

Sources: Magnetohydrodynamic Waves

- Introduction to MHD waves (and beyond)

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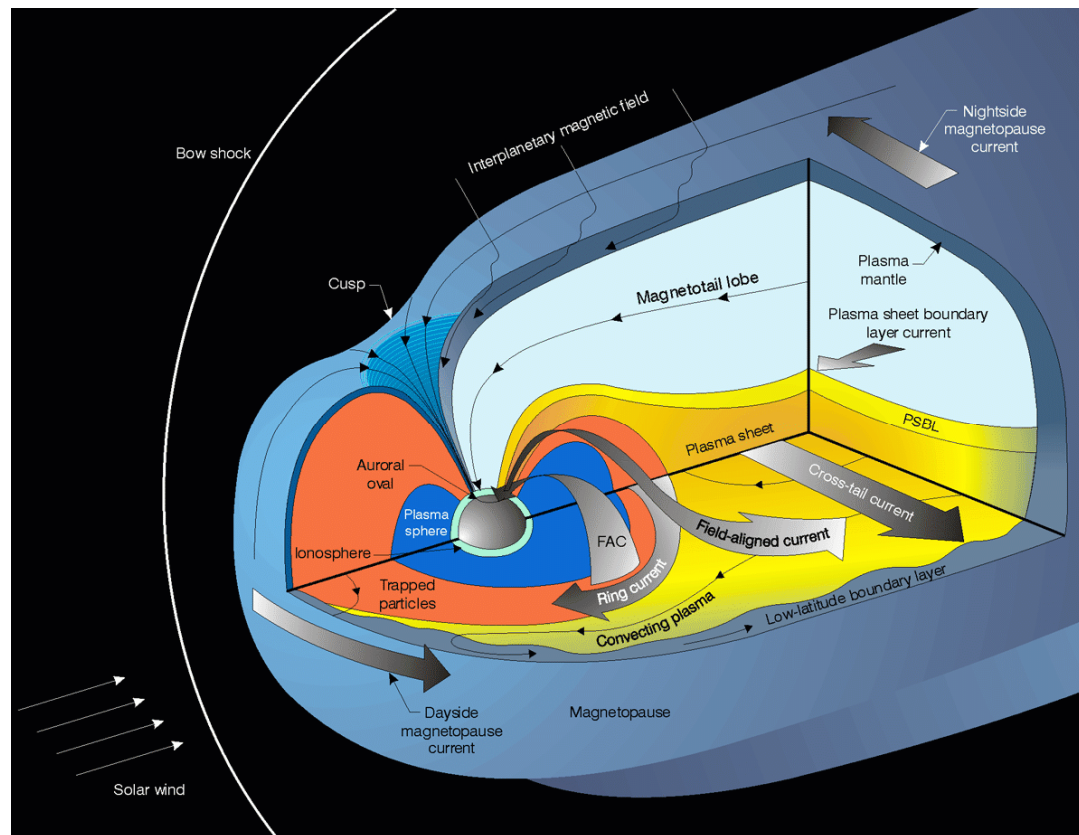
Introduction

- Space: *in situ experiment*
- Space is NOT empty and well structured.
- Space has all kinds of dynamics:

Single-ptl + Kinetic + Fluid approach

$L \sim 100,000\text{km}$

$dL \sim 100\text{km}$



Introduction

(ground)

Sea: $\sim 10^{+22} / \text{cm}^3$

Air: $\sim 10^{+19} / \text{cm}^3$

- collisions dominant
- diffusive
- neutral ptls
- mech. + gravit.

(space)

$\sim 10^{-2} - 10^{+3} / \text{cm}^3$

- collisions negligible
- well-structured
- plasma (ions, electrons)
- mech. + electromag.

cf) For CLIC beams,

$$n_e \sim 10^{12 \sim 13} / (1\text{nm}, 40\text{nm}, 150\text{ns} * c) \sim 10^{21} / \text{cm}^3$$

Background: from single-ptl to fluid

- **Single-ptl** (*e.g., $f=ma$*)

$$\vec{X}(t), \vec{V}(t) \quad \vec{F} = m \frac{d\vec{V}}{dt} = q (\vec{E} + \vec{V} \times \vec{B})$$

- **A few or many ptls** (*kinetic approach, $f(x,v,t)$*)

$$N(\vec{x}, \vec{v}, \vec{t}) = \sum_j \delta(\vec{x} - \vec{X}_j(t)) \delta(\vec{v} - \vec{V}_j(t)) \quad f(\vec{x}, \vec{v}, t) \equiv \langle N(\vec{x}, \vec{v}, t) \rangle$$

- **Multi-fluids** (*multi-ions + electrons*)

$$n_j(\vec{x}, t), \vec{V}_j(\vec{x}, t), P_j(\vec{x}, t), T_j(\vec{x}, t) \quad j = e, i$$

- **Single-fluid (MHD)** $n(\vec{x}, t), \vec{V}(\vec{x}, t), P(\vec{x}, t), T(\vec{x}, t)$

- **Ideal MHD**

Background: Multi-fluids (*multi-ions + electrons*)

- Multi-fluid equations

$$\frac{\partial n_j}{\partial t} + \nabla \cdot (n_j \mathbf{v}_j) = 0$$

$$m_j n_j \left[\frac{\partial \mathbf{v}_j}{\partial t} + (\mathbf{v}_j \cdot \nabla) \mathbf{v}_j \right] = n_j q_j (\mathbf{E} + \mathbf{v}_j \times \mathbf{B}) - \nabla p_j + \mathbf{R}_j \quad j = i, e$$

$$p_j = C_j n_j^{\gamma_j}$$

- Ideal MHD equations

$$\frac{\partial n}{\partial t} + \nabla \cdot (n \mathbf{v}) = 0$$

$$mn \left[\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right] = \mathbf{j} \times \mathbf{B} - \nabla p$$

$$p = C n^\gamma$$

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = 0$$

Approximations

- From $N(x,v,t)$ to $f(x,v,t)$:

Neglect the single-particle nature

$$r \gg \lambda_D = \sqrt{\frac{\epsilon_0 k_B T}{ne^2}} = \text{the Debye length}$$

$$\Lambda = n\lambda_D^3 \gg 1 \quad : \text{the plasma parameter}$$

cf) For CLIC beams: $r \gg \lambda_D$, but $\Lambda \ll 1$

-From $f(x,v,t)$ {plasma kinetic eq.}
to $f(x,v,t)$ {Vlasov eq.}:

Neglect *collisions (resistivity)*

weak turbulence

quasi-linear theory

.....

Approximations

- From $f(x,v,t)$ to $MF(x,t)$:

Neglect the velocity distribution

ex) *wave-particle interaction*

microscopic instabilities

Landau damping

non-thermal equilibrium

- From $MF(x,t)$ to $SF(x,t)$:

Neglect the electron inertia and the ion species

ex) *rapid EM & ES variations*

$$\omega < \omega_{ci} = \frac{eB}{m_i} \quad \text{Ion gyro-frequency}$$

$$r > r_{ci} = \frac{v_{\perp}}{\omega_{ci}} \quad \text{Ion gyro-radius}$$

Application – Waves in space

<MHD waves>

- *very low freq:* **MHD waves** $\omega \ll \Omega_i$

<multi-fluid waves>

- *low freq:* **Ion waves** $\omega \sim \Omega_i$

- *intermed. freq:* **Ion-electron waves** $\Omega_i < \omega < \Omega_e$

- *high freq:* **Electron waves** $\omega \sim \Omega_e$

<kinetic waves>

- *e.g. higher harmonics, Bernstein waves, ...*

<single-ptl resonances>

- *e.g. bounce resonance, bounce-drift resonance, ...*

Application – Waves in space

Maxwell eqs
+ Ohm's law



$$\begin{aligned}\vec{\nabla} \times (\vec{\nabla} \times \vec{E}) &= -\frac{1}{c^2} \frac{\partial^2 \vec{E}}{\partial t^2} - \mu_o \frac{\partial \vec{J}}{\partial t} \\ &= \frac{\omega^2}{c^2} \left(\mathbf{1} + \frac{i\sigma}{\omega\epsilon_o} \right) \cdot \vec{E} \\ &= k^2 \epsilon \cdot \vec{E}\end{aligned}$$

For instance, $\vec{B} = B \hat{z}$,

$$\epsilon = \begin{pmatrix} S & -iD & 0 \\ iD & S & 0 \\ 0 & 0 & P \end{pmatrix}$$

$$\begin{aligned}S &= 1 - \sum_j \frac{\omega_{pj}^2}{\omega^2 - \omega_{cj}^2} \\ D &= \sum_j \frac{|q_j|/q_j \omega_{cj} \omega_{pj}^2}{\omega(\omega^2 - \omega_{cj}^2)} \\ P &= 1 - \sum_j \frac{\omega_{pj}^2}{\omega^2}\end{aligned}$$

$$\omega_{pj} = \sqrt{\frac{n_j q_j^2}{m_j \epsilon_o}} \quad \omega_{cj} = \frac{|q_j| B}{m_j}$$

Application – Waves

- CMA diagram
- <multi-fluid waves>

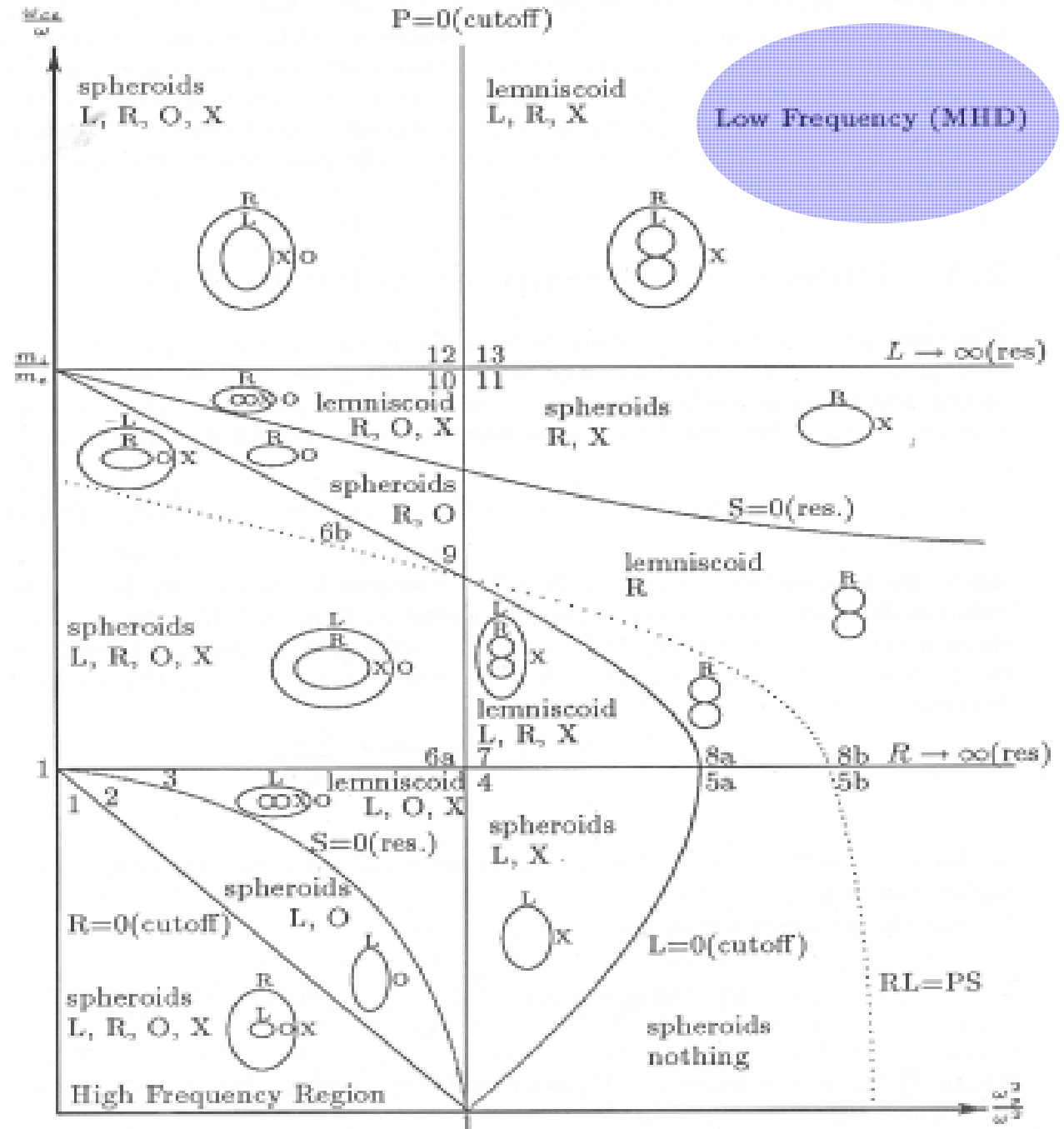
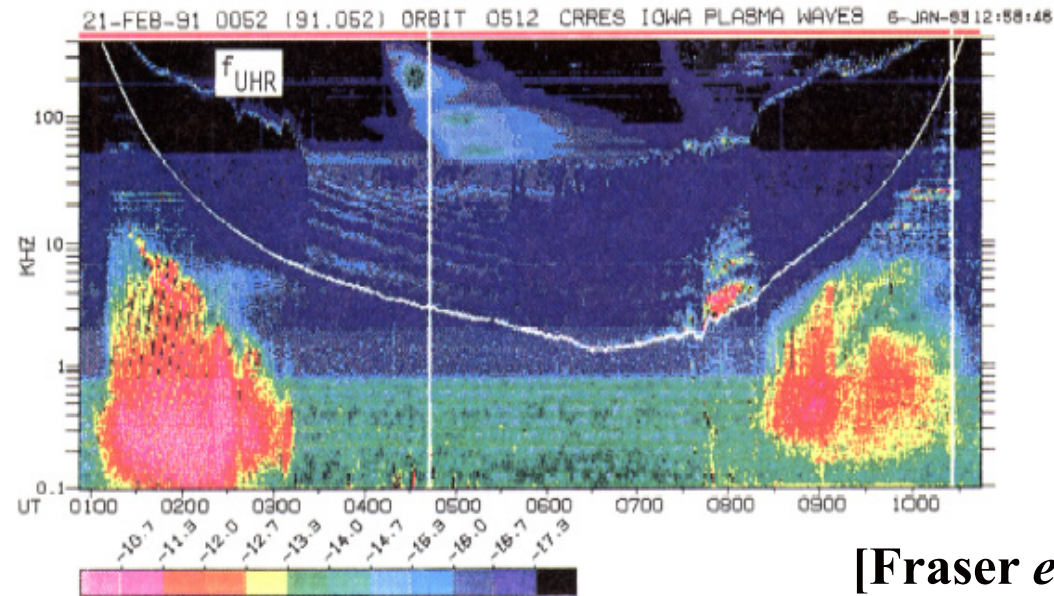


Figure 2.8: CMA diagram with all boundaries and wave normal surfaces.

Application – W

<electron waves>



[Fraser *et al.*, 1996]

<multi-ion waves>

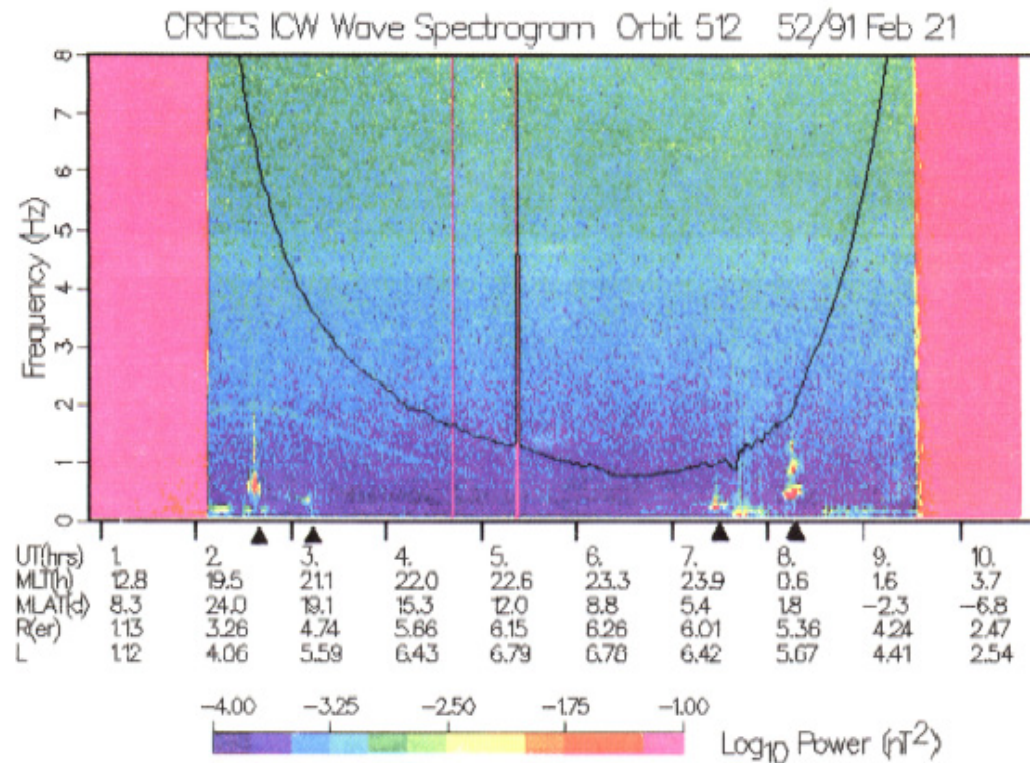


Plate 1. (Upper) CRRES EMIC wave dynamic spectrum for orbit 512 on February 21, 1991. The dark curve is the

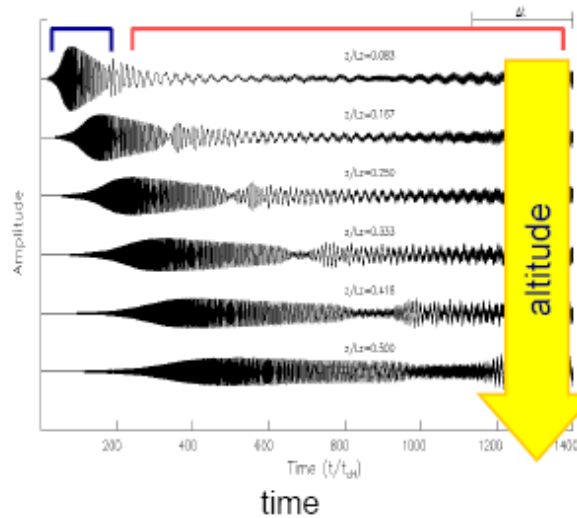
Application – Waves in space

❖ Two wave modes

- First mode —
 - Decreasing frequency with increasing time
- Second mode —
 - Appear after the reception of first wave modes

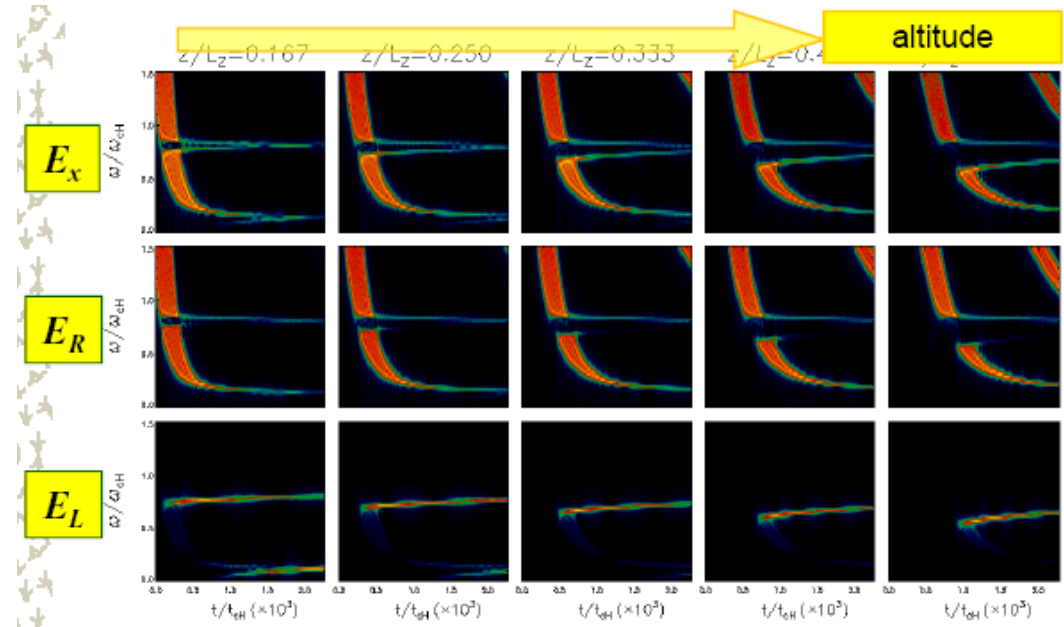
❖ Length of the wavetrains grows significantly with z .

❖ The time delay increases with z .



[Kim & Lee, 2005]

<ion-electron waves>



MHD waves

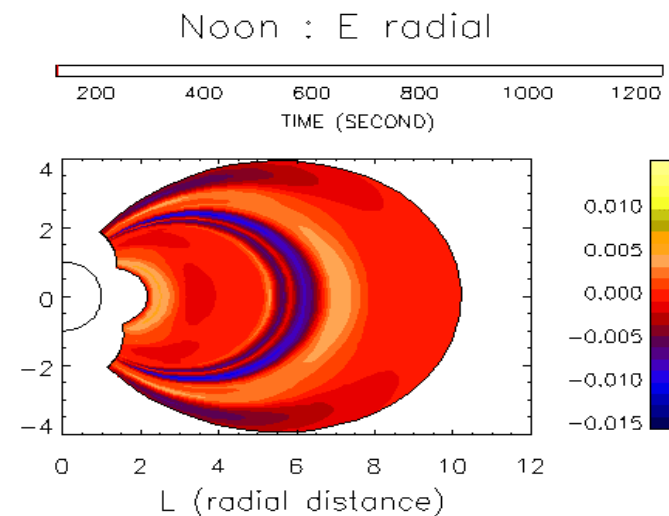
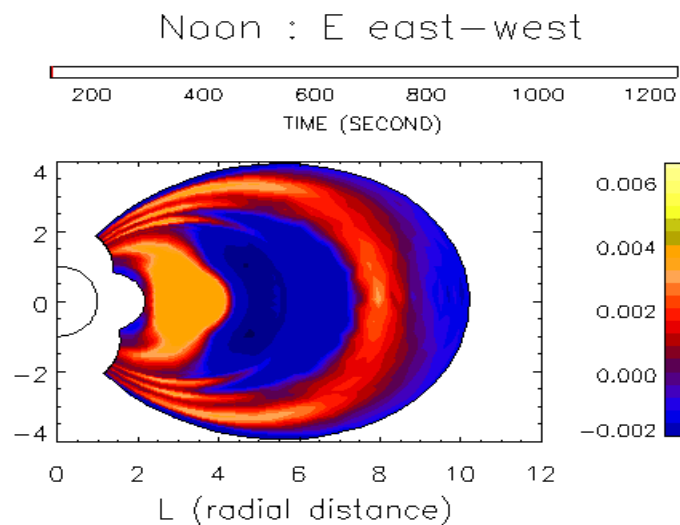
In uniform medium:

$$\omega = \frac{k V_A}{\sqrt{1 + \frac{i k^2}{\mu_o \omega \sigma}}}$$

- **Compressional waves**
- **Magnetosonic waves**
- **Isotropic mode**
- **Three-dimensional**

$$\omega = \frac{k_{\parallel} V_A}{\sqrt{1 + \frac{i k^2}{\mu_o \omega \sigma}}}$$

- **Incompressional waves**
- **Alfven waves**
- **Anisotropic**
- **One-dimensional**



* In a nonuniform plasma,

e.g., MHD waves: $\frac{\omega}{\omega_{cj}} \ll 1$ and $\rho(x), V_A(x) = \frac{B}{\mu_0 \rho(x)}$

$$S \approx \frac{c^2}{V_A^2}$$

$$D \approx 0$$

$$P \rightarrow \infty$$

Ex : Alfvén waves

Ey : Compressional waves

Ez = 0

$$\vec{E} \propto e^{i(k_y y + k_z z - \omega t)} \quad D = \frac{\omega^2}{V_A^2(x)} - k_z^2$$

$$\left(\frac{d}{dx} \frac{D}{D - k_y^2} \frac{dE_y}{dx} \right) + D E_y = 0$$

- MHD waves: *Asymptotic solutions*

At resonances,

$$E_x \propto \frac{1}{x - x_0}$$

$$E_y \propto \ln|x - x_0|$$

$$\frac{\omega^2}{V_A^2} - k_z^2 = \alpha (x - x_0) = C (\omega - \omega_0)$$

$$\longrightarrow E_y(x, t \rightarrow \infty) \propto \frac{1}{2\pi} \int_{-\infty}^{\infty} \ln|\omega - \omega_0| e^{-i\omega t} d\omega = -\frac{1}{2t} e^{-i\omega_0 t}$$

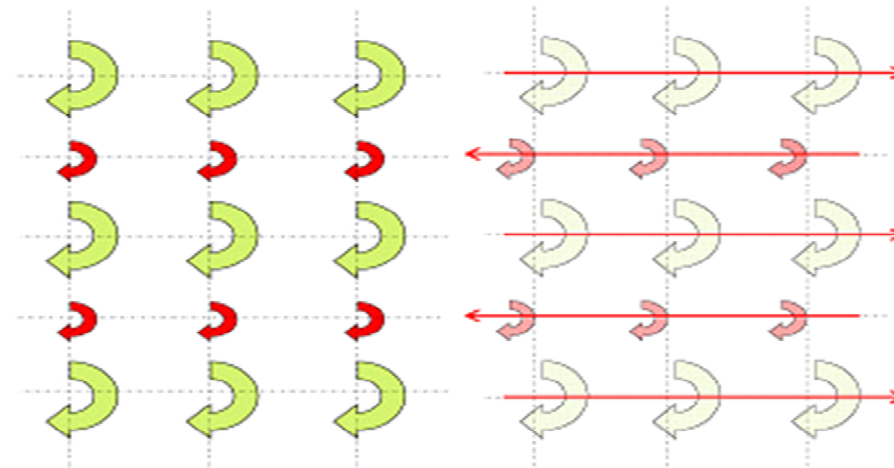
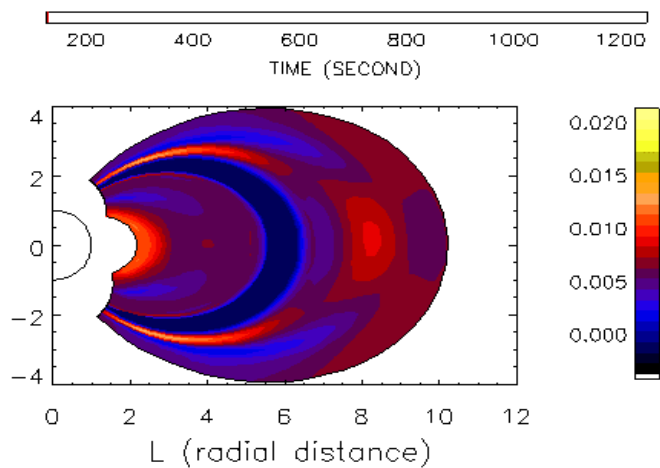
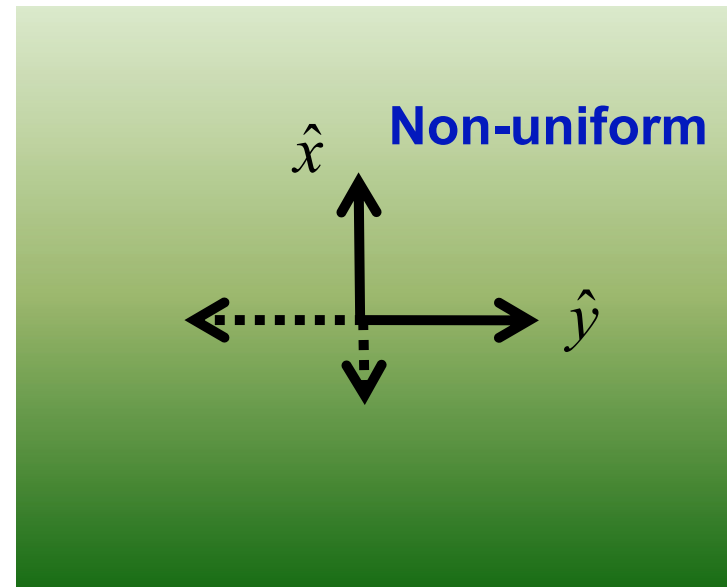
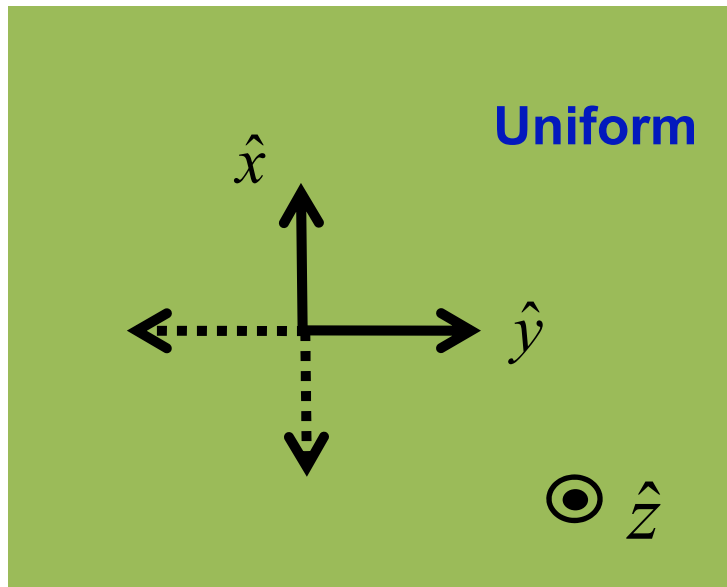
\longrightarrow E_y is being damped to E_x (even if no dissipations)

\longrightarrow Compressional waves damp, shear Alfvén waves grow.

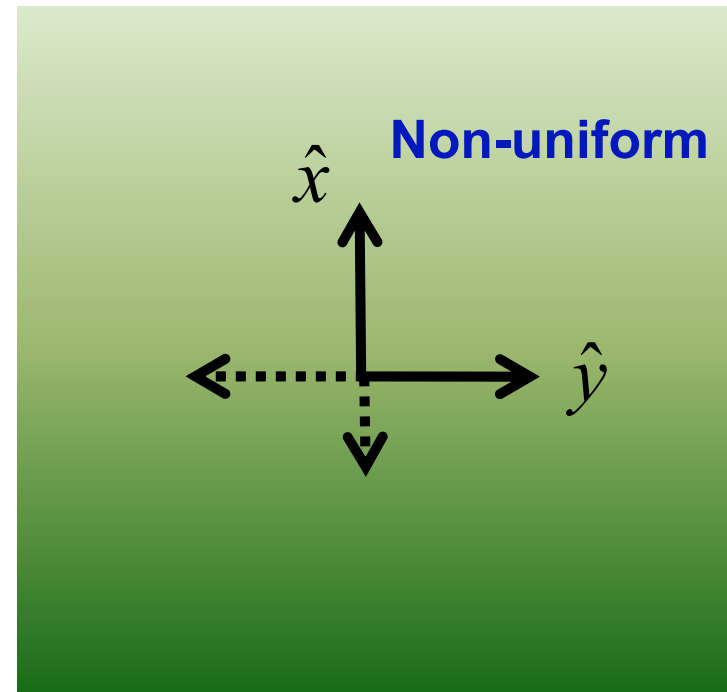
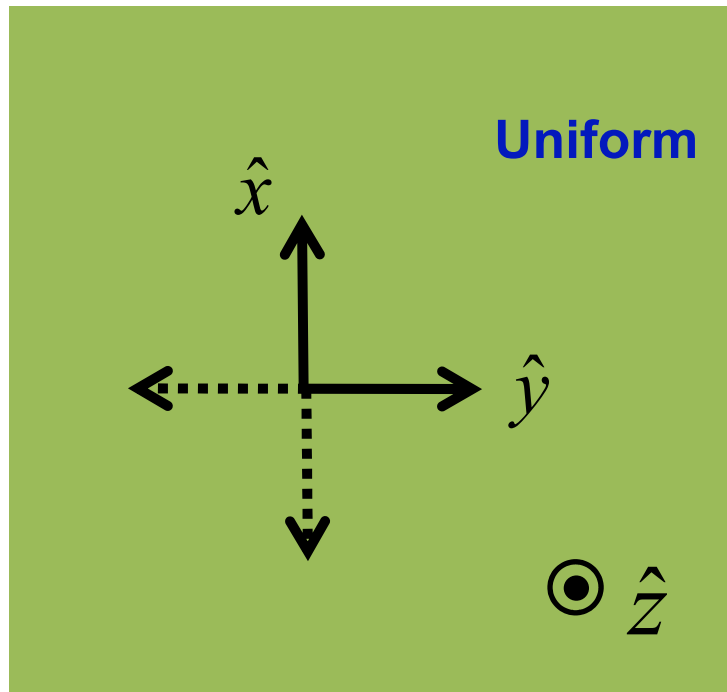
\longrightarrow Resonant absorption of Alfvén waves = Field line resonances

\longrightarrow *Mode conversion*

- Two degrees of freedom become differential in nonuniform plasmas.
- In terms of wave (collective) motion, azimuthal or shear motion is stable.



$\vec{E} + \vec{v} \times \vec{B}_0 = 0$ is valid for collective, but relatively low frequency wave motion.



- When inhom. lies perpendicular to B-field, the azimuthal (shear) motion V_y or radial E_x or azimuthal B_y are expected to be stable (and dominant?).

* Torodial & Poloidal modes

$$\vec{\nabla} \times \vec{b} = \frac{1}{V_A^2(\vec{x}, t)} \frac{\partial \vec{E}}{\partial t}$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{b}}{\partial t}$$

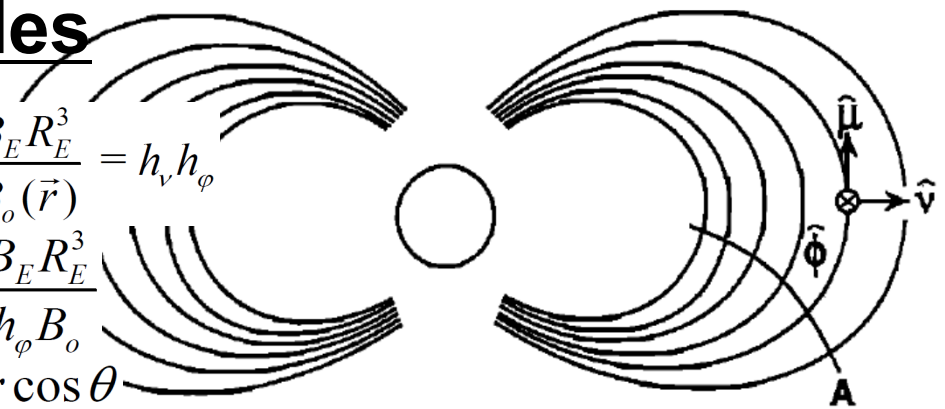
$$\varepsilon_\nu = h_\nu E_\nu$$

$$\varepsilon_\varphi = h_\varphi E_\varphi$$

$$h_\mu = \frac{B_E R_E^3}{B_o(\vec{r})} = h_\nu h_\varphi$$

$$h_\nu = \frac{B_E R_E^3}{h_\varphi B_o}$$

$$h_\varphi = r \cos \theta$$



$$\frac{\partial \beta_\mu}{\partial t} = -\left\{ \frac{\partial \varepsilon_\varphi}{\partial \nu} - \frac{\partial \varepsilon_\nu}{\partial \varphi} \right\} = -\left\{ \frac{\partial \varepsilon_\varphi}{\partial \nu} + im\varepsilon_\nu \right\}$$

In the dipole coordinate (μ, ν, φ)

$$\left\{ \frac{1}{V_A^2} \frac{\partial^2}{\partial t^2} - \frac{1}{h_\varphi^2} \frac{\partial}{\partial \mu} \left(\frac{1}{h_\nu^2} \frac{\partial}{\partial \mu} \right) \right\} \varepsilon_\nu = -\frac{1}{h_\varphi^2} \frac{\partial}{\partial \varphi} \left\{ \frac{\partial \varepsilon_\varphi}{\partial \nu} - \frac{\partial \varepsilon_\nu}{\partial \varphi} \right\} = \frac{1}{h_\varphi^2} im \left\{ \frac{\partial \varepsilon_\varphi}{\partial \nu} + im\varepsilon_\nu \right\}$$

$$\left\{ \frac{1}{V_A^2} \frac{\partial^2}{\partial t^2} - \frac{1}{h_\nu^2} \frac{\partial}{\partial \mu} \left(\frac{1}{h_\varphi^2} \frac{\partial}{\partial \mu} \right) \right\} \varepsilon_\varphi = \frac{1}{h_\nu^2} \frac{\partial}{\partial \nu} \left\{ \frac{\partial \varepsilon_\varphi}{\partial \nu} - \frac{\partial \varepsilon_\nu}{\partial \varphi} \right\} = \frac{1}{h_\nu^2} \frac{\partial}{\partial \nu} \left\{ \frac{\partial \varepsilon_\varphi}{\partial \nu} + im\varepsilon_\nu \right\}$$



$$\left\{ \frac{1}{V_A^2} \frac{\partial^2}{\partial t^2} - \frac{1}{h_\varphi^2} \frac{\partial}{\partial \mu} \left(\frac{1}{h_\nu^2} \frac{\partial}{\partial \mu} \right) \right\} \varepsilon_\nu = 0$$

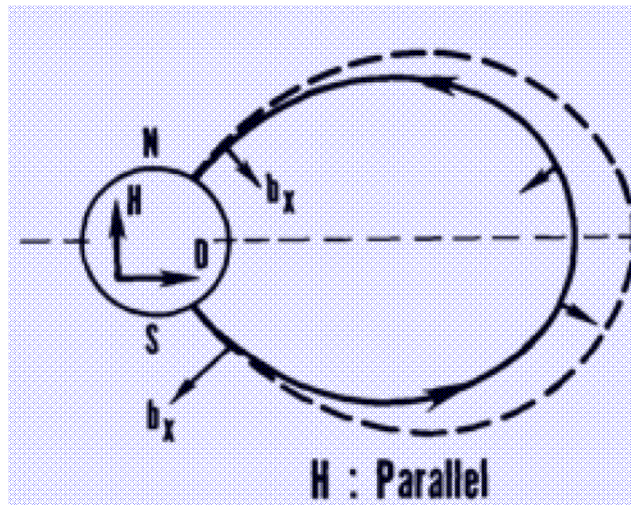
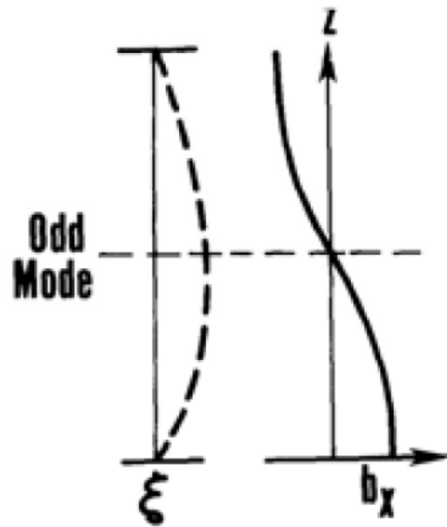
$$\left\{ \frac{1}{V_A^2} \frac{\partial^2}{\partial t^2} - \frac{1}{h_\nu^2} \frac{\partial}{\partial \mu} \left(\frac{1}{h_\varphi^2} \frac{\partial}{\partial \mu} \right) \right\} \varepsilon_\varphi = 0$$

Toroidal: $m = 0$

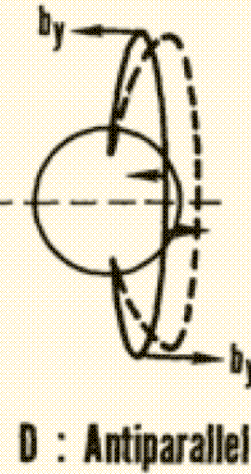
Poloidal: $m \rightarrow \infty$

* Torodial & Poloidal modes

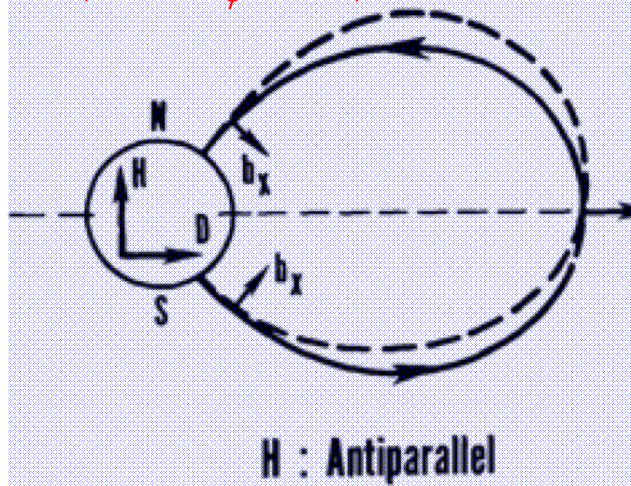
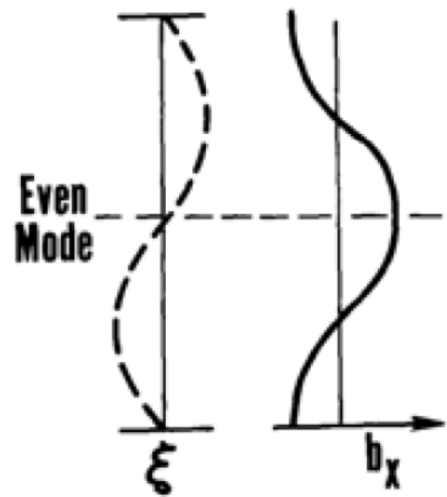
[McPherron, 2005]



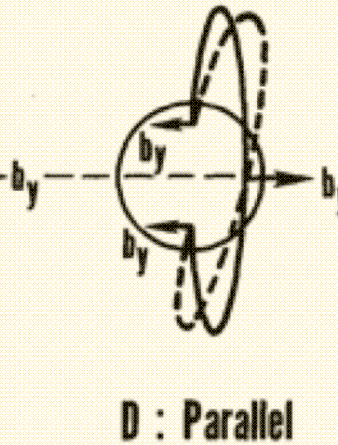
$$V_v \sim E_\phi \sim b_v$$



$$V_\phi \sim E_v \sim b_\phi$$



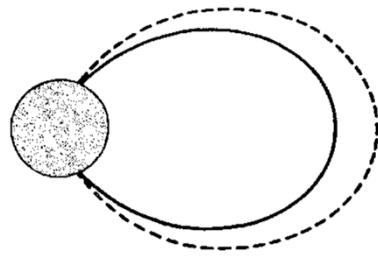
Poloidal mode



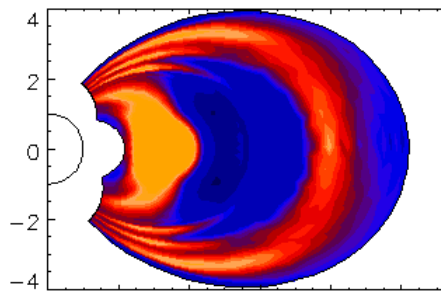
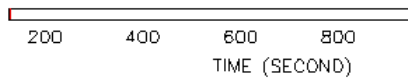
Toroidal mode

Application – Waves in space

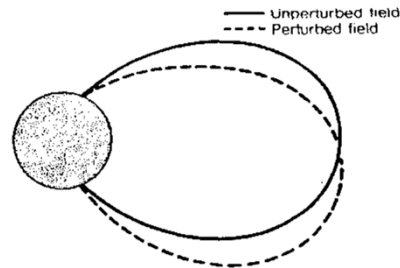
<MHD waves>



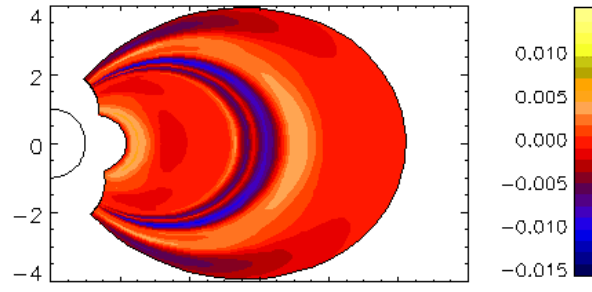
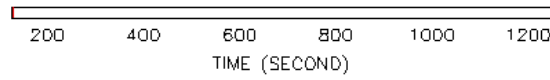
Noon : E east-w



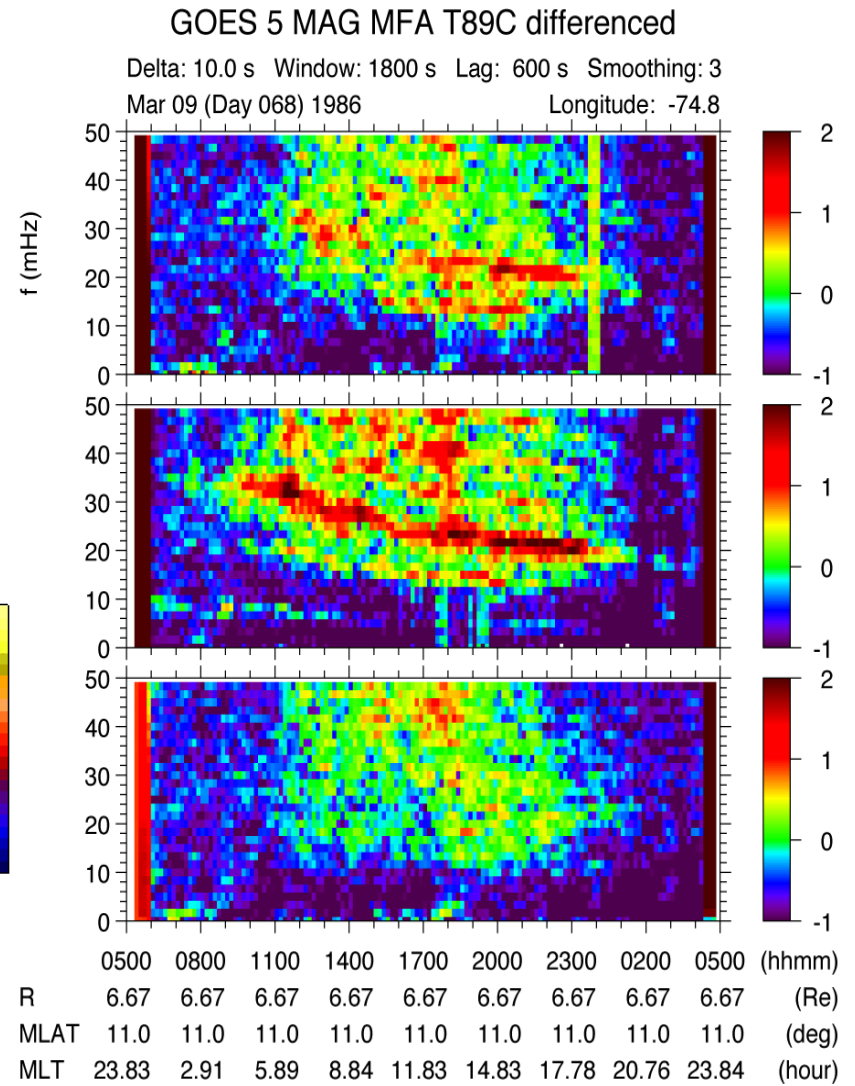
L (radial distance)



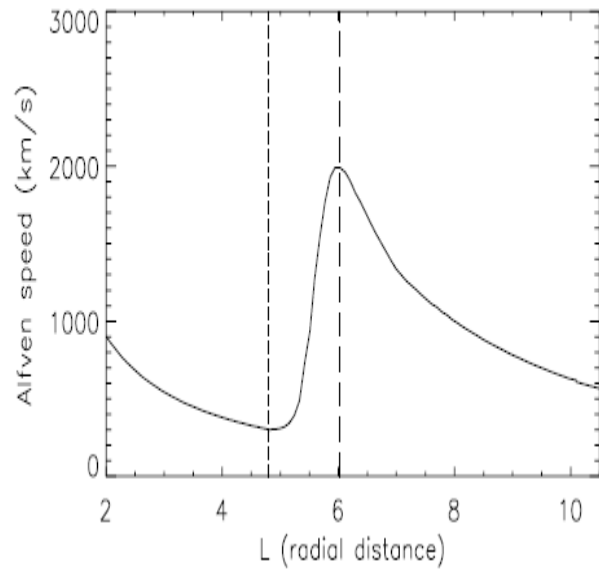
Noon : E radial



L (radial distance)



- 3-D dipole MHD waves

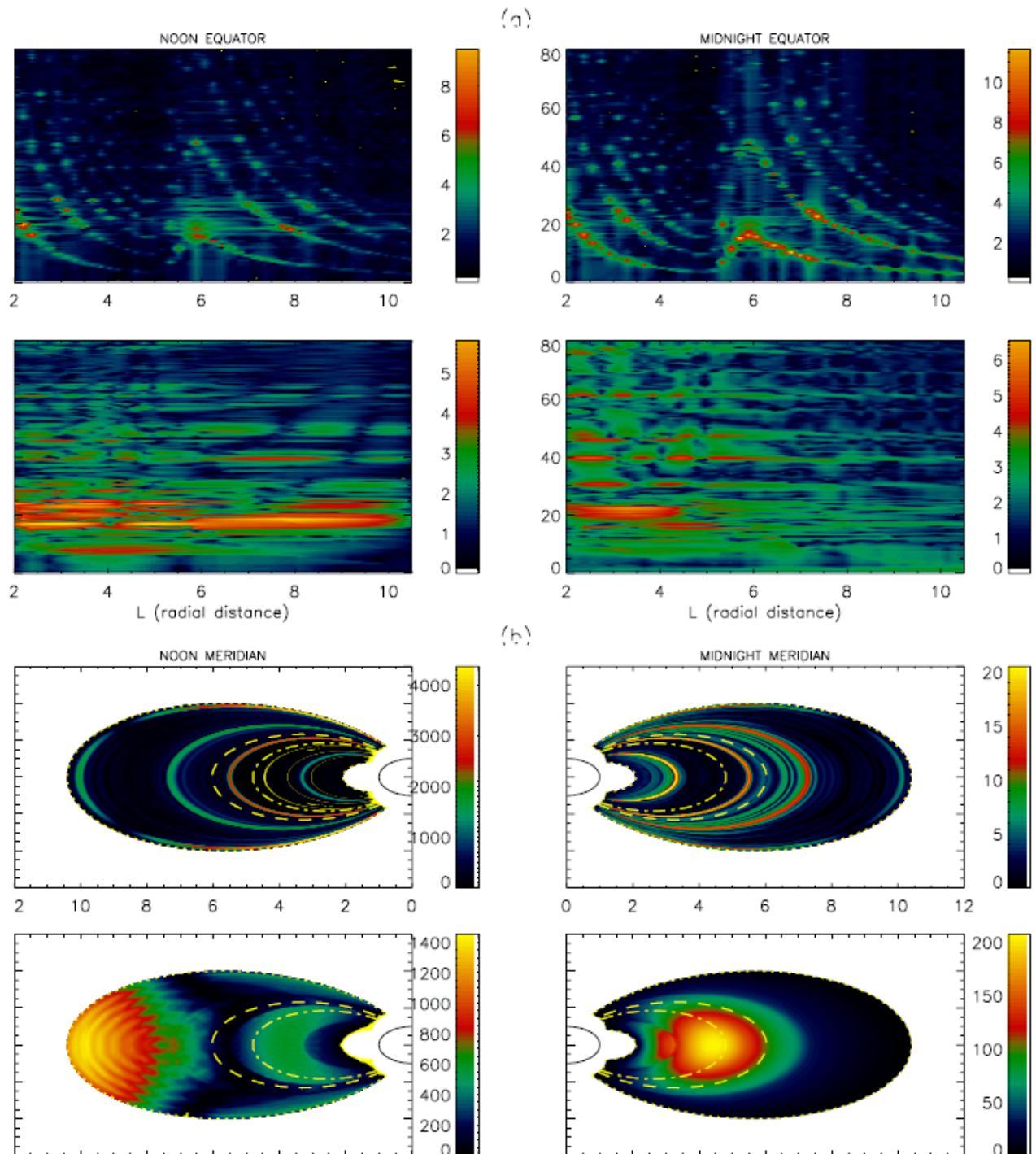


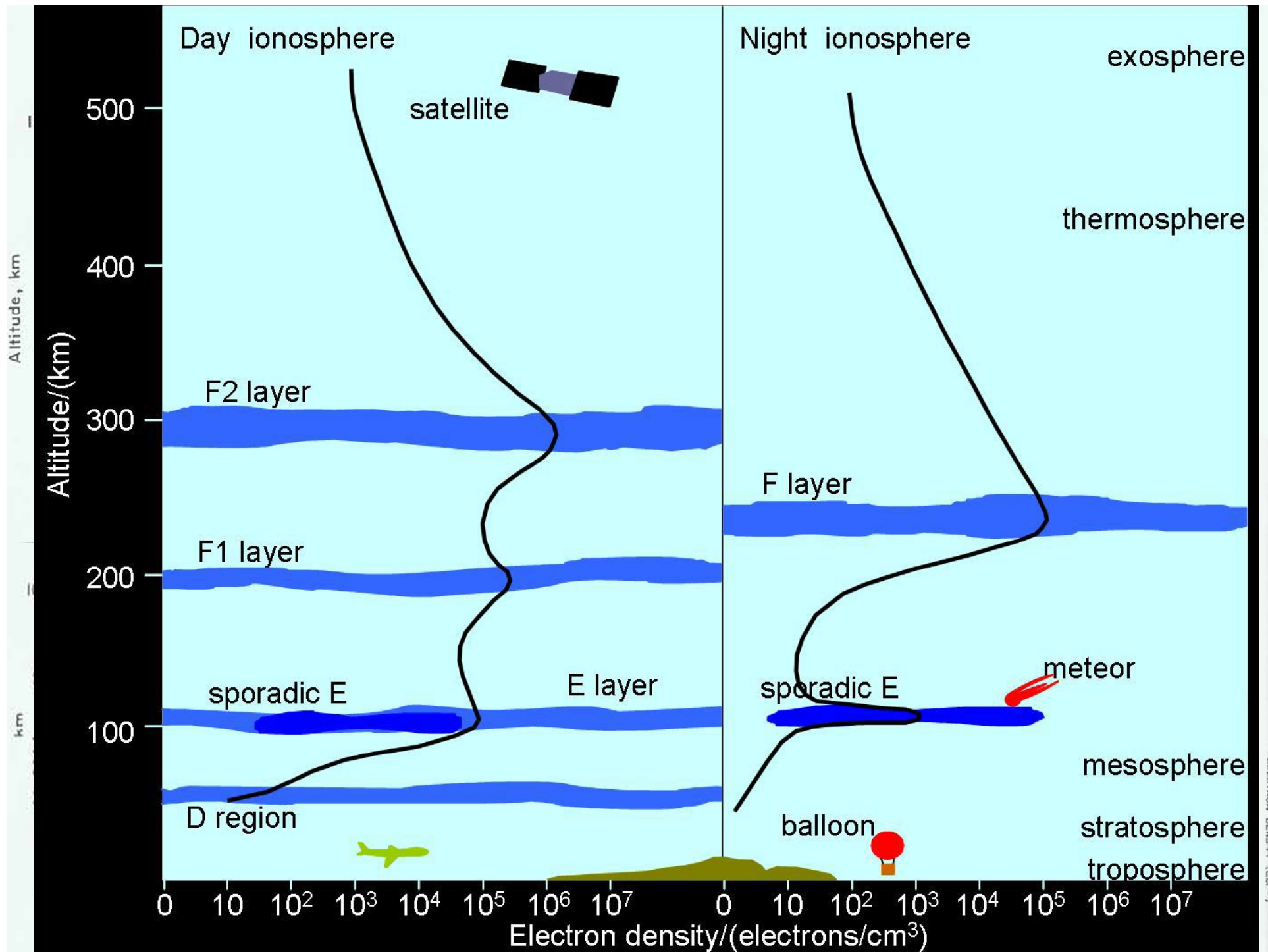
[e.g., Lee *et al.*, 2004]

cf) For CLIC,

$$\lambda_{lat} \sim 47^\circ$$

$$L \sim 2.1R_e$$





Collisions with *neutral* ptls

* Assume: $\vec{v}_n = 0$

- Eqs of motion:

$$m_i \frac{\partial \vec{v}_i}{\partial t} = e \left(\vec{E} + \vec{v}_i \times \vec{B} \right) - m_i v_{in} \vec{v}_i$$

$$m_e \frac{\partial \vec{v}_e}{\partial t} = -e \left(\vec{E} + \vec{v}_e \times \vec{B} \right) - m_e v_{en} \vec{v}_e$$

→ $\vec{J} = \overleftrightarrow{\sigma} \cdot \vec{E} = \begin{pmatrix} \sigma_p & -\sigma_H & 0 \\ \sigma_H & \sigma_p & 0 \\ 0 & 0 & \sigma_{\parallel} \end{pmatrix} \cdot \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix}$

→ $\vec{J} = \sigma_{\parallel} \vec{E}_{\parallel} + \sigma_p \vec{E}_{\perp} - \sigma_H \frac{\vec{E} \times \vec{B}}{B}$

Collisions with *neutral* ptls

where

$$\sigma_P = \epsilon_0 \sum_j \frac{\omega_{pj}^2 (v_{jn} - i\omega)}{(v_{jn} - i\omega)^2 + \omega_{cj}^2}$$

$$\sigma_H = -\epsilon_0 \sum_j \frac{\epsilon_j \omega_{pj}^2 \omega_{cj}}{(v_{jn} - i\omega)^2 + \omega_{cj}^2}$$

$$\sigma_{\parallel} = \epsilon_0 \sum_j \frac{\omega_{pj}^2}{v_{jn} - i\omega}$$

If $\omega \ll v_{jn}$

$$\rightarrow \sigma_P \cong \epsilon_0 \sum_j \frac{\omega_{pj}^2 v_{jn}}{v_{jn}^2 + \omega_{cj}^2} = \left(\frac{v_{en}}{v_{en}^2 + \omega_{ce}^2} + \frac{m_e}{m_i} \frac{v_{in}}{v_{in}^2 + \omega_{ci}^2} \right) \frac{n_e e^2}{m_e}$$

$$\sigma_H \cong -\epsilon_0 \sum_j \frac{\epsilon_j \omega_{pj}^2 \omega_{cj}}{v_{jn}^2 + \omega_{cj}^2} = \left(\frac{\omega_{ce}}{v_{en}^2 + \omega_{ce}^2} - \frac{m_e}{m_i} \frac{\omega_{ci}}{v_{in}^2 + \omega_{ci}^2} \right) \frac{n_e e^2}{m_e}$$

$$\sigma_{\parallel} \cong \epsilon_0 \sum_j \frac{\omega_{pj}^2}{v_{jn}} = \left(\frac{1}{v_{en}} + \frac{m_e}{m_i} \frac{1}{v_{in}} \right) \frac{n_e e^2}{m_e}$$

Collisions with *neutral* ptls

since $\frac{\sigma_P(j)}{\sigma_H(j)} \approx \frac{v_{jn}}{\omega_{cj}}$

$$\omega_{cj} \ll v_{jn} \quad \sigma_P(j) \gg \sigma_H(j)$$

$$\omega_{cj} \gg v_{jn} \quad \sigma_P(j) \ll \sigma_H(j)$$

$$\frac{\omega_{ce}}{\omega_{ci}} = \frac{m_i}{m_e} = 1836$$

$$\frac{v_{en}}{v_{in}} = \sqrt{\frac{m_i}{m_n}} = \sqrt{1836} \cong 43$$

There are 3 choices:

$$\omega_{ci} \ll \omega_{ce} \lesssim v_{in} \ll v_{en}$$

: both P currents dominant

$$\omega_{ci} \ll v_{in} \ll v_{en} \ll \omega_{ce}$$

: P(i) and H(e)

$$v_{in} \ll v_{en} \ll \omega_{ci} \ll \omega_{ce}$$

: both H currents dominant



* Ionosphere: *Composition*

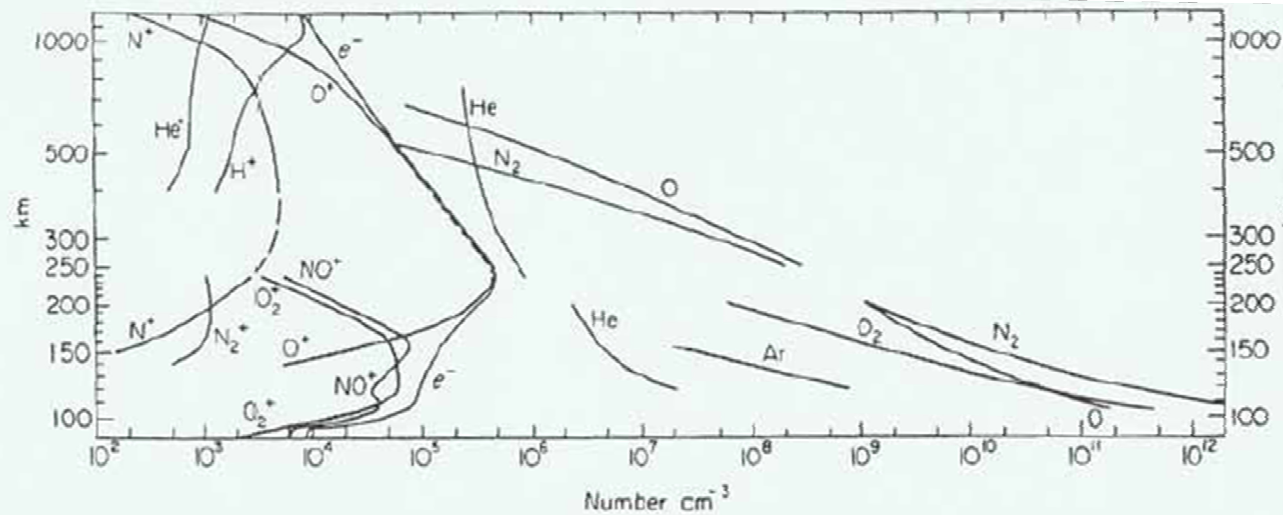
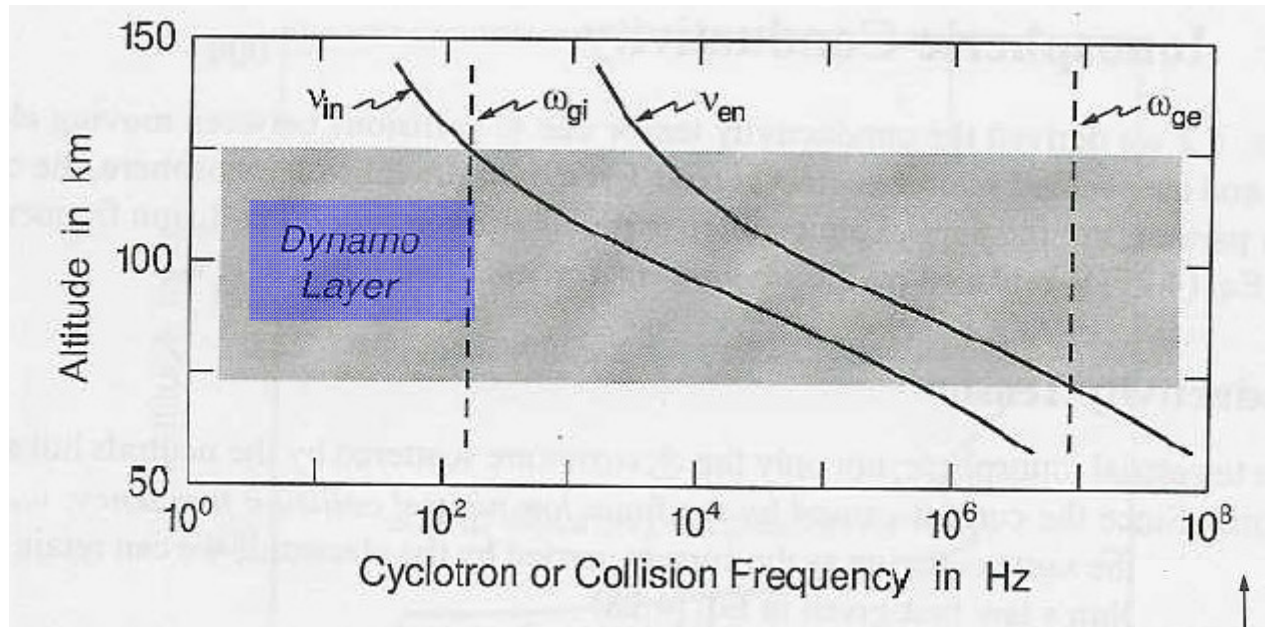


Fig. 1.2. International Quiet Solar Year (IQSY) daytime atmospheric composition, based on mass spectrometer measurements above White Sands, New Mexico (32°N, 106°W). The helium distribution is from a nighttime measurement. Distributions above 250 km are from the Elektron II satellite results of Istomin (1966) and Explorer XVII results of Reber and Nicolet (1965). [C. Y. Johnson, U.S. Naval Research Laboratory, Washington, D.C. Reprinted from Johnson (1969) by permission of the MIT Press, Cambridge, Massachusetts. Copyright 1969 by MIT.]

Collisions with *neutral* ptls



$$\omega_{ci} \ll v_{in} \ll v_{en} \ll \omega_{ce}$$

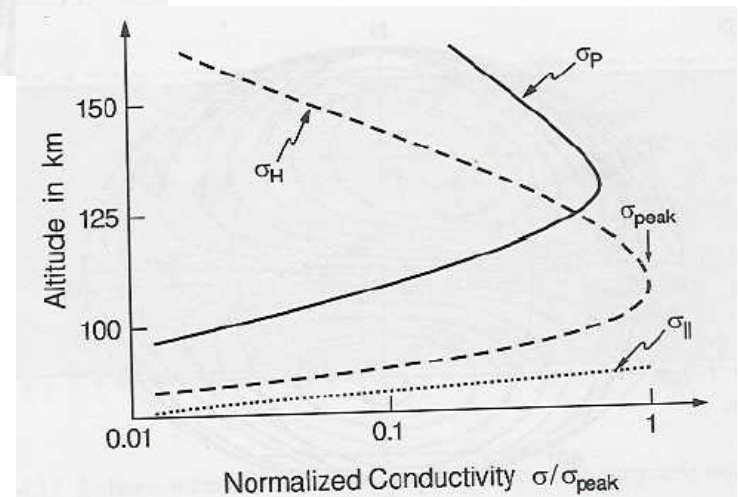
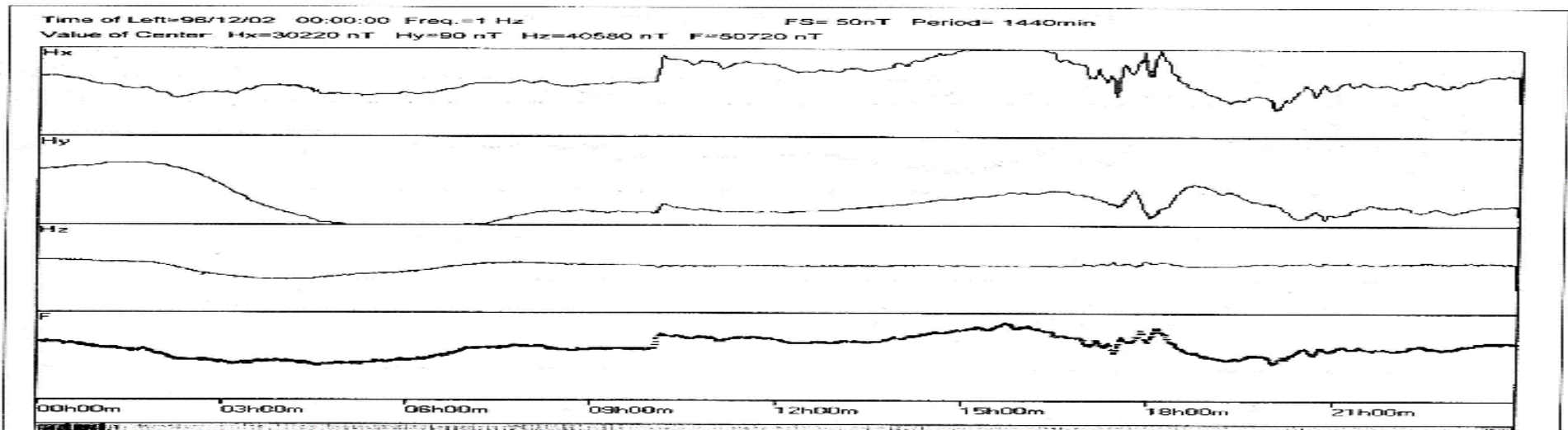
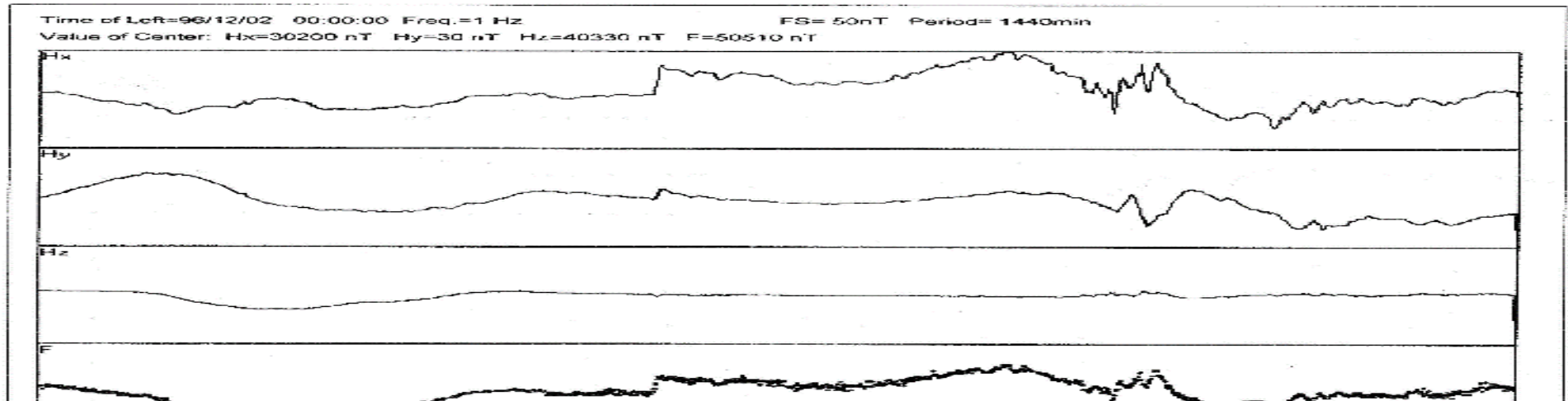


Fig. 4.11. Height profiles of normalized conductivities.

(After Baumjohann & Treumann, 1996)

* CME observations at the two near-by stations (< 60km)

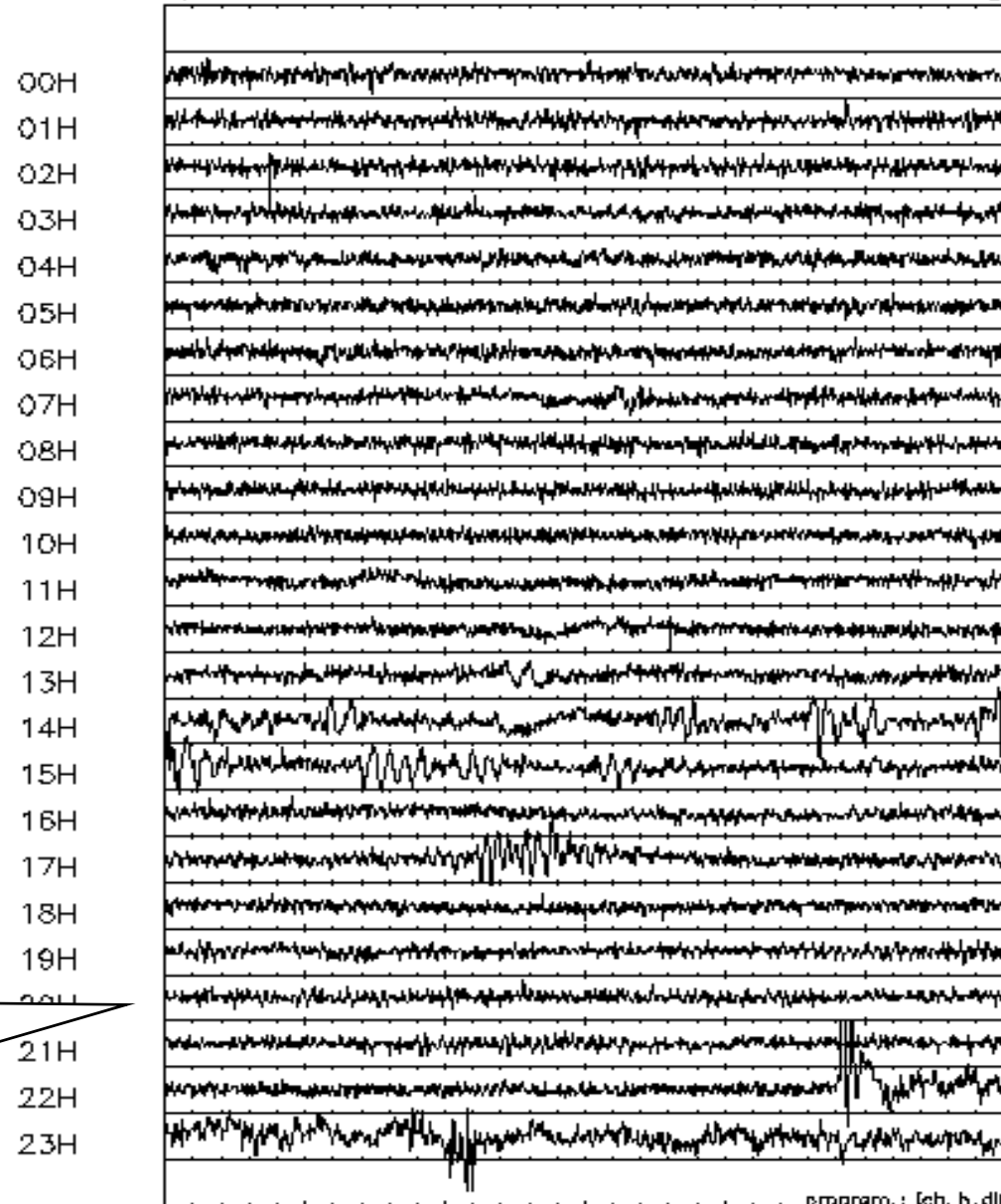
• 1996.12.02 09:30 - 10:30(UT) at Icheon, Yongin station



Magnetic Field Data of Branch of RRL
ICHON (dH/dT-comp) 97/11/06
Compensation Field 30250 nT 0.25 nT/di(4sec averaged)

- daily variations

97/11/06
이천 전파연구소
관측자료

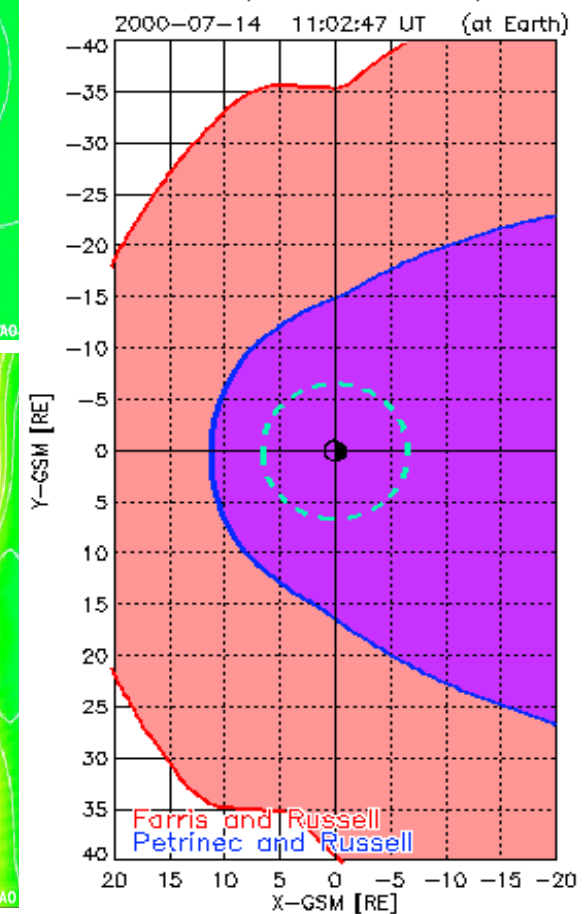
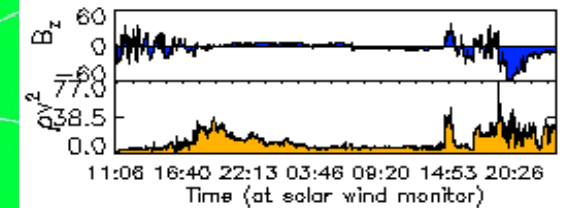
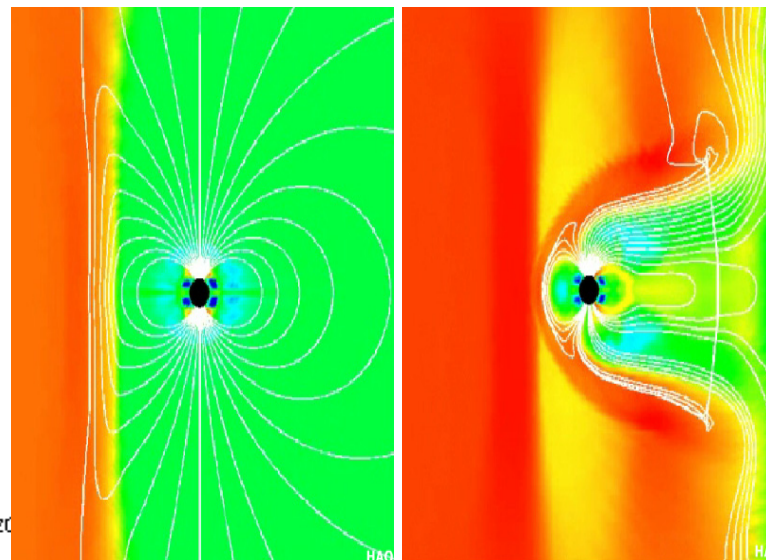
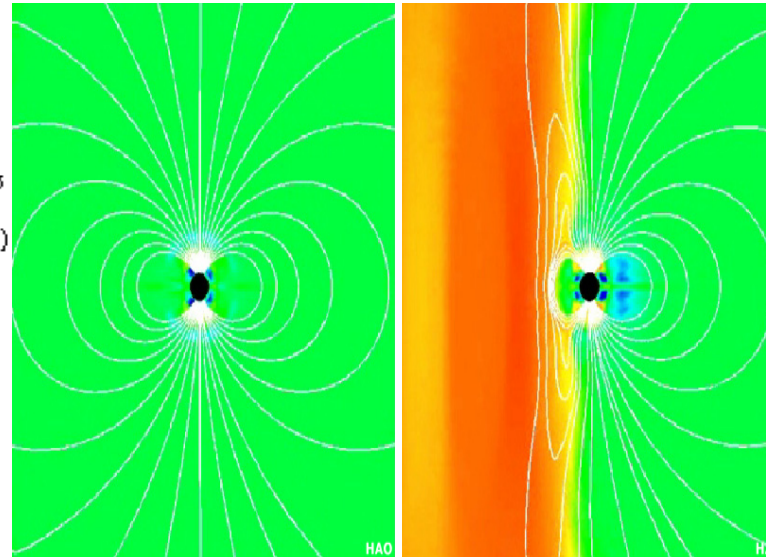
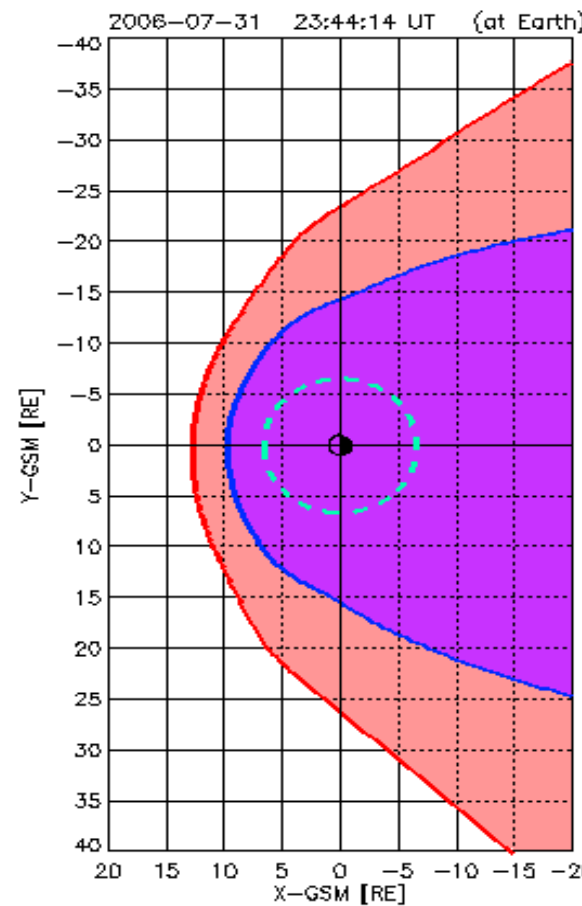
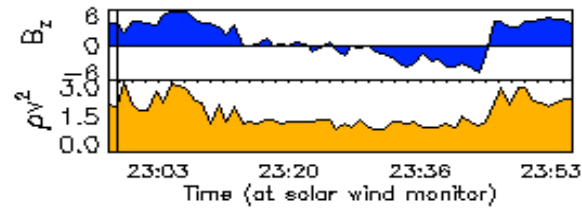


Application - Magnetospheric dynamics

□ 2006년 7월 31일(평온)

[Petrinec, 1994]

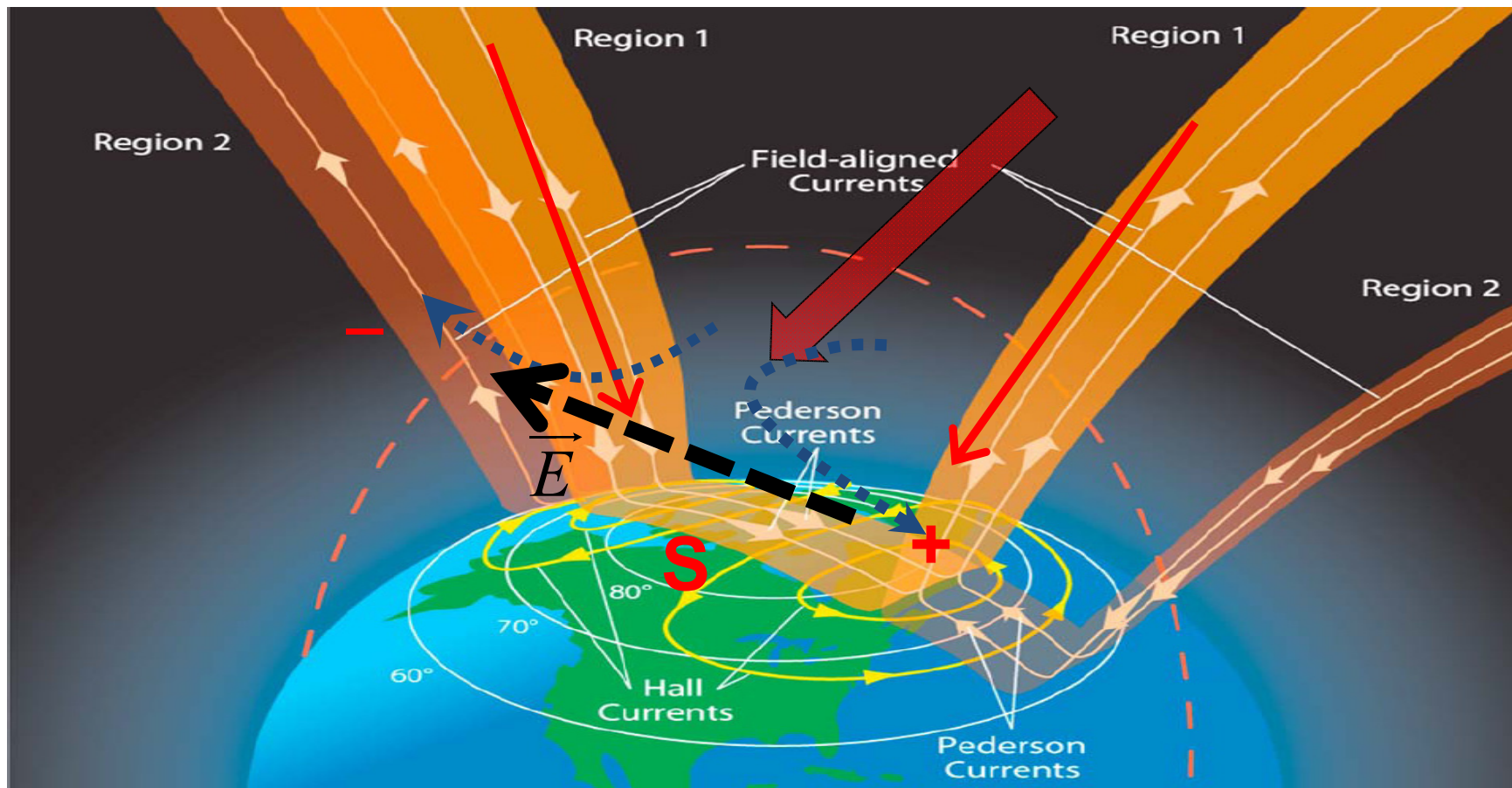
□ 2000년 7월 14일



Application - Magnetospheric dynamics

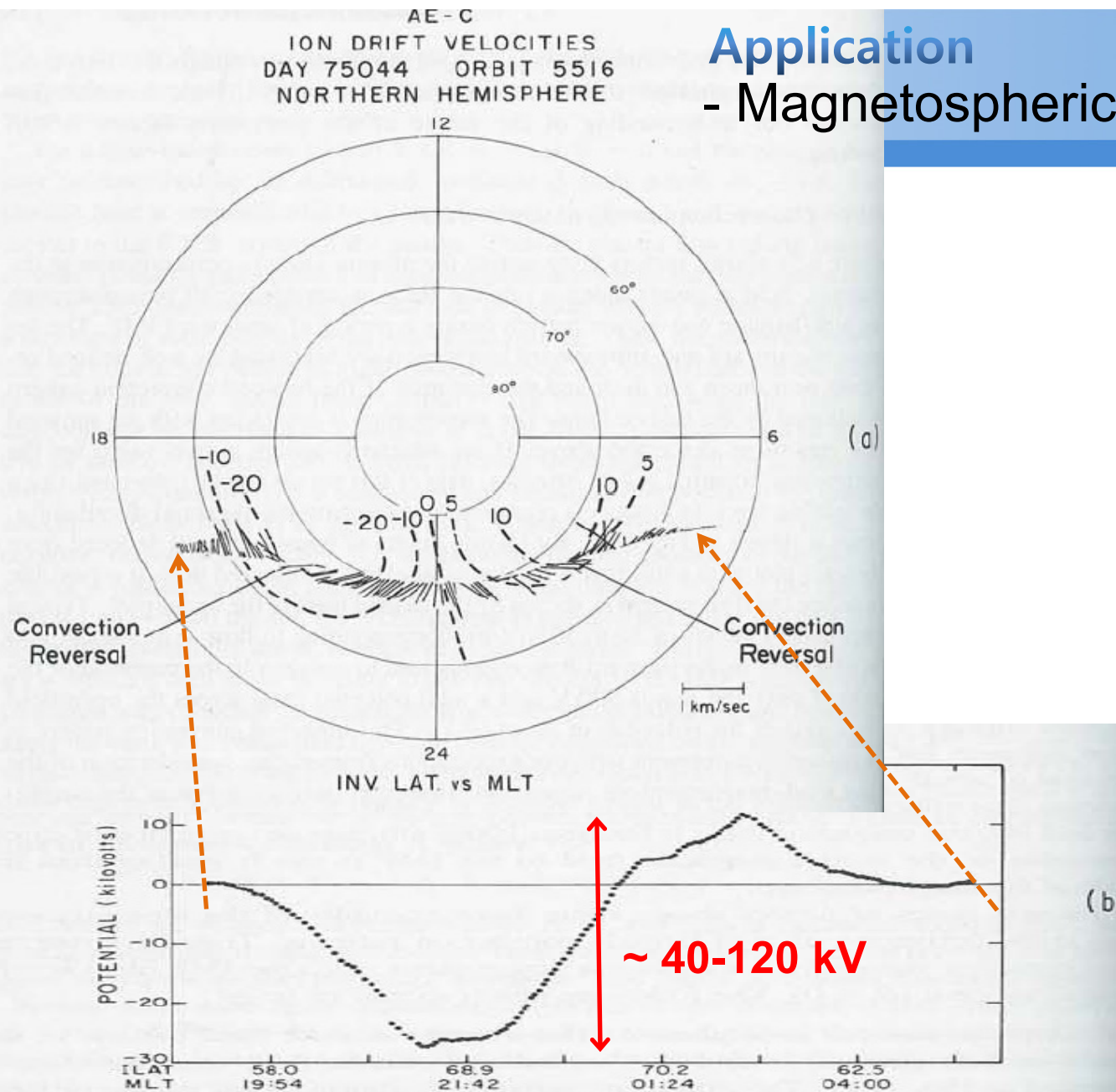
* **MHD Dynamo:** $\vec{E} + \vec{V} \times \vec{B} = 0$ (*ideal MHD eq.*)

- **EM energy generates mechanical energy** *or*
- **Mechanical energy generates EM energy**

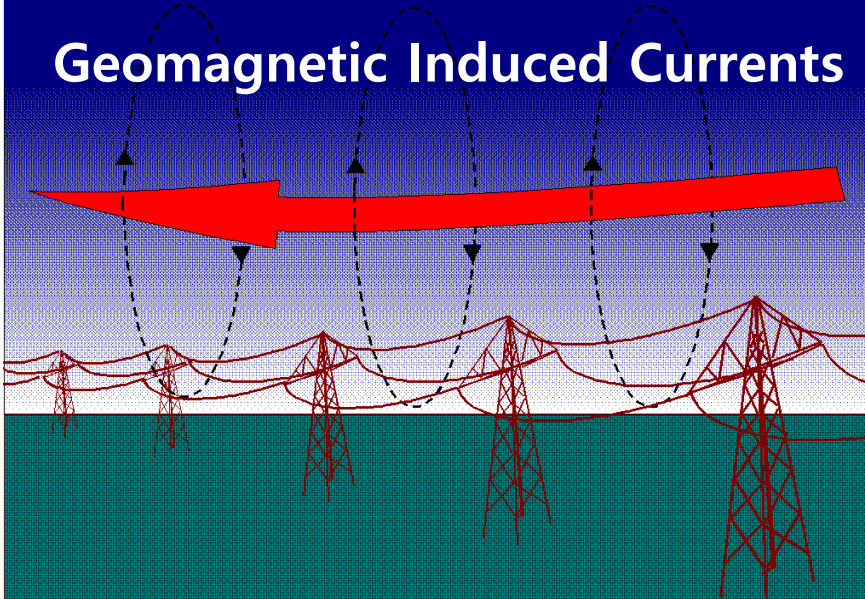


Application

- Magnetospheric dynamics



Geomagnetic Induced Currents



1989.3.13

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EARLY ED
The Gazette
 MONTREAL TUESDAY MARCH 14, 1989 50¢

"Do not wait for extraordinary circumstances to do good; try to use ordinary situations."
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We're sorry for the delay

Yesterday's power failure may have delayed delivery of your paper. We're sorry. Before the blackout hit at 2:45 a.m., The Gazette had printed 125,000 copies. After power returned at 1:30 p.m., another 60,000 copies containing coverage of the blackout were printed for delivery to homes and stores. About 70 per cent of subscribers received their copies at the morning as usual.

Hydro will be kept on short leash: Bourassa

By SARAH SCOTT
 Gazette Quebec Bureau
 QUEBEC — The government will keep Hydro-Québec on a short leash, Premier Robert Bourassa said yesterday after calling on officials of the giant utility to account for the second province-wide blackout in a year. Hydro will have to report monthly to the province on the progress of its \$1-billion plan to halve the number of yearly blackouts by 1991, Bourassa said. And the utility will have to speed up its plan to make the system more reliable, he said after meeting Hydro chairman Richard Drouin and president Claude Boudreux.

Bourassa observed, however, that technical problems could prevent any significant spending up of the plan. The plan calls for Hydro to spend \$700 million over seven years to upgrade the distribution system and \$1.3 billion by 1994 on transmission facilities for power from the northern hydroelectric dams. In 1988, the average Quebecer sat in the dark for 9.1 hours due to power failures, including 100 province-wide blackouts last April. Between 1981 and 1988, the average

was 5.5 hours a year. Parti Québécois energy critic Christian Claveau charged that Hydro is spending too much time and money on producing electricity for export to the United States and neglecting maintenance on its own system. Bourassa wants Quebec to export 12,000 megawatts of power and said so frequently before and after he was elected. But so far only 2,250 megawatts of firm long-term power have been sold, including a deal with Maine which hasn't yet received regulatory approval by the state. Claveau called for a "complete moratorium" on contracts to export Quebec hydro-electricity.

Bourassa agreed that Hydro's reduced maintenance spending is responsible for the increased number of blackouts in recent years, but he rejected Claveau's other criticisms. "We know very well that none of the contracts that were signed — except surplus sales and contracts signed before we came to power — call for delivery before 1995 or 1996. So how can you talk deliveries that won't happen until 1995 to a lack of electric power in 1989?"

Hydro blames sun for power failure



It says solar storm overloaded system

By PEGGY CURRAN
 of The Gazette

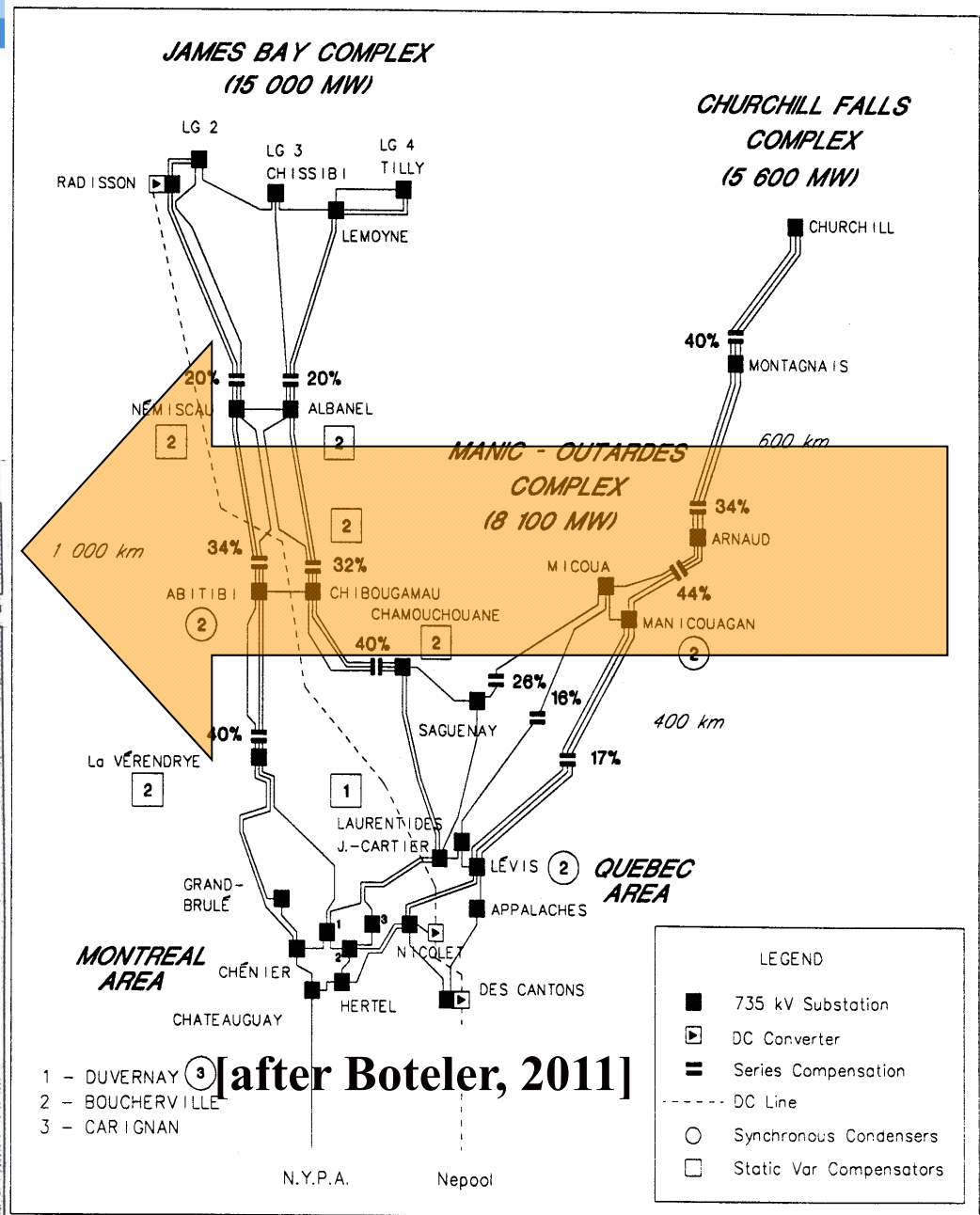
Hydro-Québec is blaming yesterday's massive power failure on the sun. Officials at the utility are citing a magnetic storm — touched off by an explosion on the sun and marked by a spectacular display of the northern lights — as the main culprit in the third province-wide blackout in less than a year. Scientists at the National Research Council in Ottawa say they recorded the strongest pulse in the earth's magnetic field in a decade of 14.8 a.m. yesterday.

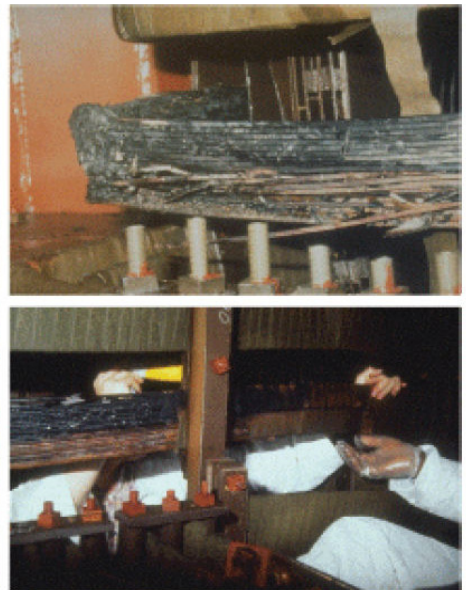
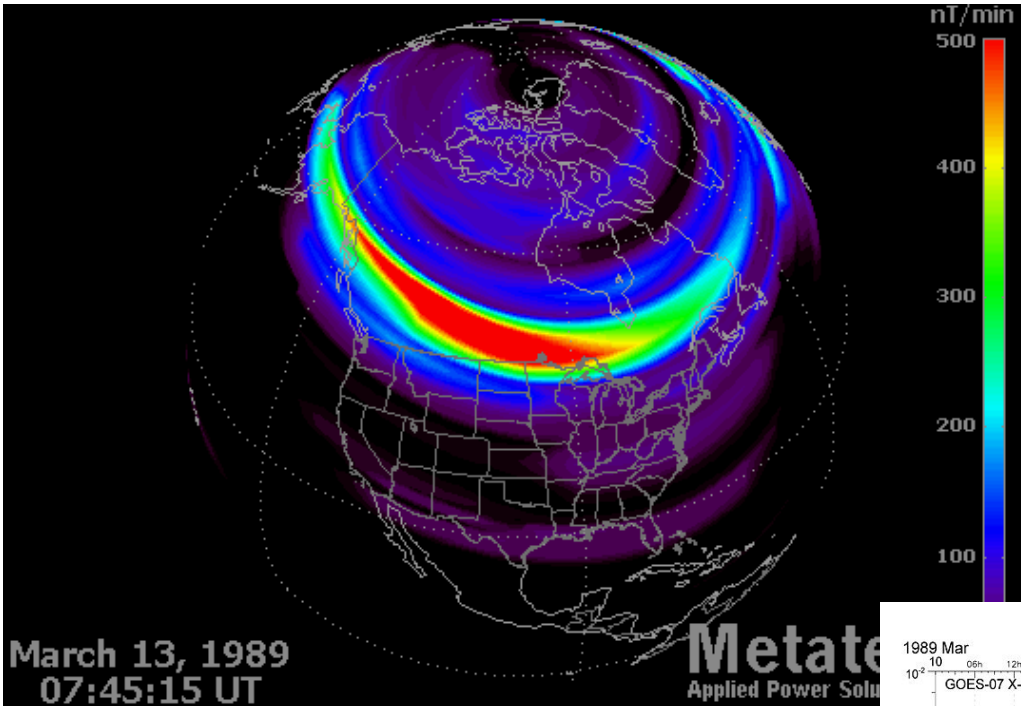
Giant generator
 That's was about two minutes after the lights went out across the province. Ken Tapping, a solar physicist at the NRC, said the magnetic charge acted like a giant solar generator causing transmission lines to overload.

Disruptions in the magnetic field also played havoc with power lines in British Columbia and Ontario. But Quebec was by far the hardest hit. That's because the province's vast hydroelectric system extends farther north and because all Hydro-Québec's transmission lines are connecting. Now Hydro officials say they may have to abandon the province's "unique" grid system if they

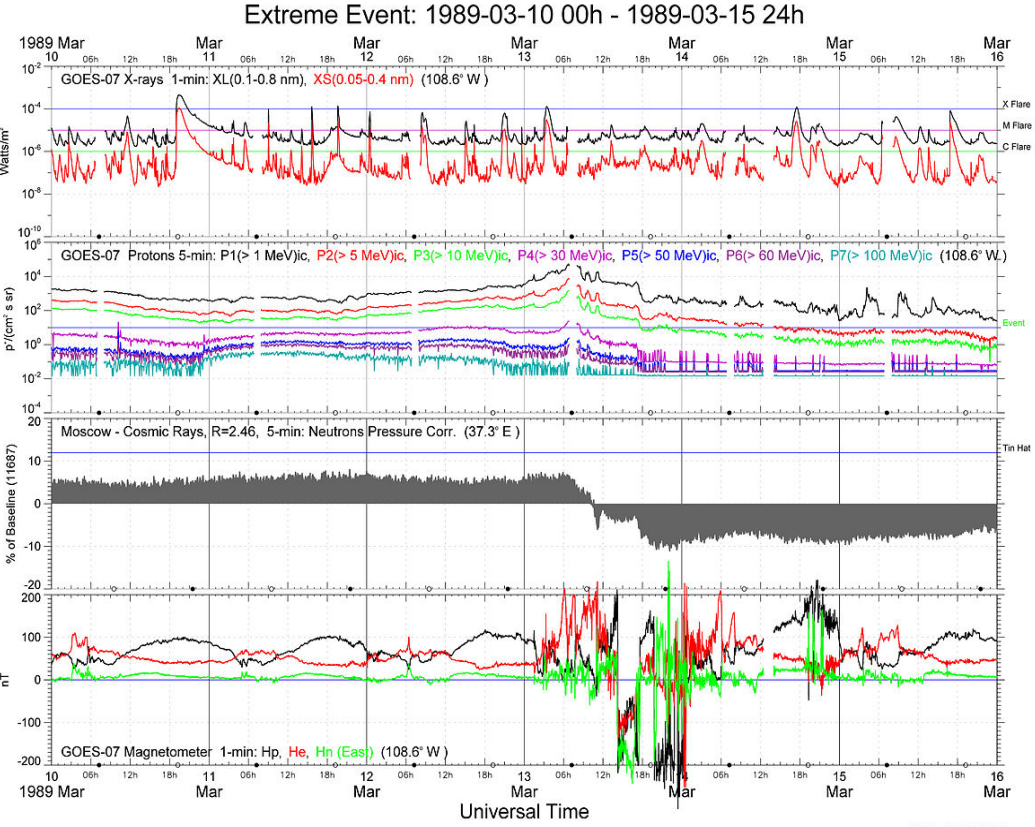


Hydro-Québec ran into problems everywhere yesterday. Hoping to regain public confidence, the utility has promised to spend \$704 million on new equipment over the next few years. Energy Minister John Claveau suggested labor problems at Hydro may have contributed to yesterday's blackout. But some officials said the power failure was the result of Hydro scrapping maintenance at 5 a.m. with a total blackout. By 10 a.m., power had been restored to about 50 per cent of Hydro customers in the Montreal region. By evening, power had been restored to all but about 25,000 of the utility's 842,000 customers on the island. But Hydro official Michel Turcotte warned clients to expect



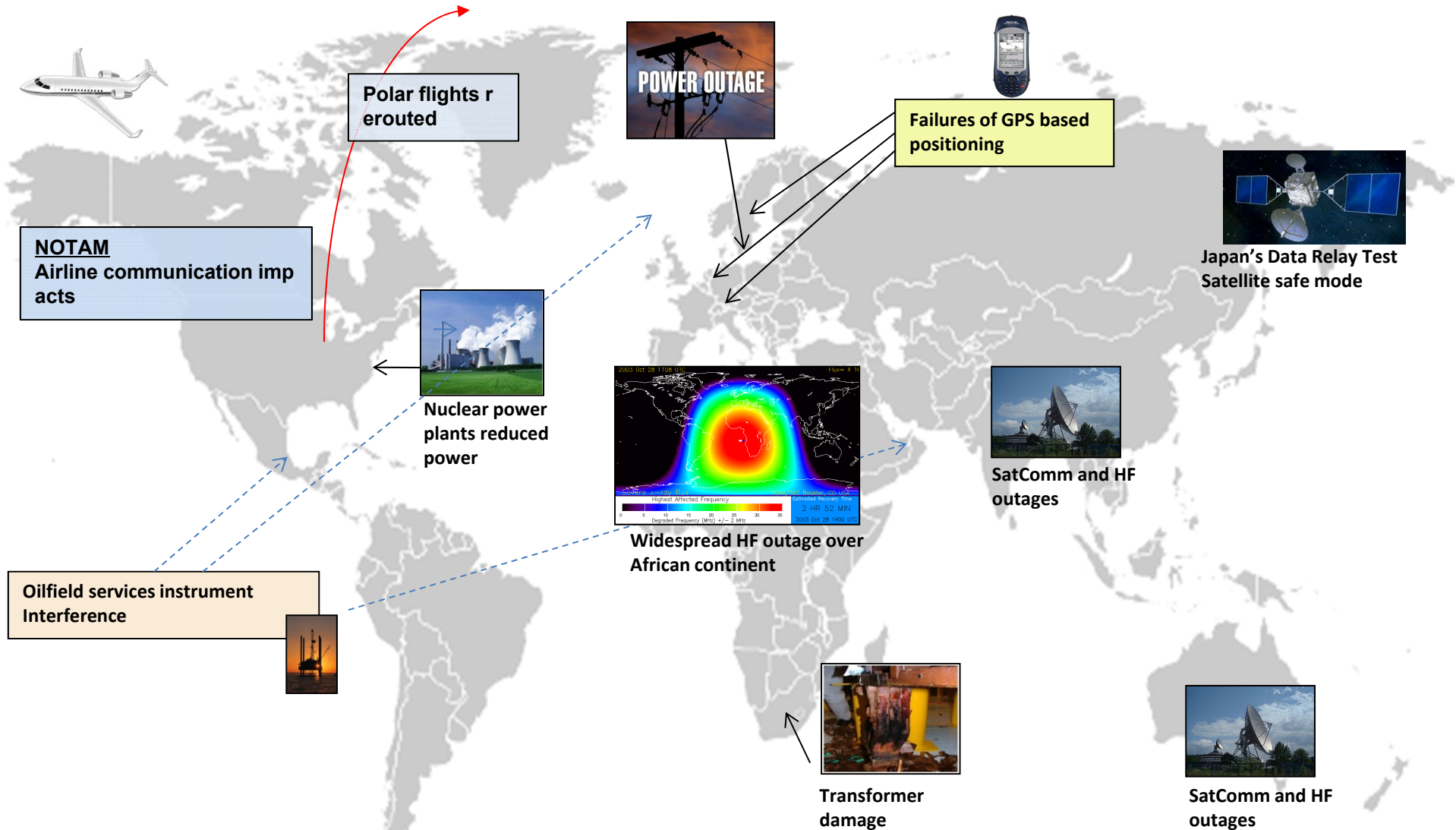


POWER SYSTEM EVENTS DUE TO SMD MARCH 13, 1989



Space Weather: Global feature

Reported impacts from a storm in October, 2003



Over 130 hours of HF communication blackout in Anarctic



ISES

International Space Environment Service



ISES | URSIgram Codes | Reports | **Regional Warning Centres** | Info | Geo-Calendar

Regional Warning Centres

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Japan (Tokyo)



<http://www.spaceweather.org/>

Summary

- The near-Earth space provides a broad range of temporal and spatial phenomena from single-ptl to MHD, which can be confirmed in *in situ* observations.
- MHD disturbances & waves tend to effectively affect geomagnetic variations in the sense that relatively large-scale EM variations occur with considerable amplitude.
- In terms of spatial and temporal scales over CLIC's criterion, it seems that natural sources from "Space" such as $dB \sim nT$ over $dT \sim 1$ sec can be well incorporated (Space Weather should be monitored, though).
- In addition, local conductivity variation should be checked in advance by comparing $B(t)$ at the two "Ground" ends.

Legend

— CERN existing LHC

Potential underground siting :

●●●● CLIC 380 GeV

●●●● CLIC 1.5 TeV

●●●● CLIC 3 TeV

