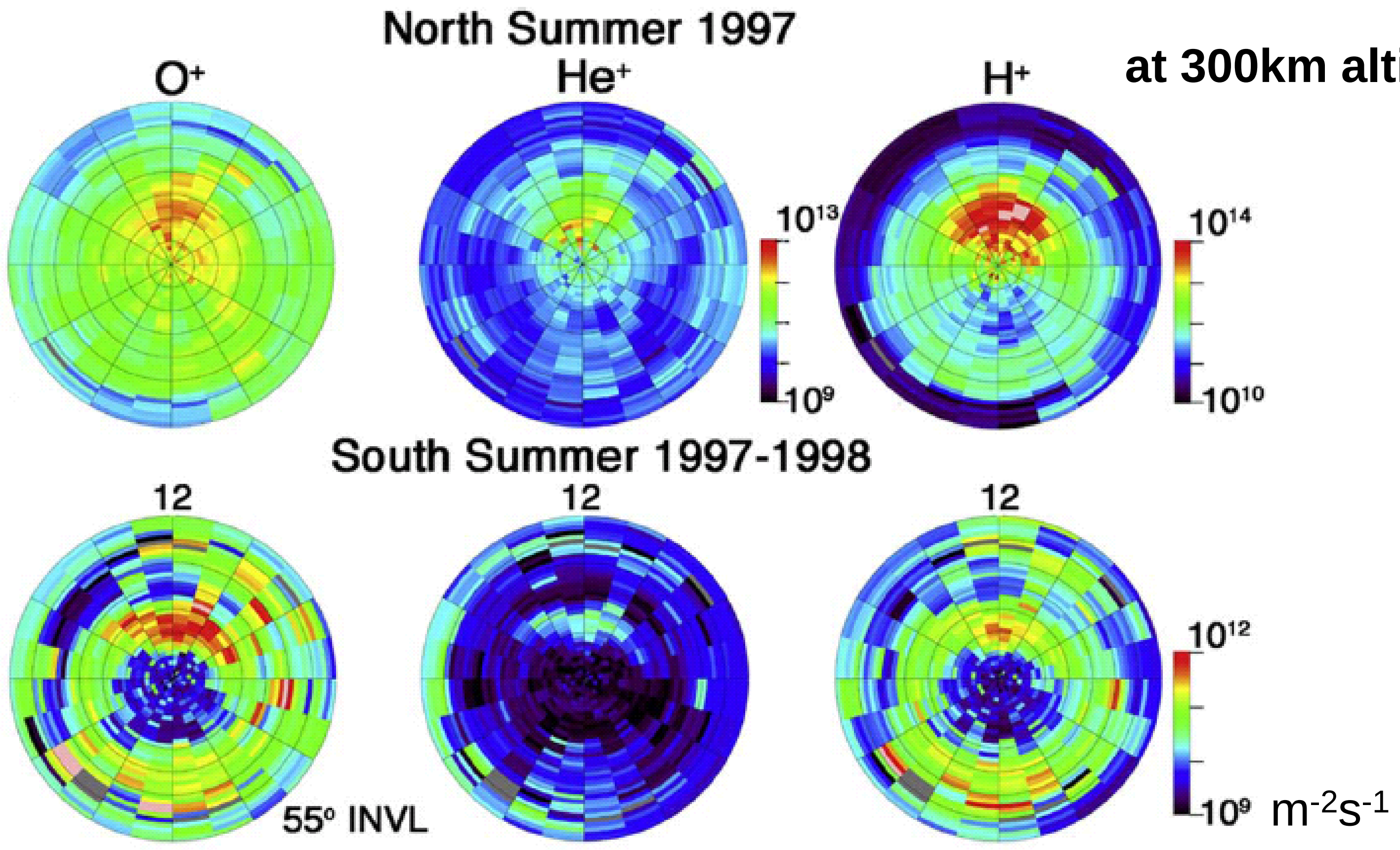




Kp <2+ 3- ~ 4+ >5-

Amount of Outflow

at 300km altitude



~10^{26} ions/s per hemisphere

20 GW energy flow rate

POLAR / Toroidal Imaging Mass-Angle Spectrograph

Lennartsson et al., 2004

Transversely Acceleration

- **Acceleration by Cyclotron Resonance**

Ion Motion

$$m\frac{d\mathbf{v}_{//}}{dt} = -\mu\frac{\partial \mathbf{B}}{\partial s} - \frac{GMm}{r^3}\hat{\mathbf{s}}$$

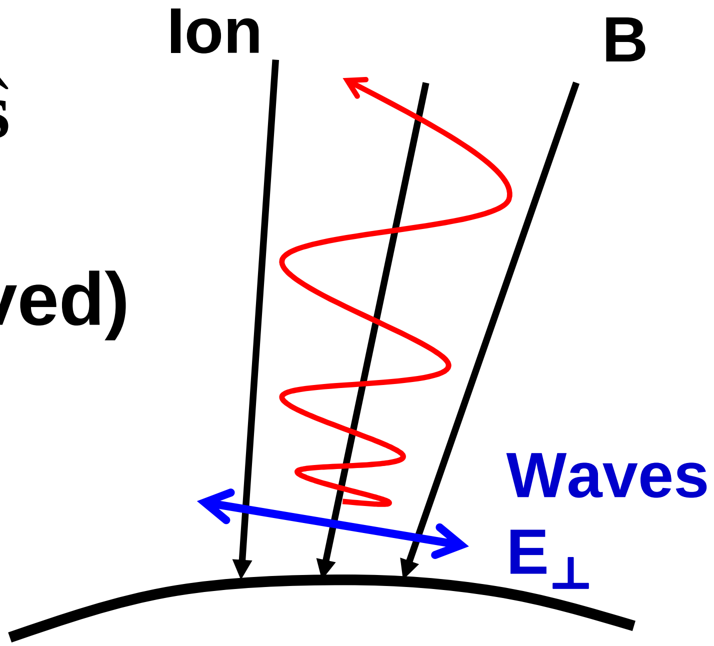
Lorentz force

Magnetic Moment (conserved)

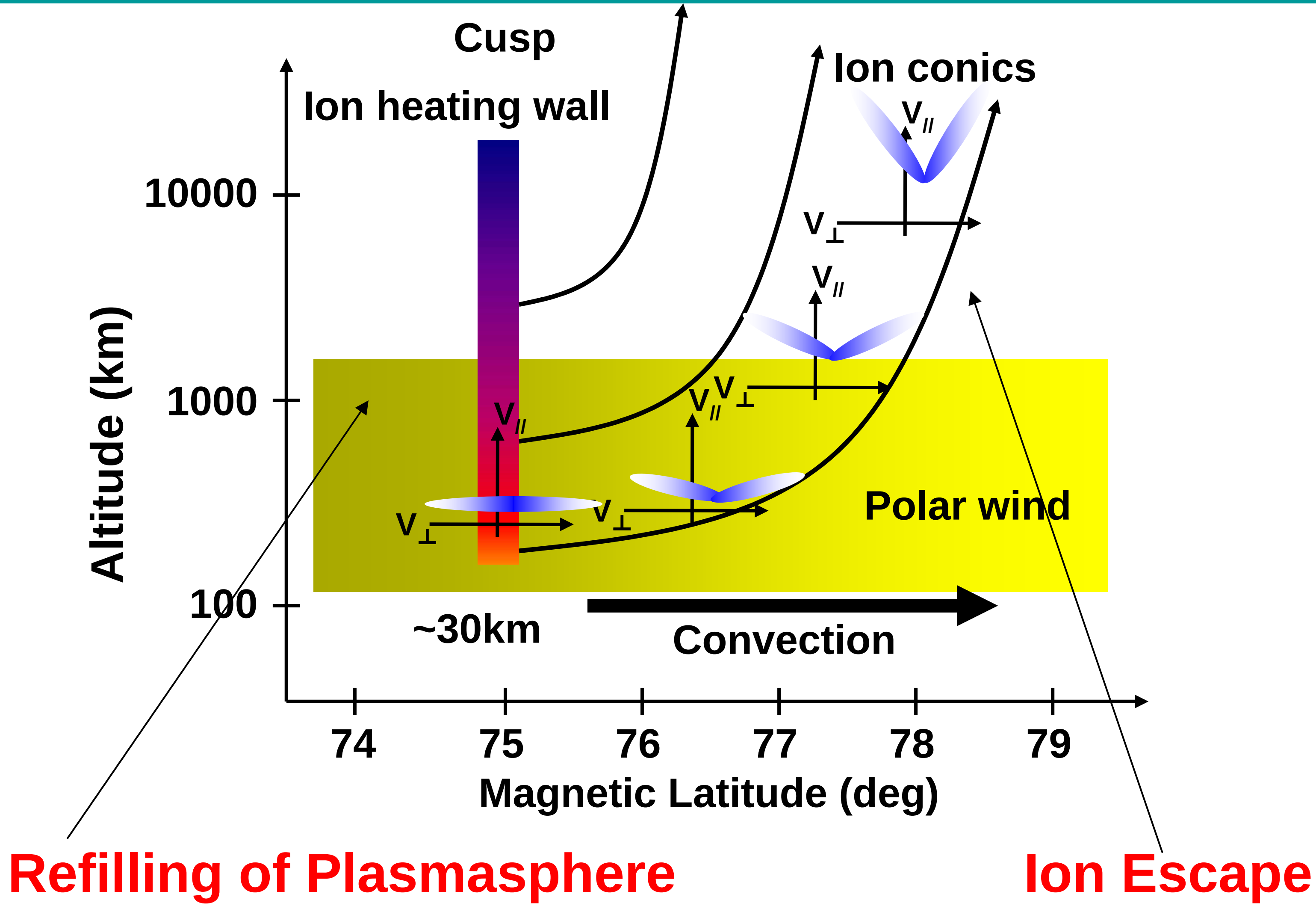
$$\mu = \frac{m\mathbf{v}_{\perp 0}^2}{2\mathbf{B}_0}$$

Ion Energy

$$\frac{d}{ds}\left(\frac{1}{2}m\mathbf{v}_{//}^2 + \mu\mathbf{B} + GMm\left(\frac{1}{r_0} - \frac{1}{r}\right)\right) = 0$$



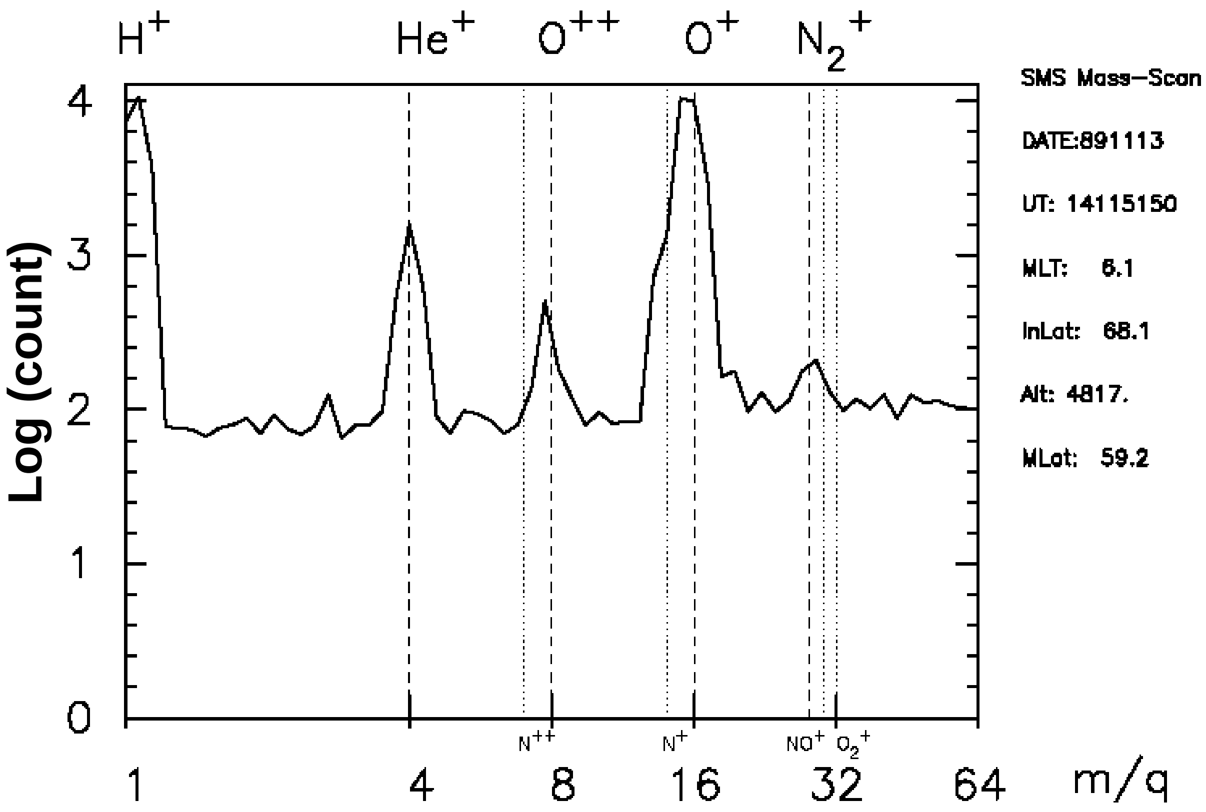
Heating Wall

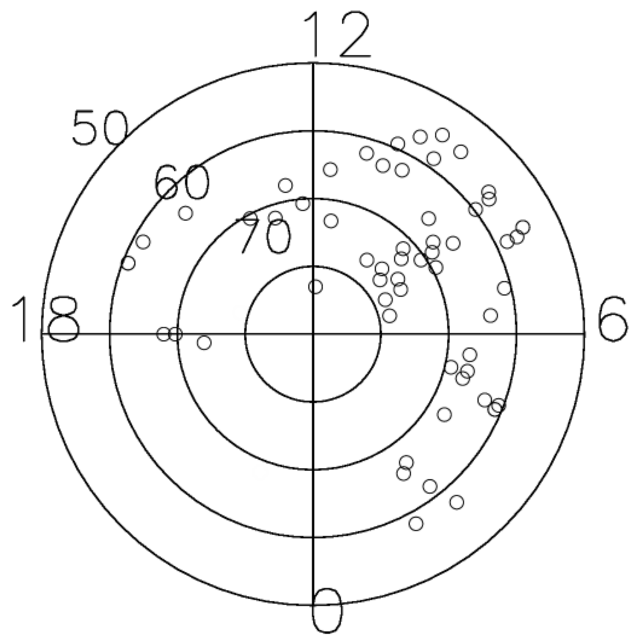


Correlation between Transversely Accelerated Ion and Broadband Extremely Low Frequency (BBELF) Turbulence.

Molecular Ion Heating

Akebono (EXOS-D)





N_2^+ Occurrence

In the polar ionosphere, all ions are heated and flow to the magnetosphere.

N_2^+ Ion Heating in Cusp

Optical observation of N_2^+ by MSX satellite (Romic et al. 1999)

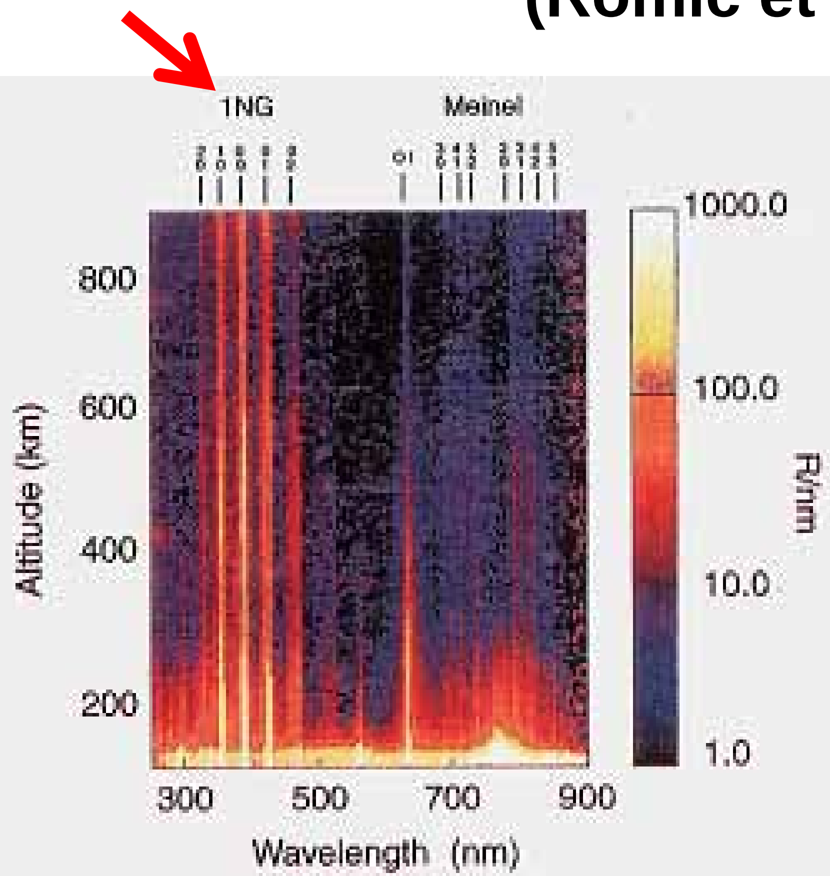


Figure 2. The altitude dependence of the emissions seen on November 7, 1997 over the wavelength interval 250 – 890 nm. The major N_2^+ 1[st] Negative and Meinel Band locations are identified.

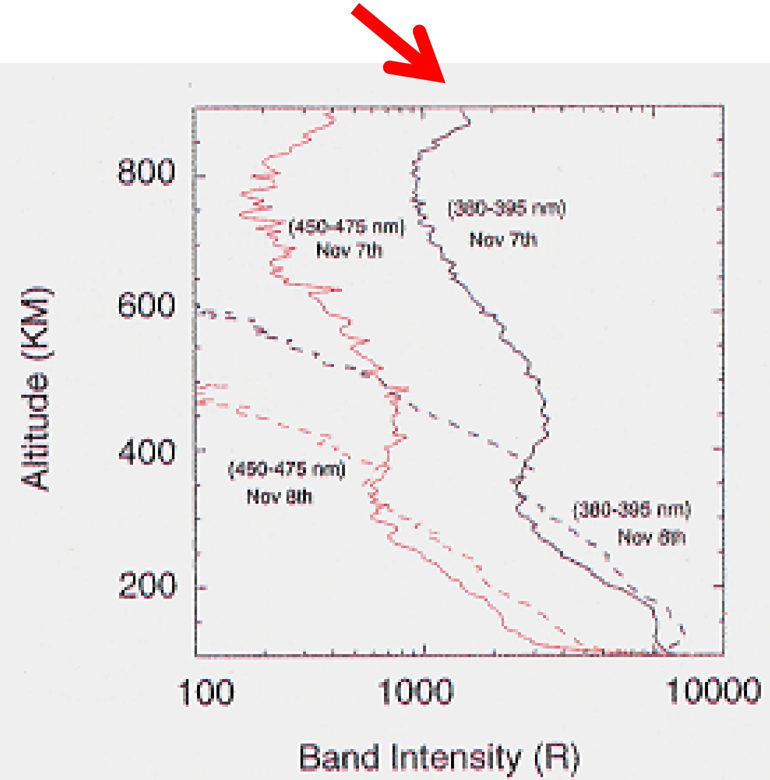
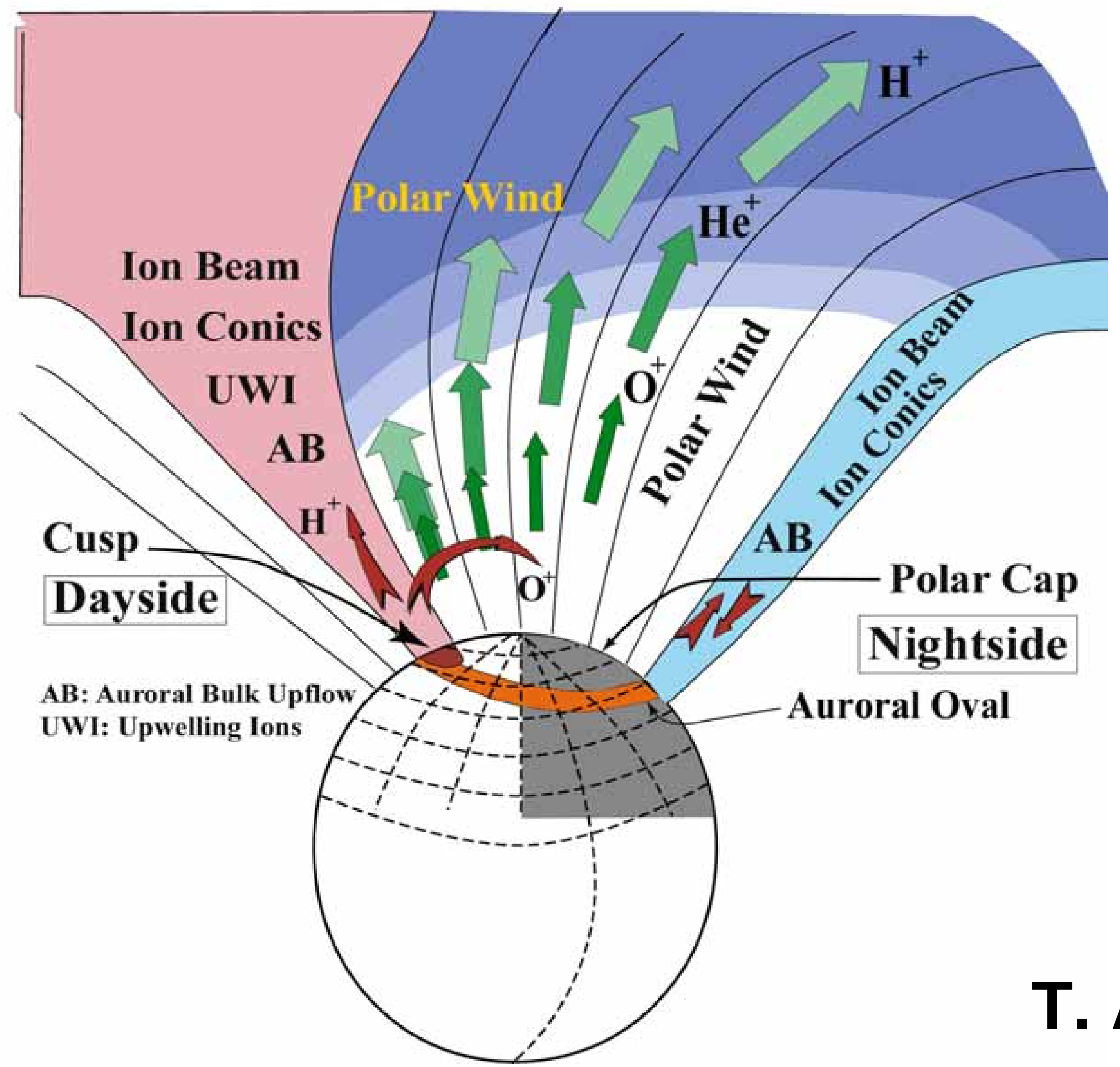


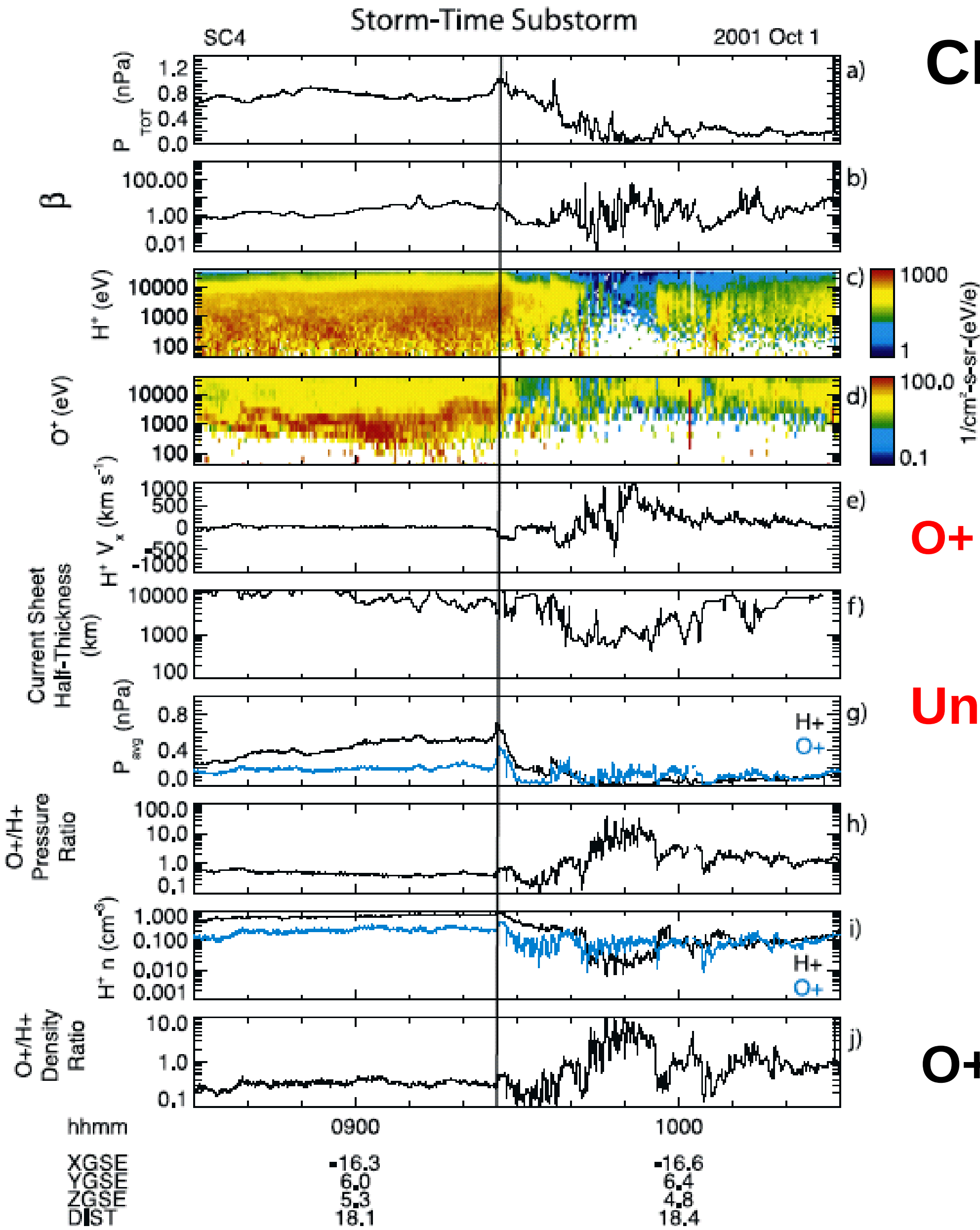
Figure 5. This figure shows the four altitude plots between 100 and 900 km of the emission intensity for both November 7 and 8, 1997 over the wavelength intervals 380 - 395 nm and 450 - 475 nm.

Ion Outflow from Topside Ionosphere



T. Abe

Oxygen Ion in Magnetosphere



CLUSTER

O+ in plasma sheet.

O+ energy >10keV

larger than TAI energy

Unknown acceleration process!

O+ density is larger than H+.

Kistler et al., 2006

Oxygen Ion in Magnetosphere

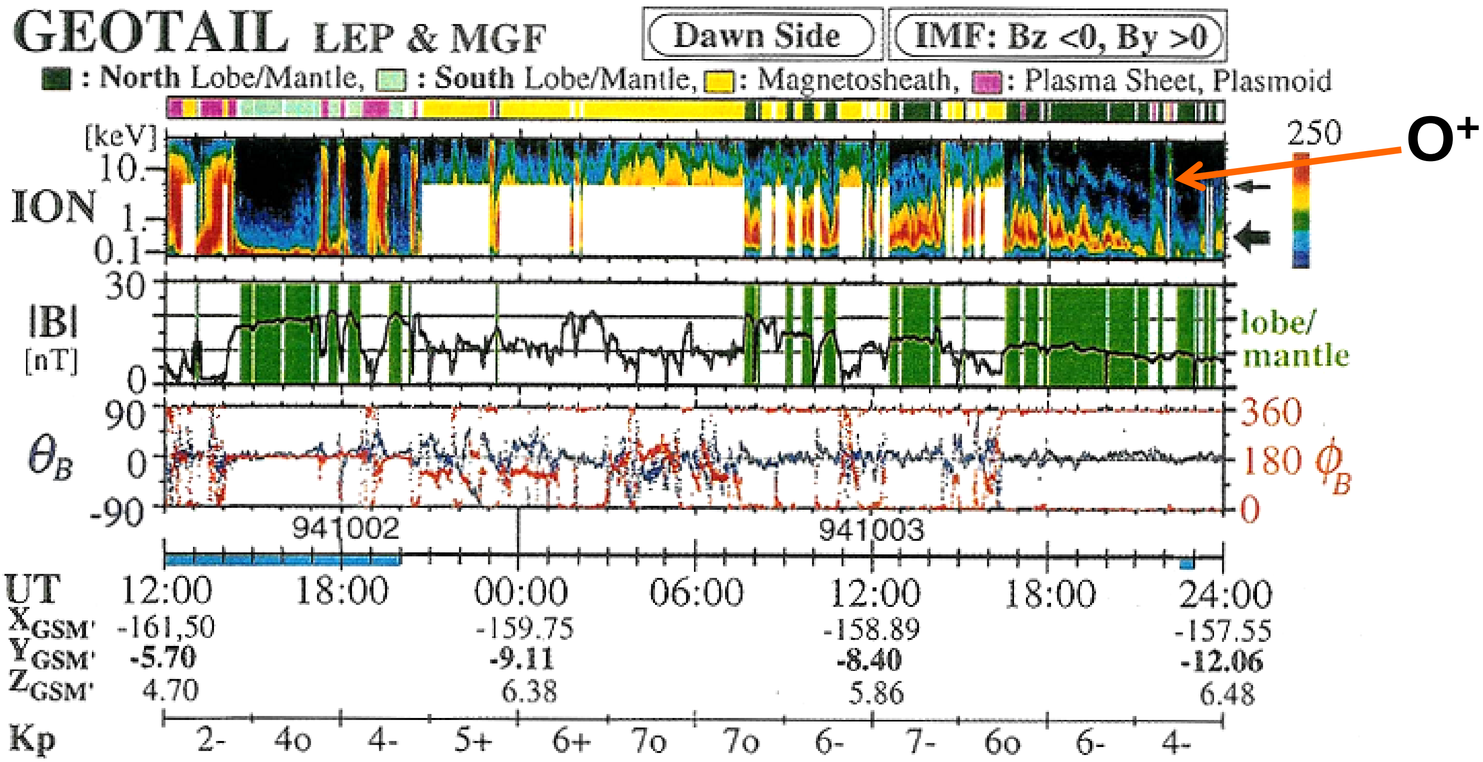


Plate 2. The Geotail observation during a geomagnetic storm on October 2 and 3, 1994. The top panel shows the energy-time (E-t) diagram for ions flowing in the anti-sunward direction. The ordinate is particle energy (per charge) and the color-coded intensity shows counts/sample with a logarithmic scale. By the right-hand two arrows at higher and lower energies, O^+ and H^+ components are indicated, respectively. The lower two panels display the magnetic field as magnitude |B|, elevation θ_B from the X-Y plane, and azimuth ϕ_B from the X axis. From just below the panels, the DATE, the universal time (UT), and the Geotail location in the modified GSM coordinates are denoted. As suggested by negative $Y_{GSM'}$, the spacecraft is located at dawnside in this case. The blue shades on the UT line indicate the intervals when the IMF data are available, and the obtained concurrent IMF is southward (B_z <0) and duskward (B_y >0). At the bottom of the figure, simultaneous *Kp* index is shown. The intervals shaded by green color on the panel of |B| correspond to the "lobe/mantle" regions determined with the criteria proposed in the text. With color bars above the ion E-t diagram, the in situ plasma regime is indicated, i.e., the light-green color corresponds to the south lobe/mantle, dark-green to the north lobe/mantle, rose to the plasma sheet or plasmoid, and light-yellow to the magnetosheath. In this positive IMF B_y case, thus, the spacecraft was initially located at the south-dawn quadrant of the lobe/mantle (light green) and then moved into the north-dawn (dark green).

O+ Flow in Magnetosphere

SEKI ET AL.: STATISTICAL PROPERTY OF O^+ BEAMS IN LOBE/MANTLE

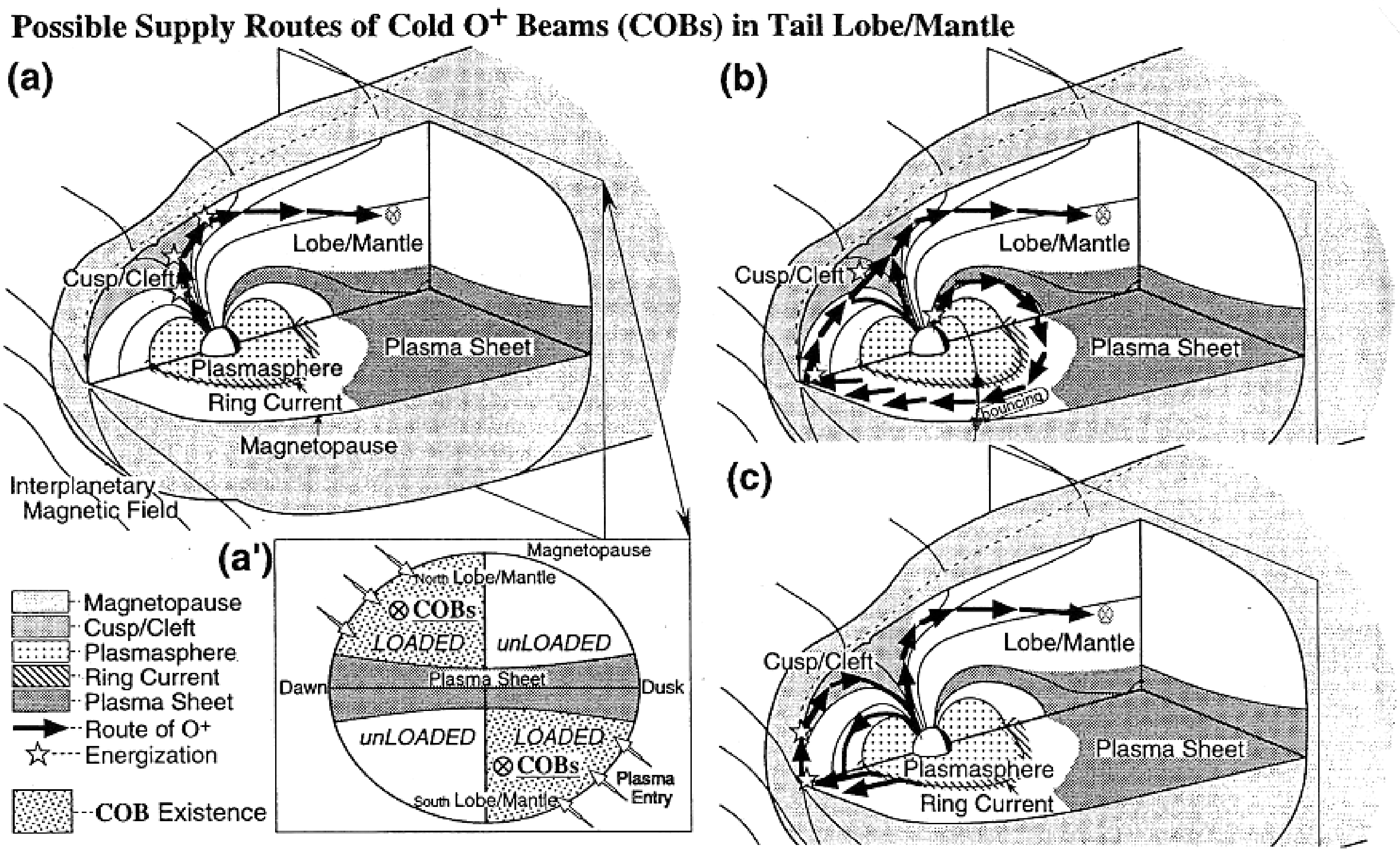


Figure 6. Three-dimensional schematic cutaways of the magnetosphere together with its north-south dawn-dusk cross-section. The figure explains schematically the positive IMF B_y case. In the cross-section (**a'**), the observed spatial distribution of COBs is shown with the tail plasma asymmetry. The each cutaway panel illustrates the supply scenario of COBs with (**a**) the dayside polar ionospheric outflow, (**b**) the energetic UFI beams, and (**c**) the equatorially trapped ions in dayside magnetosphere, respectively.

Ion Outflow Model

How much ions are escaping from ionosphere?

To investigate the ion escape flux, an empirical model of topside polar ionosphere is made from Akebono/SMS data

(>1 solar cycle from 1989 ~
>1,000,000 datasets)

The model provides Density, Velocity, Flux for H+, He+, O+ with functions of MLT, LAT, ALT, Season, F10.7 and Kp.

Ion Outflow Model

Base Functions

$$B_{1i}(f_{10.7},k_p) = a_{0i} + a_{1i} f_{10.7} + a_{2i} k_{p0h} + a_{3i} k_{p3h} + a_{4i} k_{p6h} + a_{5i} k_{p9h}$$

$$B_{2i}(z) = a_{6i} + a_{7i} z$$

$$B_{3i}(d,h) = a_{8i} + a_{9i}\sin(d) + a_{10i}\cos(d) + a_{11i}\sin(2d) + a_{12i}\cos(2d) + a_{13i}\sin(h) + a_{14i}\cos(h) + a_{15i}\sin(2h) + a_{16i}\cos(2h)$$

$$B_{4i}(l) = a_{17i} + a_{18i}\sin(l) + a_{19i}\cos(l) + a_{20i}\sin(2l) + a_{21i}\cos(2l) + a_{22i}\sin(3l) + a_{23i}\cos(3l)$$

Density, Velocity, Flux for H^+, He^+, O^+

$$\log n_i\left(f_{10.7},k_p,z,d,h,l\right) = B_{1ni}(f_{10.7},k_p)B_{2ni}(z)B_{3ni}(d,h)B_{4ni}(l)$$

$$\mathbf{v}_i\left(f_{10.7},k_p,z,d,h,l\right) = B_{1\mathbf{v}i}(f_{10.7},k_p)B_{2\mathbf{v}i}(z)B_{3\mathbf{v}i}(d,h)B_{4\mathbf{v}i}(l)$$

$$\mathbf{f}_i\left(f_{10.7},k_p,z,d,h,l\right) = n_i\left(f_{10.7},k_p,z,d,h,l\right)\mathbf{v}_i\left(f_{10.7},k_p,z,d,h,l\right)$$

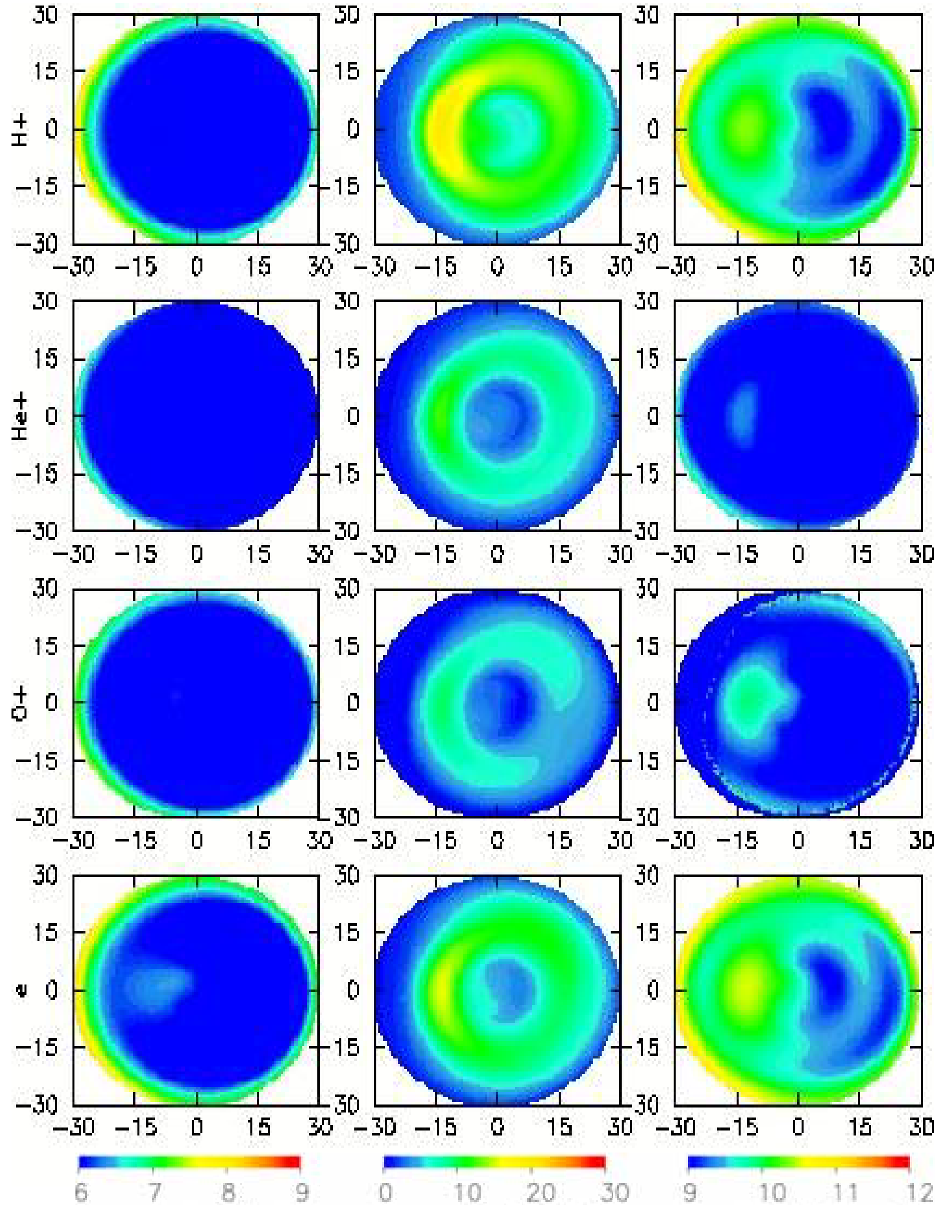
Ion Outflow Model

H^+

He^+

O^+

Ne



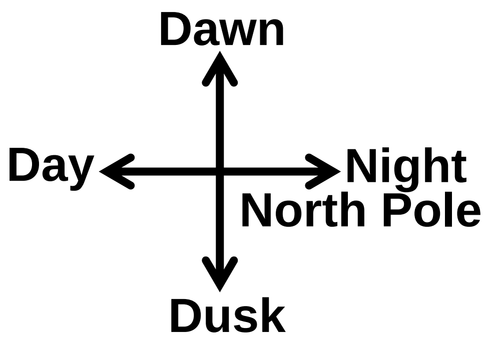
Density Velocity Flux

2003/1/25

Kp: 3

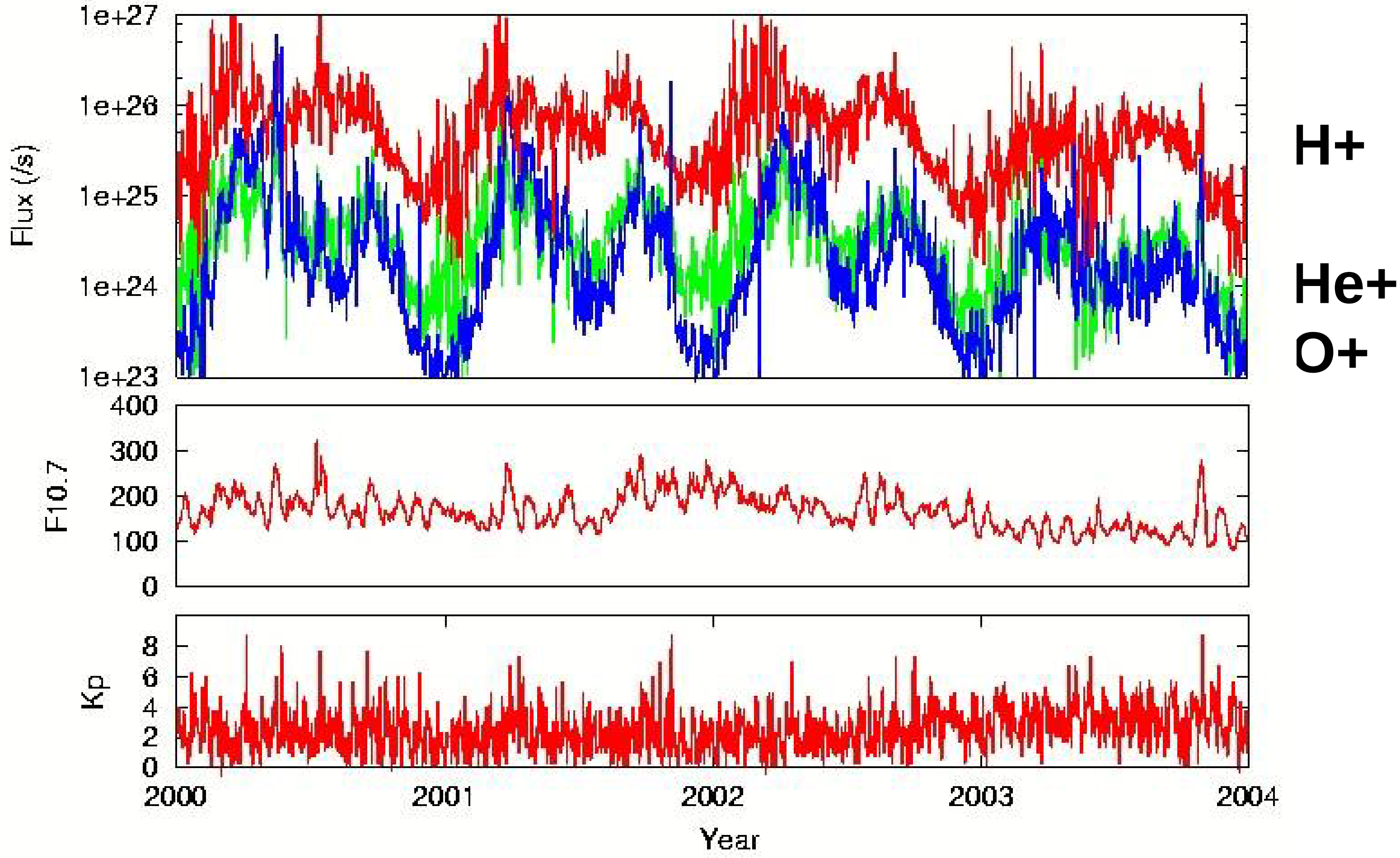
$F_{10.7}$: 125

Altitude: 6000km

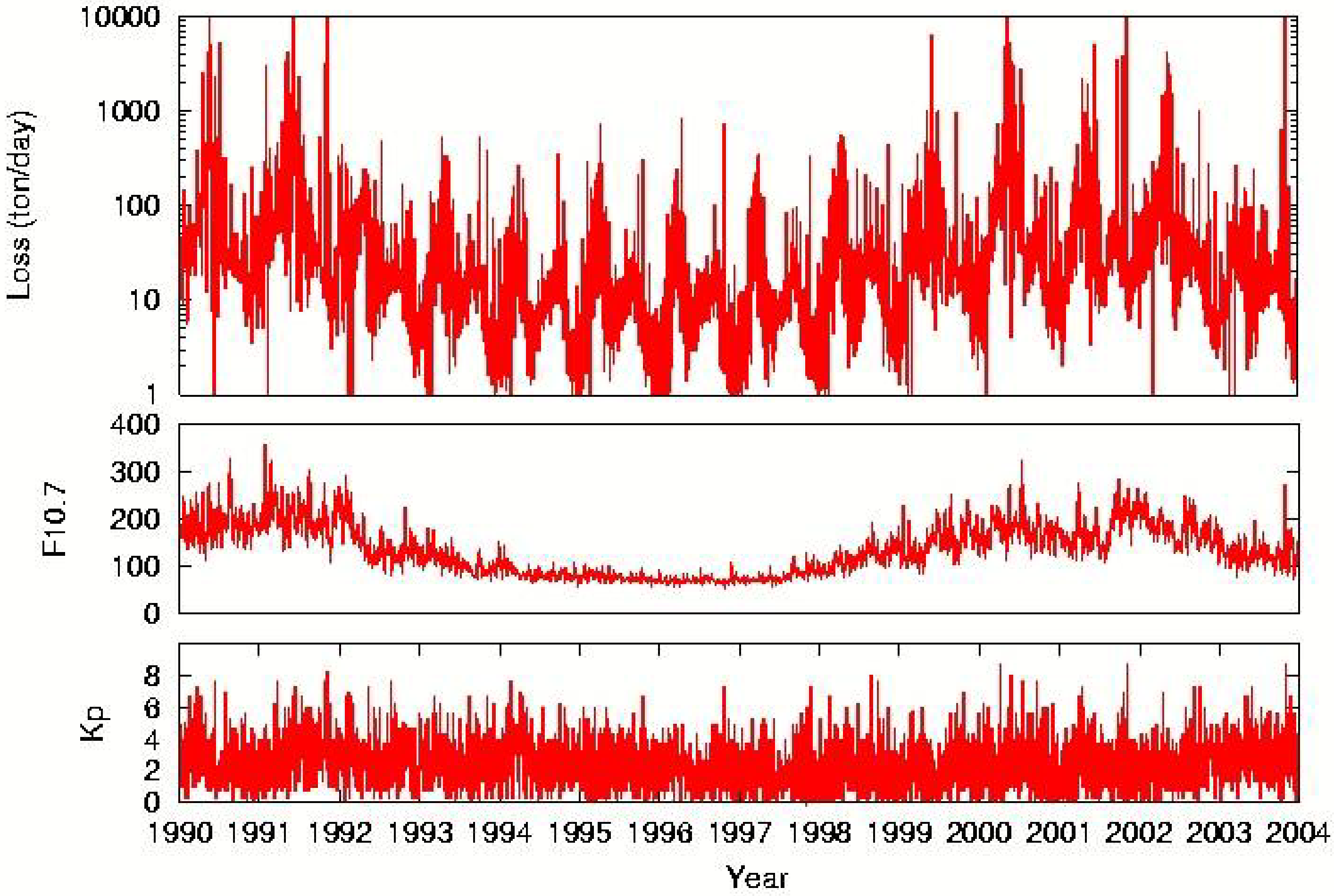


Ion Flux from Ion Outflow Model

Escape Flux at 6000 km altitude in the northern hemisphere



Mass Loss from Topside Polar Ionosphere



Total Oxygen Mass in Thermosphere

$$M_t = 4\pi r^2 m_O n_O H = 3\times 10^7\,ton$$

Summary

(1)Ionospheric ion is flowing to magnetosphere as a polar wind.

(2)In the cusp and aurora regions, all ionospheric ions are accelerated by waves, as TAI (transversely accelerated ion) and conics, and the ions are escaping to magnetosphere.

(3)Ion escape from topside ionosphere is one of the source mechanisms of magnetospheric plasma.

(4)Ion escape flux depends on solar activity, magnetic activity, magnetic local time, latitude and season.

(5)Mass loss from ionosphere is >10tons/day depending on ionosphere, thermosphere and solar wind conditions.

~0.26×10^8 el/cm^2/s (Saxton and Smith, 1989)

~3×10^8 el/cm^2/s (Park, 1970)

~10^8 el/cm^2/s (Akebono, 1993)

~10^8 el/cm^2/s (Polar, 2004)

Refilling of plasmasphere requires several days.

Questions for Future Work

(1)Ion energy is ~1eV in topside ionosphere, but ~10keV in magnetosphere.

Where is the ion heated?

What is the heating mechanism?

(2)How is the formation and dynamics of magnetosphere affected by ion injection from ionosphere?

(3)How about ring current and radiation belt?

(4)Is it possible to visualize the magnetosphere with O^+?

(5)How does ion escape affect the Earth's atmospheric evolution?

(6)How is ion escape during low geomagnetic field intensity?

(7)How about other planets?

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http://www.ep.sci.hokudai.ac.jp/~shw/WinterSchool.pdf