Magnetoseismology for the inner magnetosphere

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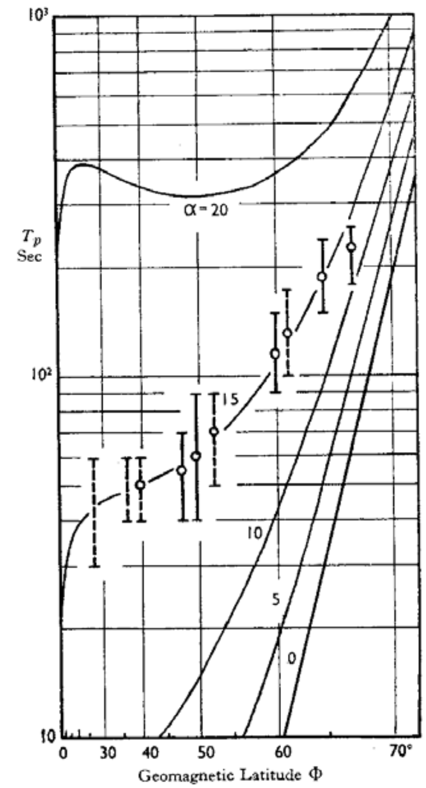
Outline

- Introduction
- Techniques
- Examples
- Summary

Magnetospheric seismology (Magnetoseismology)

- Extraction of information from ULF waves to probe the magnetosphere
- Two wave modes
  - Shear (Alfvén) waves
  - Compressional (fast mode) waves
- Two approaches
  - Normal mode
  - Travel time
- Long history (Alfvén waves)
  - *Obayashi and Jacobs* [1958]
- Improved measurement and modeling techniques make "Magnetoseismology" relevant
  - *Peter Chi* [2001]: Fall AGU Meeting

$$\rho = \rho_s \exp(-R/H_0)$$



Obayashi and Jacobs [1958]

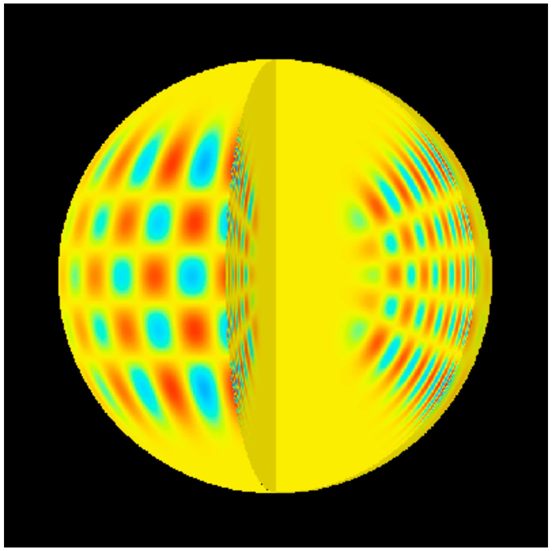
Applications

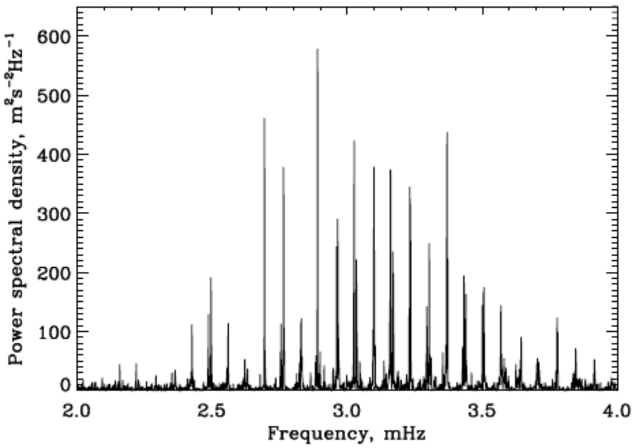
- Inferring field line mass distribution
  - Multiple harmonics observed from spacecraft
  - Better density models from single-harmonic measurements on the ground
  - Physics of forces acting on ions
- Getting information on heavy ions
  - Comparison with electron density measurements
  - Global ion transport and its dependence on geomagnetic activity
- Monitoring global mass distribution
  - Ground magnetometer arrays
  - Plasmapause location and its dependence on the solar wind and geomagnetic activity

Comparison with other seismology

- Sun and Solid Earth
  - Steady background medium
  - High-*Q* resonances
  - Many spectral lines
- Magnetosphere
  - Variable background medium
  - Low-*Q* resonances
  - Small number of observable spectral lines

Solar seismology





http://soi.stanford.edu/results/heliowhat.html

MHD wave equation for a cold plasma

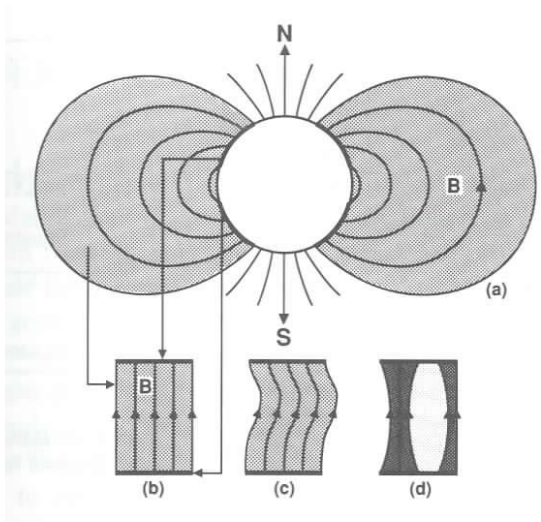
- Shear waves
  - Alfvén mode
- Compressional waves
  - Fast mode
- Mode coupling
  - Field line resonance

$$\rho_0 \frac{\partial \mathbf{v}}{\partial t} = \frac{1}{c}\left(\mathbf{j} \times \mathbf{B}_0\right)$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{b}}{\partial t}$$

$$\nabla \times \mathbf{b} = -\frac{4\pi}{c}\mathbf{j}$$

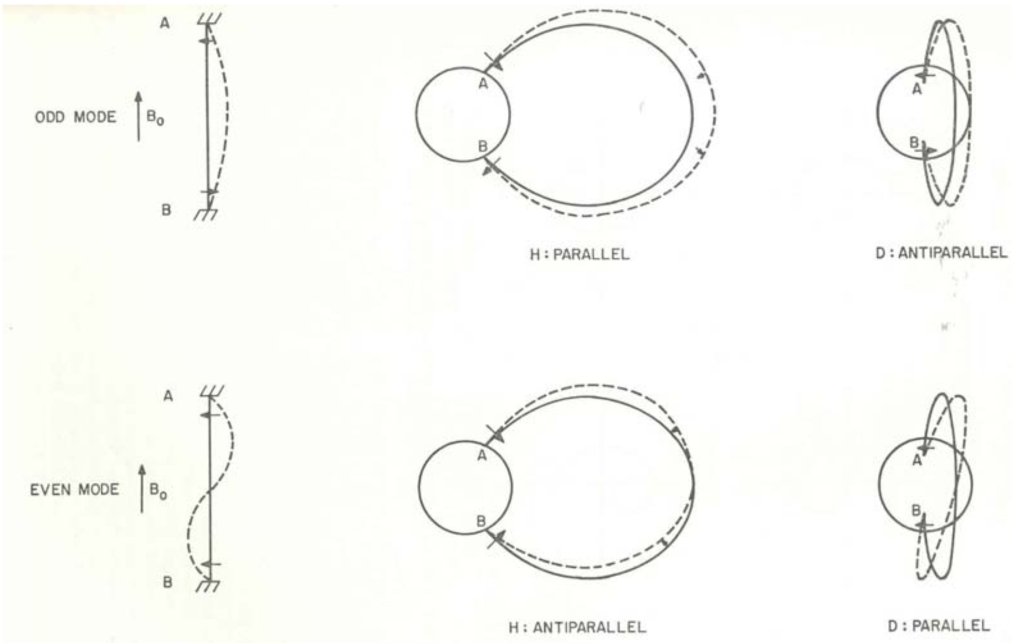
$$\mathbf{E} = -\frac{1}{c} v \times \mathbf{B}_0$$



Kivelson and Russell [1995]

Magnetospheric normal mode: Standing Alfvén waves

Poloidal mode	Toroidal mode
E_azimuthal	**E**_radial
B_radial	**B**_azimuthal



Fundamental harmonic (n = 1)

Second harmonic (n = 2)

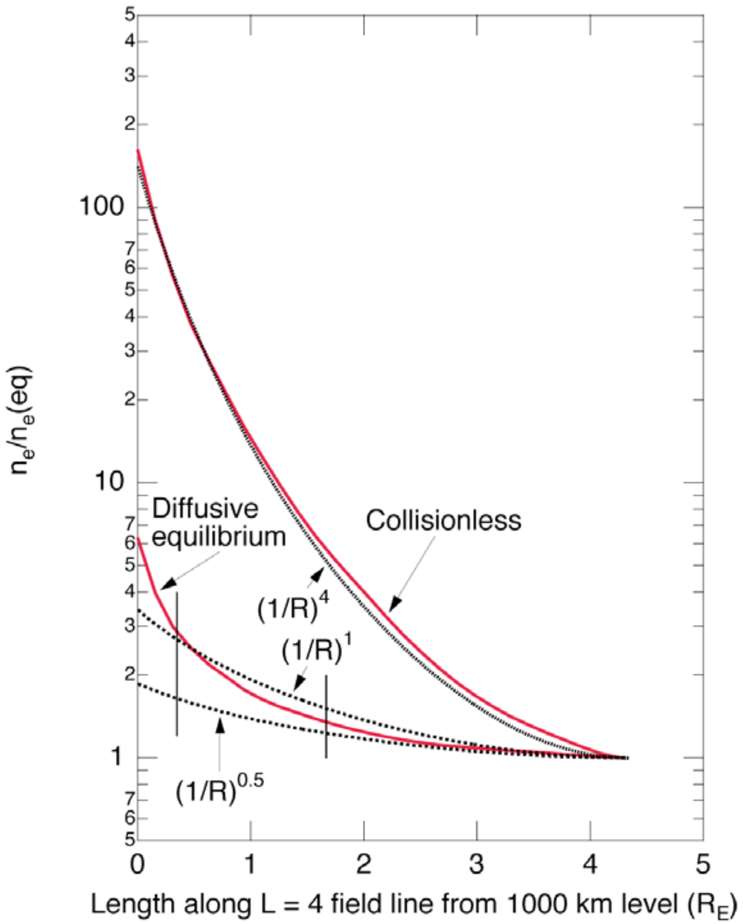
Sugiura and Wilson [1964]

Properties of the inner magnetosphere

- Magnetic field
  - Rigid compared to the outer magnetosphere
  - Numerical models (e.g., Tyganenko)
- Boundary conditions
  - Perfect reflection at the ionosphere a good assumption
- Mass distribution
  - Varies significantly with time and position
  - Functional form not known along field line

Theoretical models of field line distribution of plasma

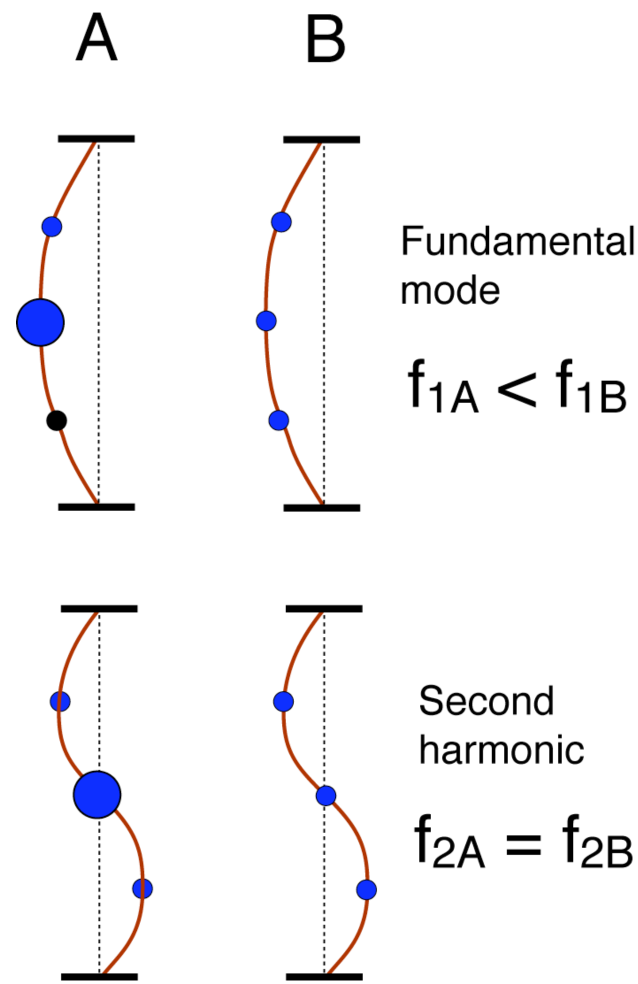
- Diffusive equilibrium
  - Plasmasphere
  - $\sim R^{-1}$ near the equator
- Collisionless distribution
  - Plasmatrough
  - $\sim R^{-4}$ near the equator
  - Has been popular in the ULF waves community



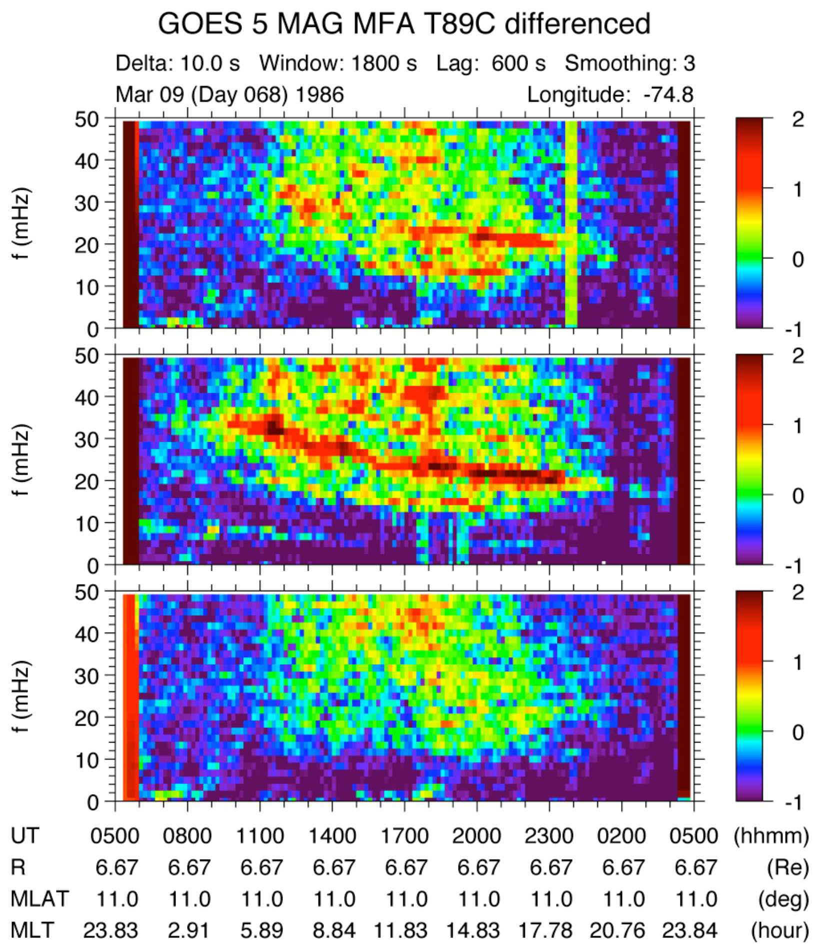
Angerami and Carpenter [1964]

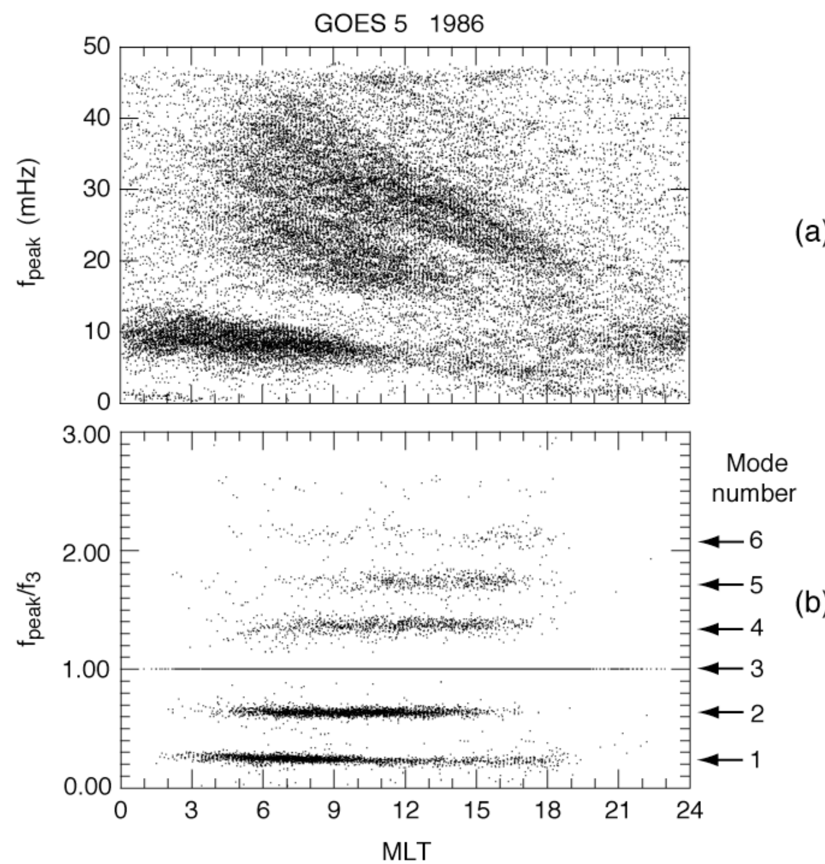
Inferring field line mass distribution

- The frequency of standing waves depends on the spatial mode structure and mass distribution.
  - For example, odd mode (e.g., fundamental mode) is more sensitive to the equatorial mass than even mode (e.g., second harmonic)
- More observable harmonics means more density model parameters (inversion).
  - $N < 10$, realistically, not quite like helioseismology
- Spacecraft measurements are better suited than ground measurements.
  - Frequently yield several harmonics



Toroidal waves at geosynchronous orbit

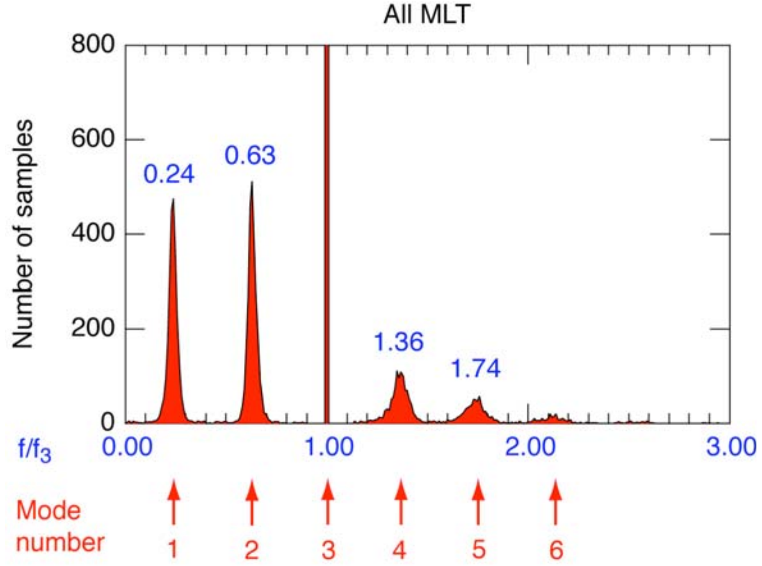


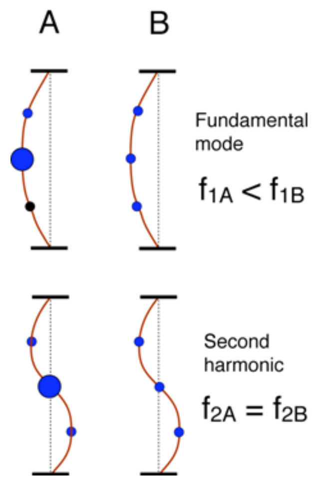


Takahashi and Denton [2006a]

Statistics of normalized frequency

- Spacing between harmonics
  - Fundamental-second:
    - 0.29-0.32, depends on LT
  - Higher harmonics:
    - ~0.37, varies little





MLT	f_1/f_3	f_2/f_3	f_3/f_3	f_4/f_3	f_5/f_3
03-06	0.25	0.64	1.00	-	-
06-09	0.24	0.63	1.00	1.36	-
09-12	0.23	0.63	1.00	1.36	1.74
12-15	0.22	0.63	1.00	1.37	1.73
15-18	0.22	0.64	1.00	1.37	1.74

Takahashi and Denton [2006a]

Standing Alfvén wave equation for realistic magnetospheric fields

- Developed by *Singer et al.* [1981].
- Solved for toroidal harmonics
- Inversion:
  - Parameters of the density models are adjusted so that the observed frequencies match the theoretical frequencies

MHD wave equation:

$$\partial^2(\mathbf{B}_0 \times \mathbf{s})/\partial t^2 = \mathbf{V}_A \times \mathbf{V}_A \times [\nabla \times \nabla \times (\mathbf{B}_0 \times \mathbf{s})]$$

For a give model filed $\mathbf{B}_0$:

$$\mu_0 \rho \frac{\partial^2 (s_\alpha / h_\alpha)}{\partial t^2} = \frac{1}{h_\alpha^{\ 2}} \mathbf{B}_0 \bullet \nabla \left\{ h_\alpha^{\ 2} [\mathbf{B}_0 \bullet \nabla (s_\alpha / h_\alpha)] \right\}$$

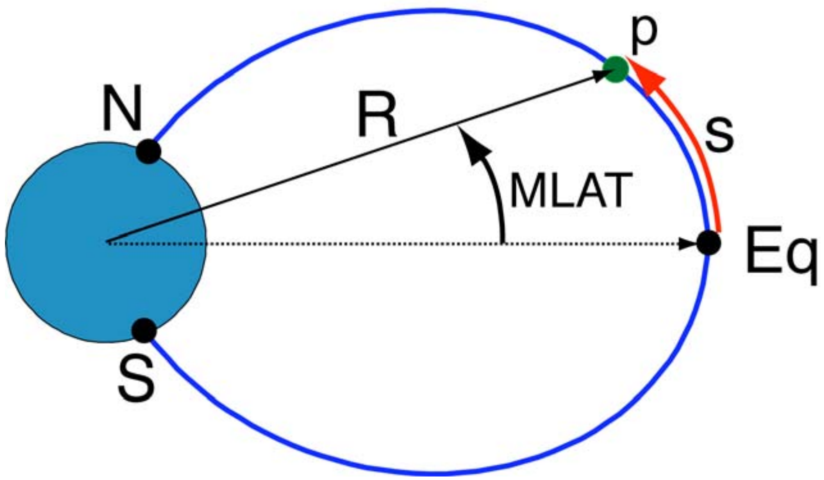
Model for mass density variation along field line

Denton et al. [2004]

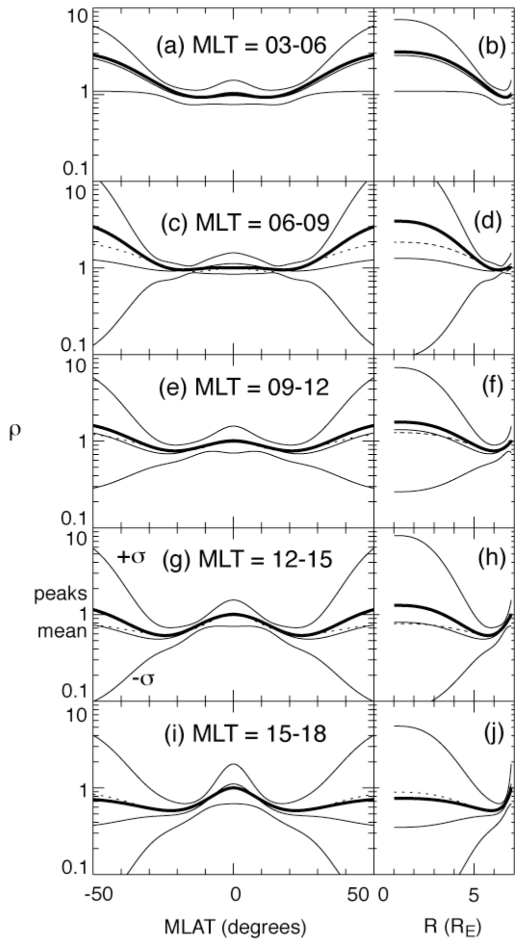
$$\log_{10}\rho = c_0 + c_2\tau^2 + c_4\tau^4 + c_6\tau^6 + \ldots$$

$$\tau \equiv \int_{Eq}^{p} \frac{ds}{V_A} \Bigg/ \int_{Eq}^{N} \frac{ds}{V_A}$$

= 1, Foot point, North
= 0, Equator
= -1 Foot point, South



Density modeling results

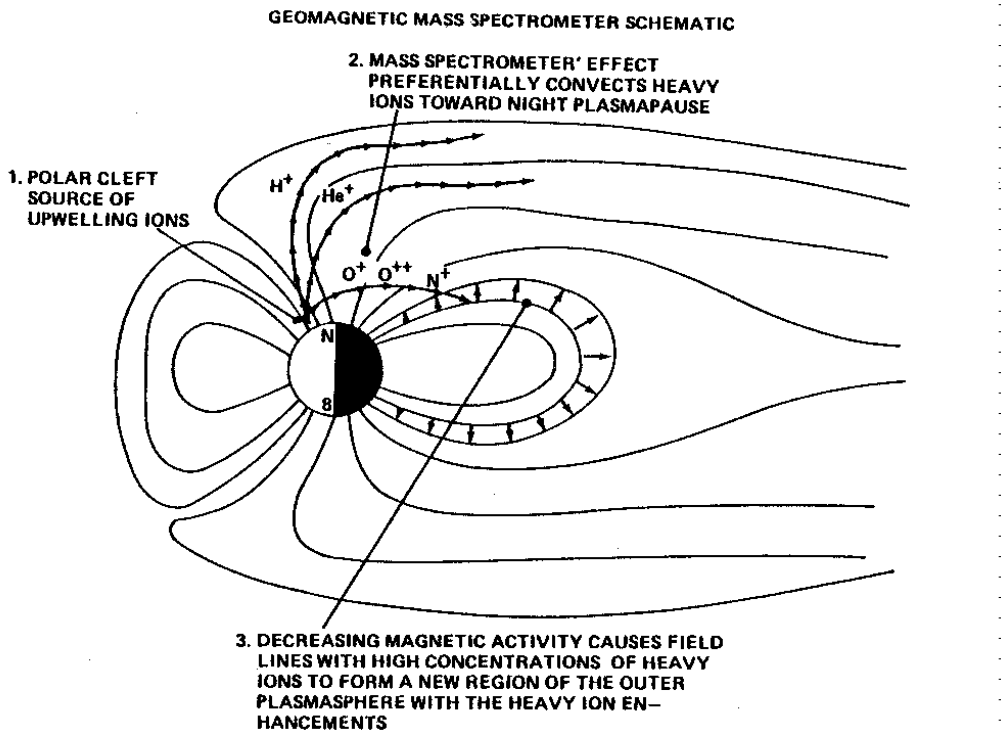


Takahashi and Denton [2006a]

- Weaker-than-expected *R* dependence
  - Closer to R^{-1} (diffusive) than to R^{-4} (collisionless) distribution, although most samples come from the plasmatrough
  - Not far from Polar results for plasmatrough electrons ($\sim R^{-1.7}$) [*Goldstein et al.*, 2001]
- Equatorial maximum in the afternoon
  - Not reported for electrons
  - Equatorial concentration of heavy ions?
  - Potential well at the equator due to rotation?

Ion transport within the magnetosphere

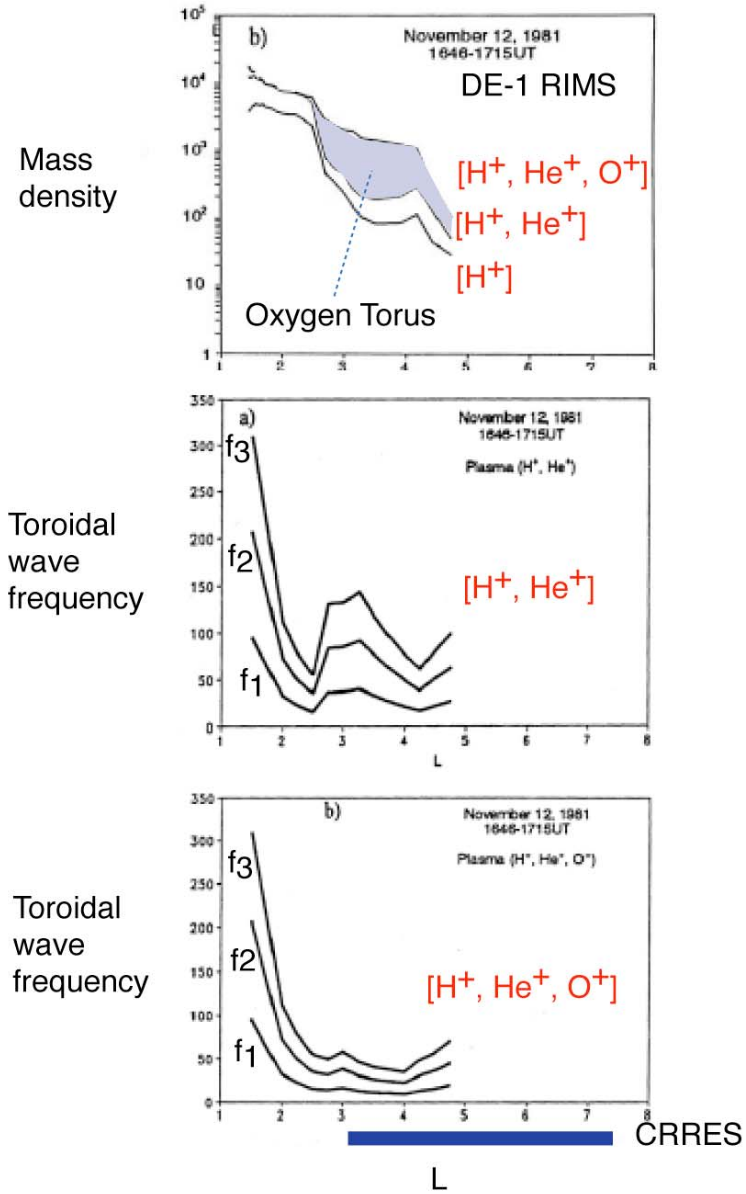
- Magnetoseismology provides information on the total ion mass density



Roberts et al. [1987]

Oxygen Torus

- Field line resonance frequency depends on the total mass density
- Plasmapause location depends on particle species



Fraser et al. [2005]

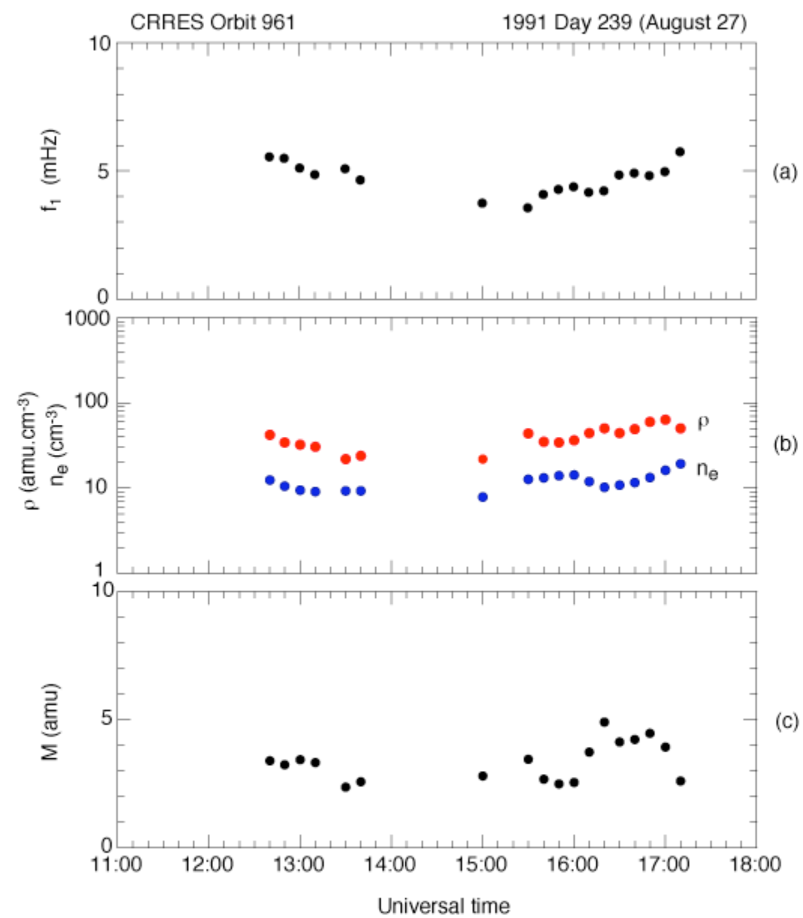
Estimating average ion mass: CRRES results

$$\rho = n_e m_e + \sum_i n_i m_i + n_e m_e$$

$$\cong \sum_i n_i m_i$$

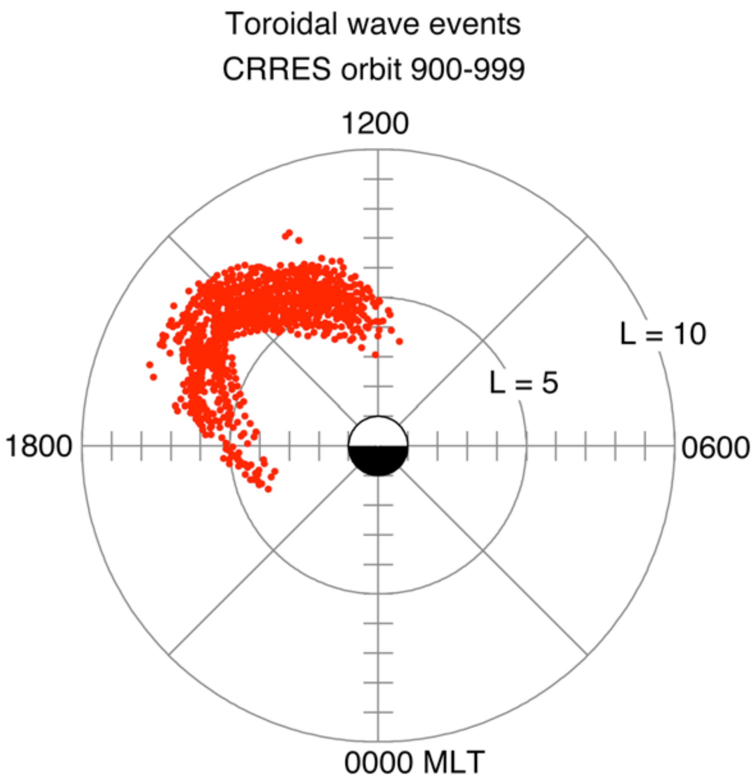
$$\equiv n_e M$$

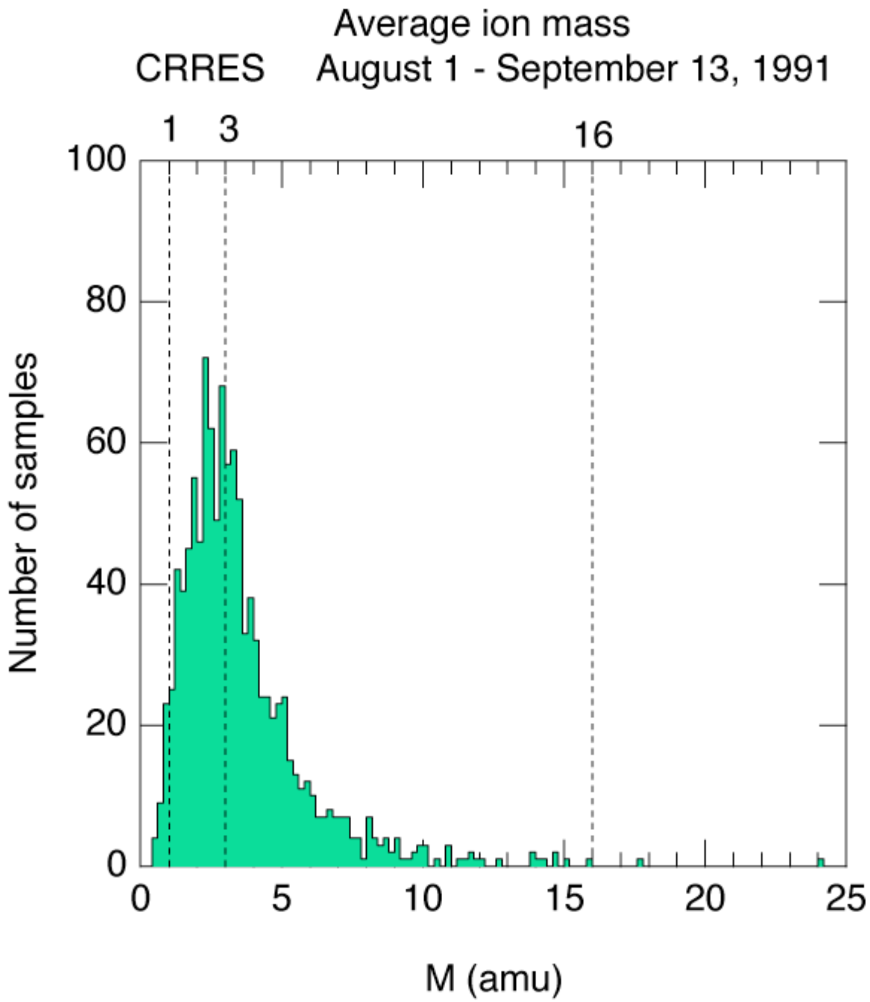
- ρ: Mass density estimated from toroidal frequency, assuming $R^{-0.5}$ density variation along field line
- n_e: Electron density determined from plasma wave spectra
- M: Average ion mass



Takahashi et al., [2006b]

Inferred average ion mass

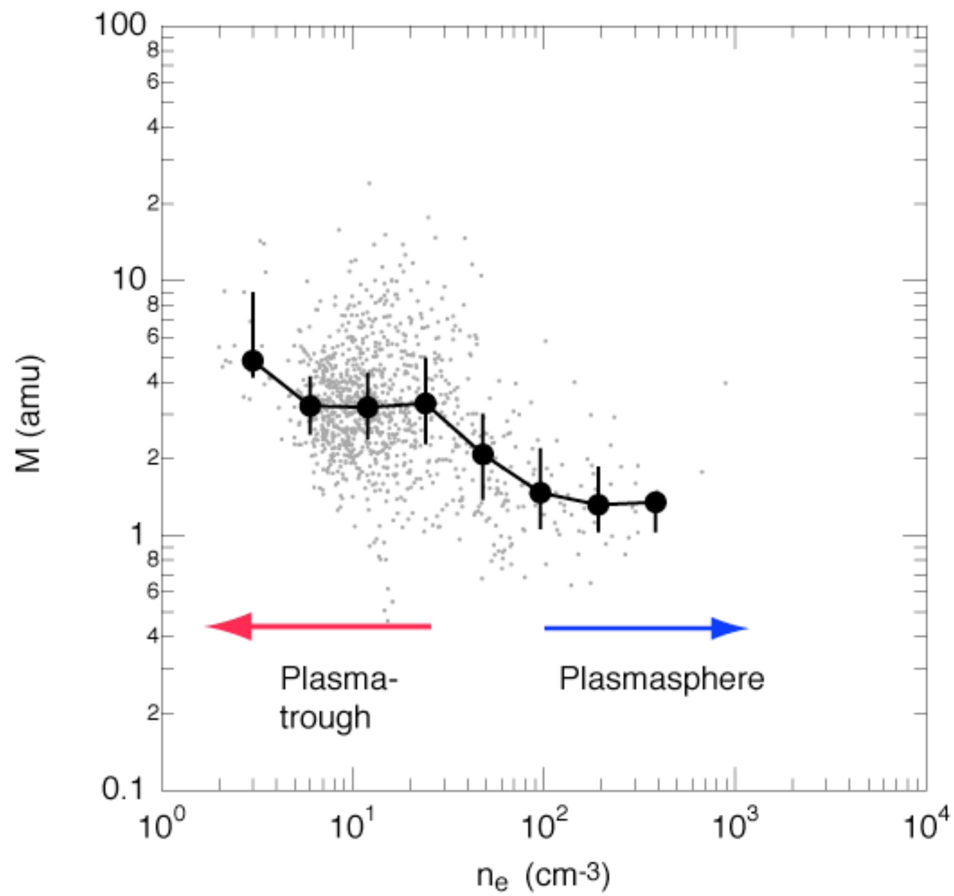




Average ion mass: Plasmasphere and plasmatrough

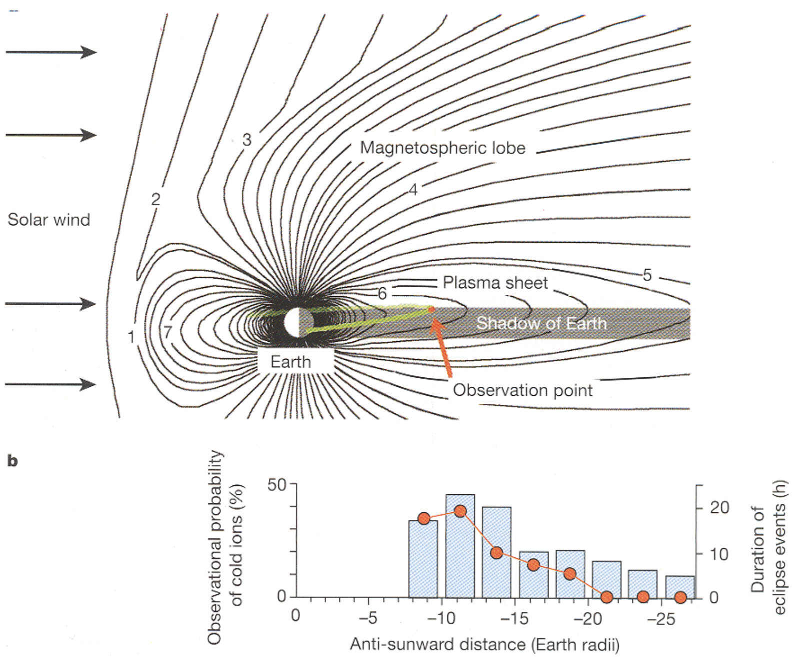
- *M* depends on electron density:
  - High (> 2 amu) when n_e is low (plasmatrough)
  - Low (< 2 amu) when n_e is high (plasmasphere)

- If [H^+, O^+] plasma
  - 13% O+ in the plasmatrough

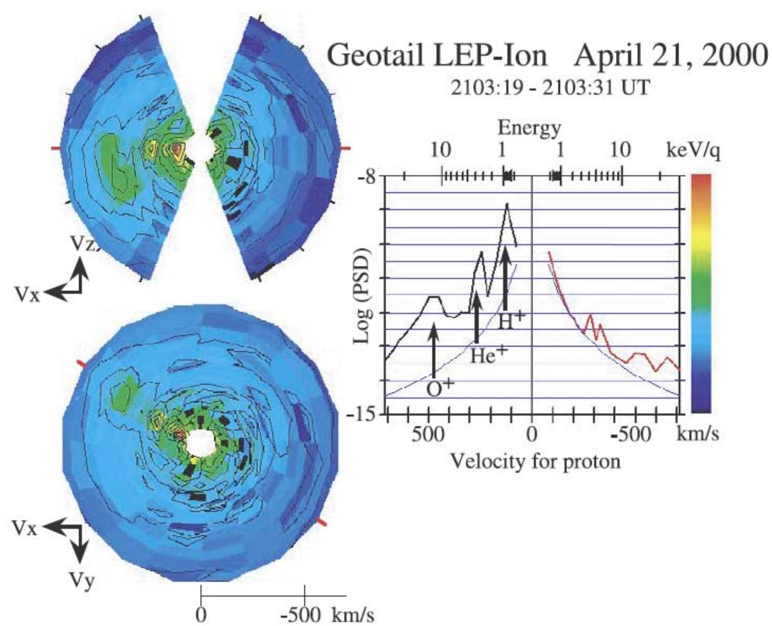


Takahashi et al. [2006b]

Cold ions in the plasmasheet: GEOTAIL observations

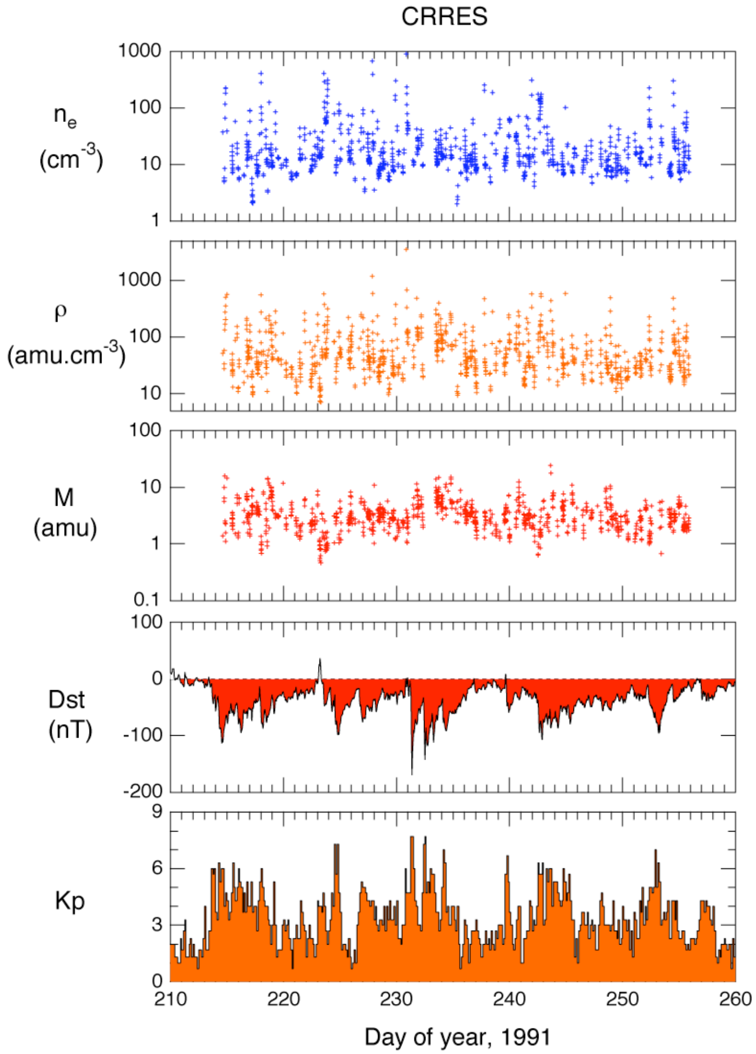


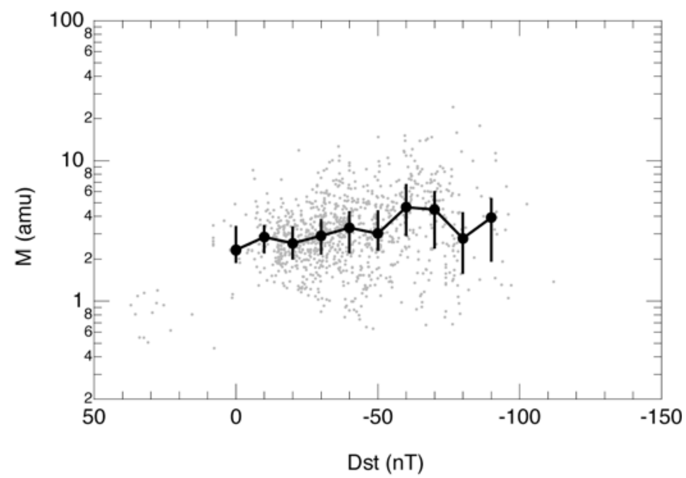
Seki et al. [2003]



Hirahara et al. [2004]

Average ion mass: Dependence on geomagnetic activity





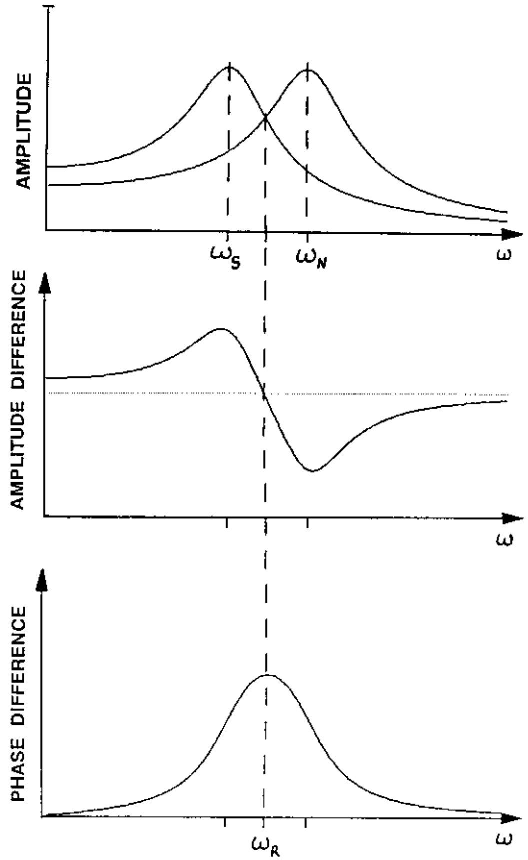
Dst (nT)	*M* (amu)
0	2.3
-20	2.6
-40	3.3
-60	4.7

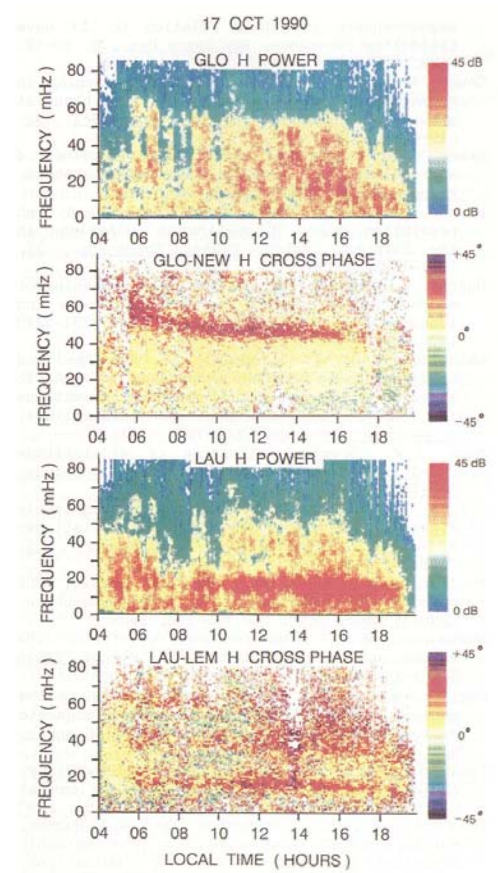
Heavy ions

- Present both inside and outside the plasmasphere
- Increases with geomagnetic activity (*D*st)
- Consistent with GEOTAIL studies of the plasmasheet and dayside outer magnetosphere
- Cold ion transport processes yet to be identified

Cross phase technique: How it works

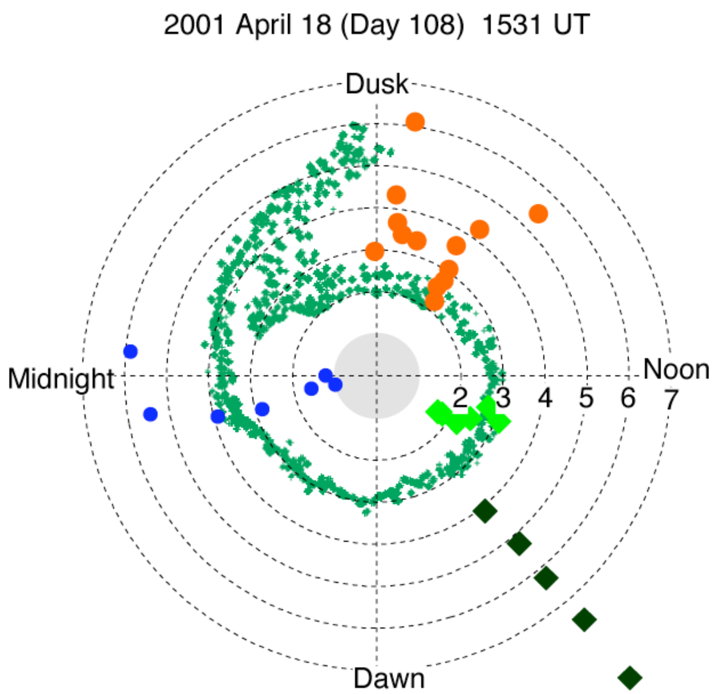
- Based on the concept of field line resonance
- Uses latitudinal pairs separated by ~100 km
- Cross phase shows a peak at the resonance frequency of the field line at the midpoint of the stations.
  - Clearer signature than amplitude ratio or spectral peak in the single-station power spectra





Waters et al. [1991]

Cross phase technique:
Tracking the temporal variation of density



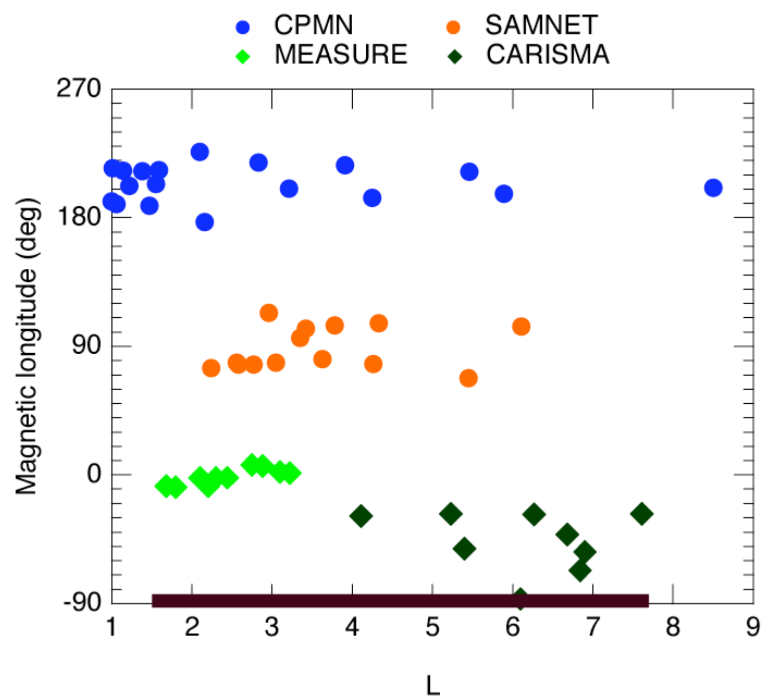
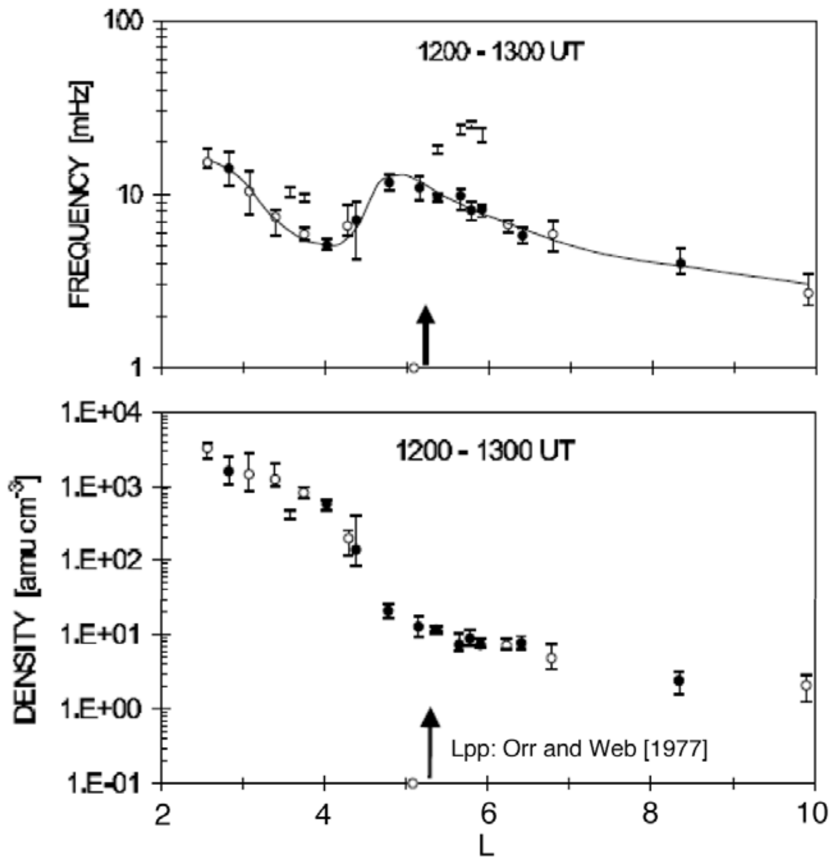


IMAGE EUV plasmapause:
courtesy of J. Goldstein

Mid-latitude ($L \sim 4$)
toroidal wave frequencies

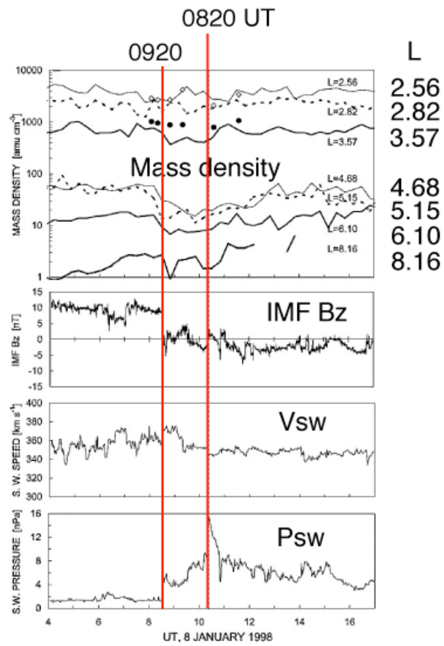
- FLRs are always present on the dayside.
- With dense latitudinal ground magnetometer arrays we can monitor the density structure near the plasmapause as a function of time.

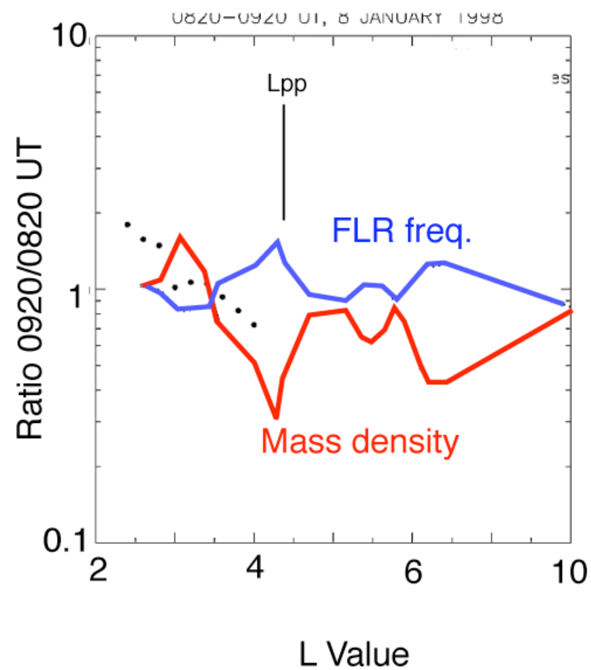


[*Menk al.*, 2004]

Short-time scale (1 hour) density variation

- Possible causes
  - Enhanced convection electric field
  - **E** x **B** drift
  - Redistribution of O^+ ions near the plasmapause

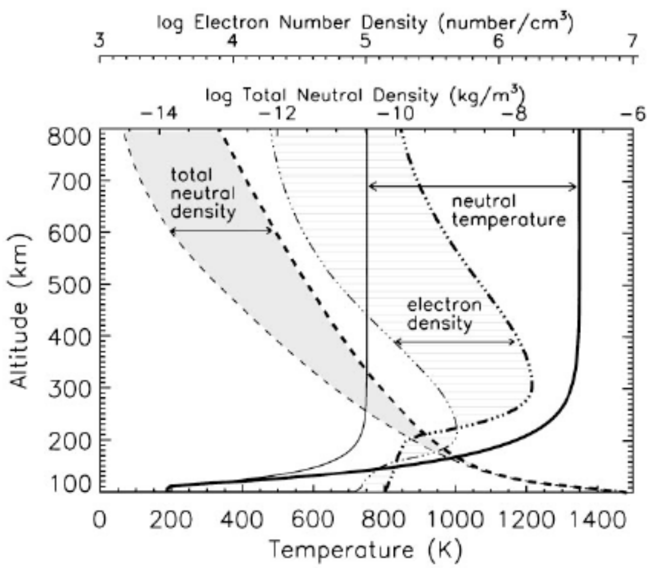




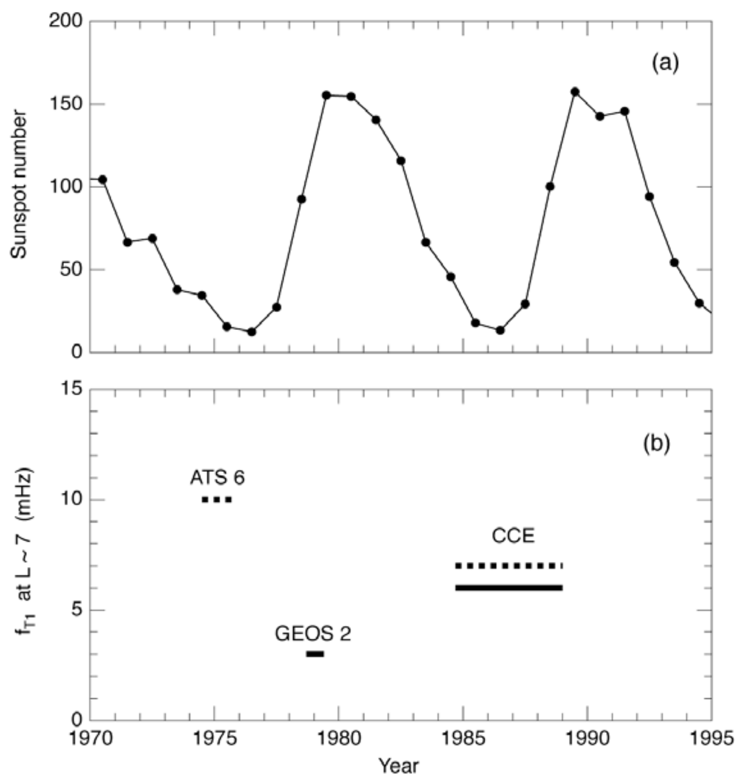
[*Menk al.*, 2004]

Solar cycle variation

- Mass density variation at *L* ~ 7
  - Changes by a factor of ~10
  - Comparable to changes at the topside ionosphere



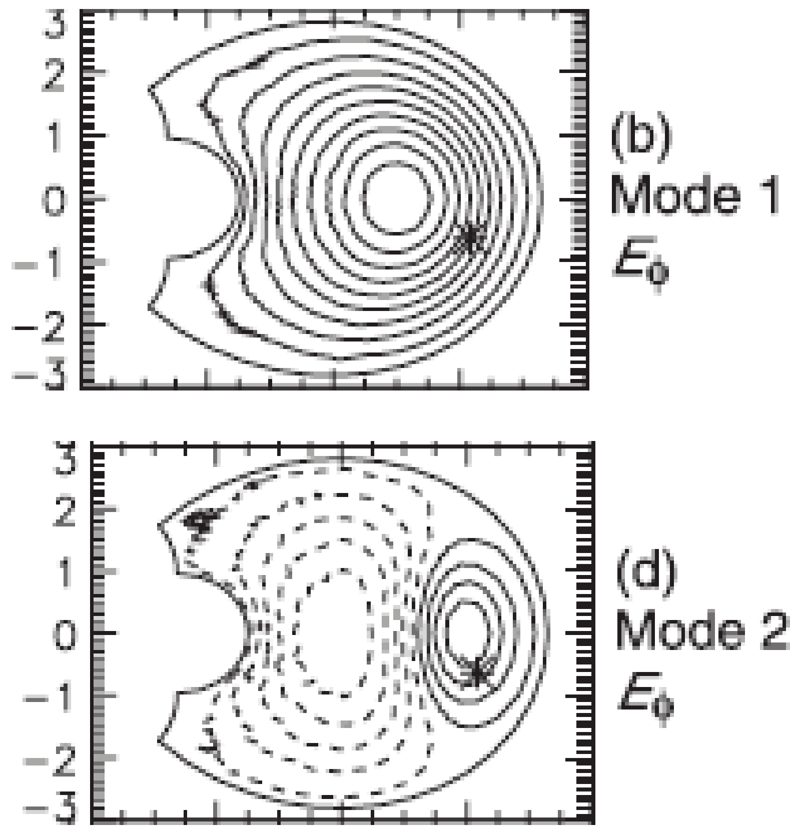
[*Lean*,1997]



[*Takahashi et al.*, 2002]

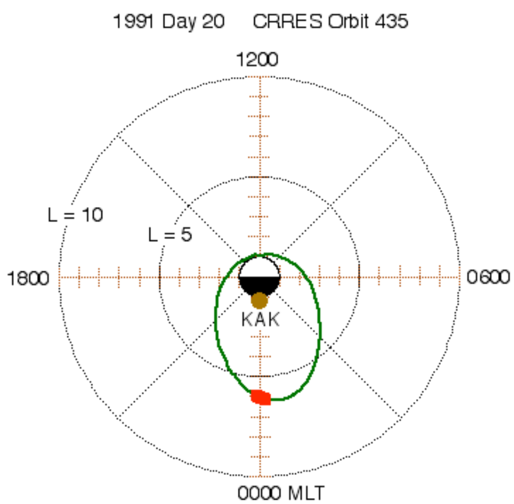
Fast mode waves: cavity mode resonance

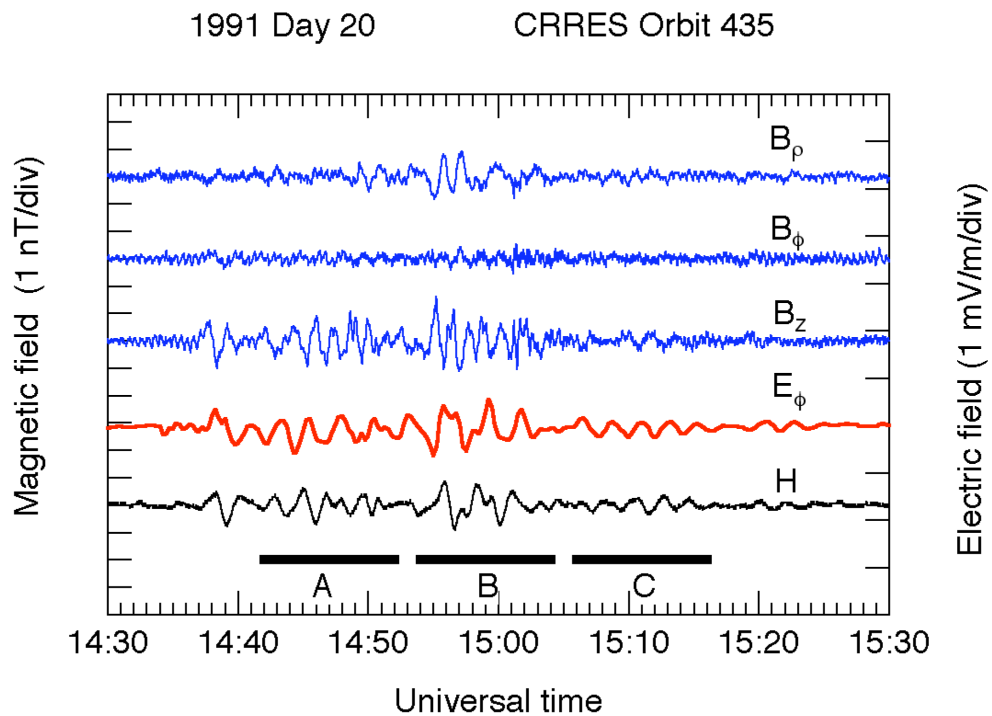
- Pi2 pulsations (nightside)
- Si/Sc-associated pulsations (dayside)
- Strongly damped
- Boundaries
  - Magnetopause
  - Plasmapause



Denton et al. [2002]

Low-latitude Pi2: plasmaspheric normal mode

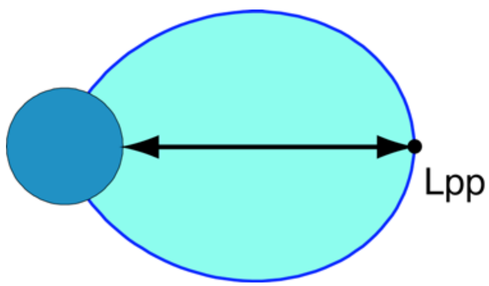


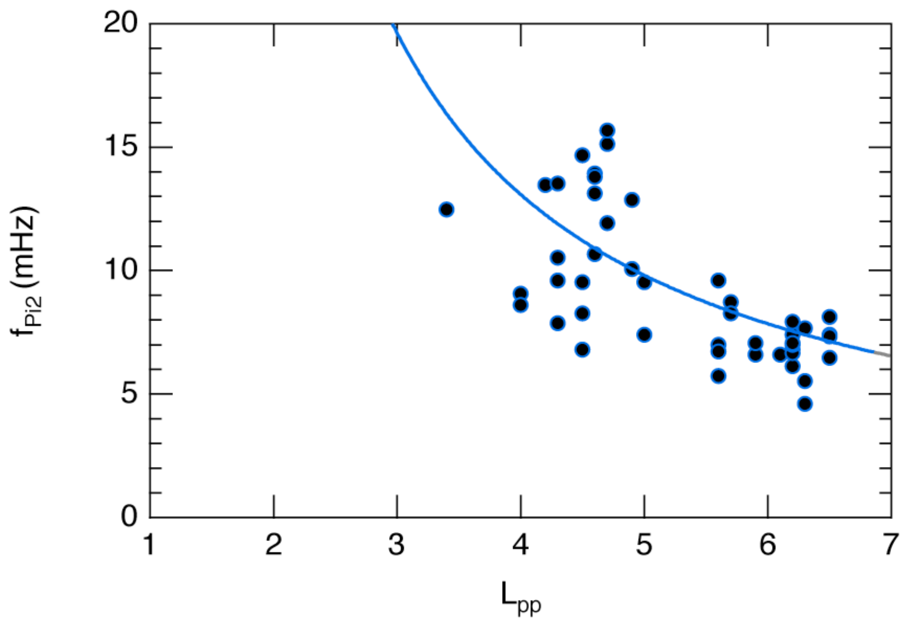


Takahashi et al. [2003]

Pi2 frequency: Dependence on Lpp

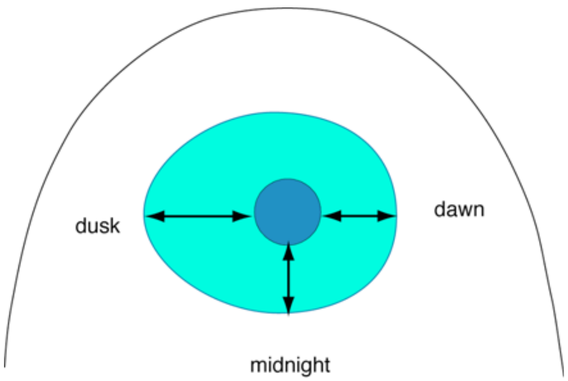
$$f_{Pi2} = \frac{V_A}{2R_E(L_{pp} - 1)}$$



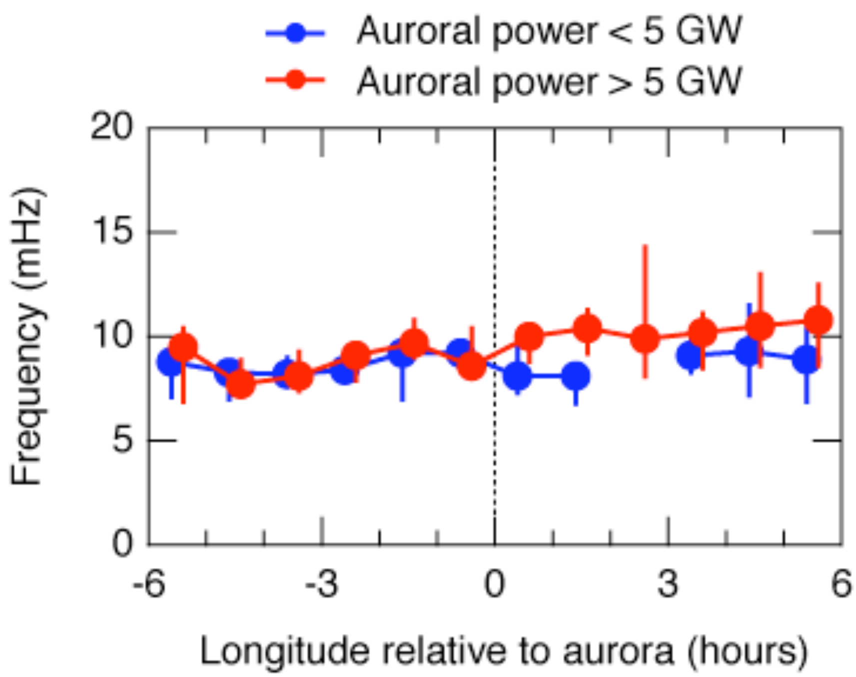


Takahashi et al. [2003]

Pi2 frequency: Dependence on local time

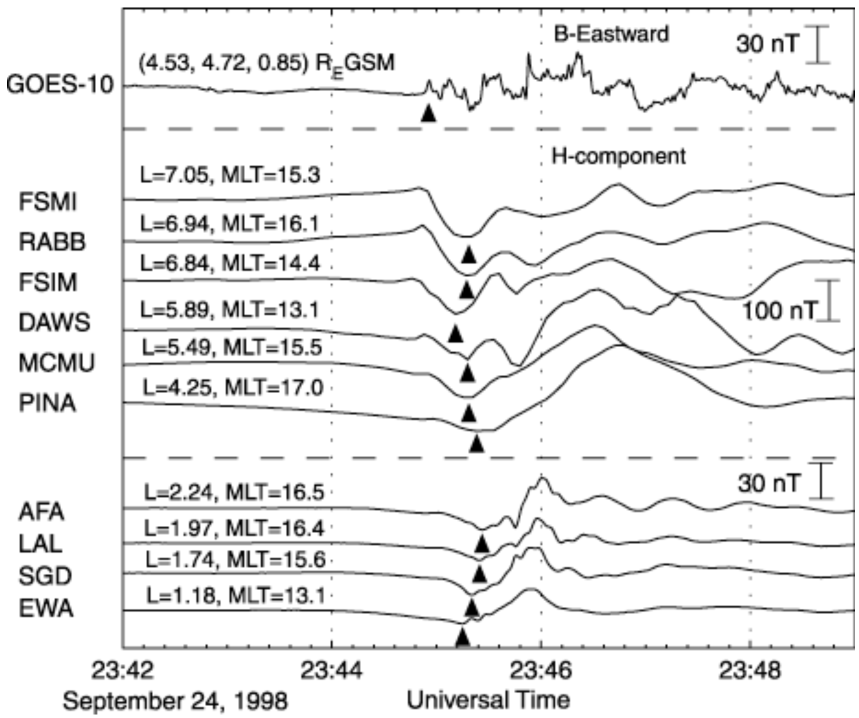


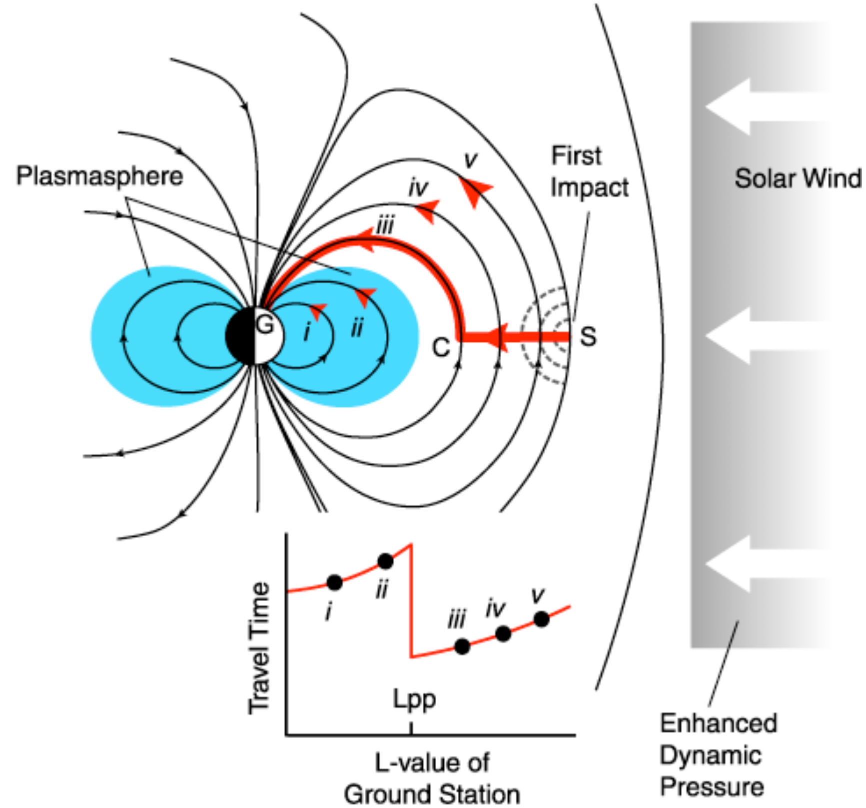
$$f_{dusk} < f_{midnight} \sim f_{dawn}$$



Takahashi and Liou [2004]

Fast mode/shear mode waves: travel time seismology





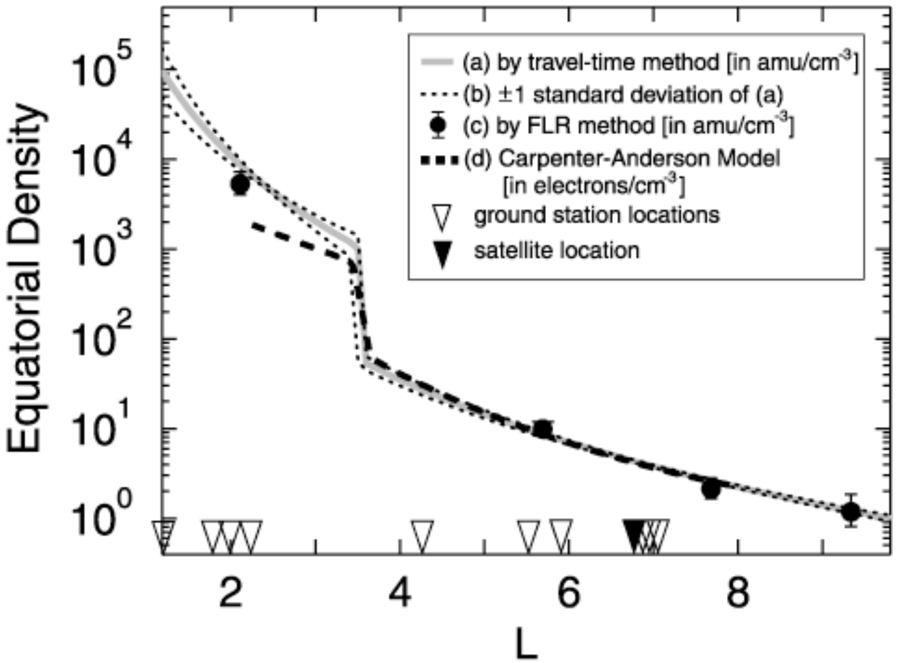
[*Chi et al.*, 2005]

Travel time seismology

Density model:
Power-law variation with
L with 5 free parameters

$$t_{Tamao} = \int_{l_1} \frac{ds}{v_f(\mathbf{r})} + \int_{l_2} \frac{ds}{v_A(\mathbf{r})}$$

$$\chi^2 = \sum_i \left(\frac{t_{obs,i} - t_0 - t_{Tamao,i}}{\sigma_i} \right)^2$$



[*Chi et al.*, 2005]

Summary

- Magnetospheric seismology is a unique technique for probing the magnetosphere
  - Spatial and temporal variation of mass distribution
  - Total mass density (heavy ion contribution to the magnetospheric plasma)
- Various approaches
  - Spacecraft and ground observations
  - Fast mode and shear mode
  - Normal mode and travel time
- Recent results
  - Storm time ion transport
  - Plasmapause dynamics
- Future directions
  - More magnetometers on the ground
  - Improvement in magnetic field model and inversion techniques

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