Plasma Waves in the Radiation Belts of Earth and Jupiter

Richard B. Horne
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Invited talk, 42nd IoP Plasma Physics Conference, Milton Keynes, 1st April 2015.

Outline

- Plasma waves in the Earth's magnetosphere
- Diffusion rates and electron acceleration
- Application - space weather forecasting
- Wave acceleration at Jupiter
- Wave acceleration at Saturn

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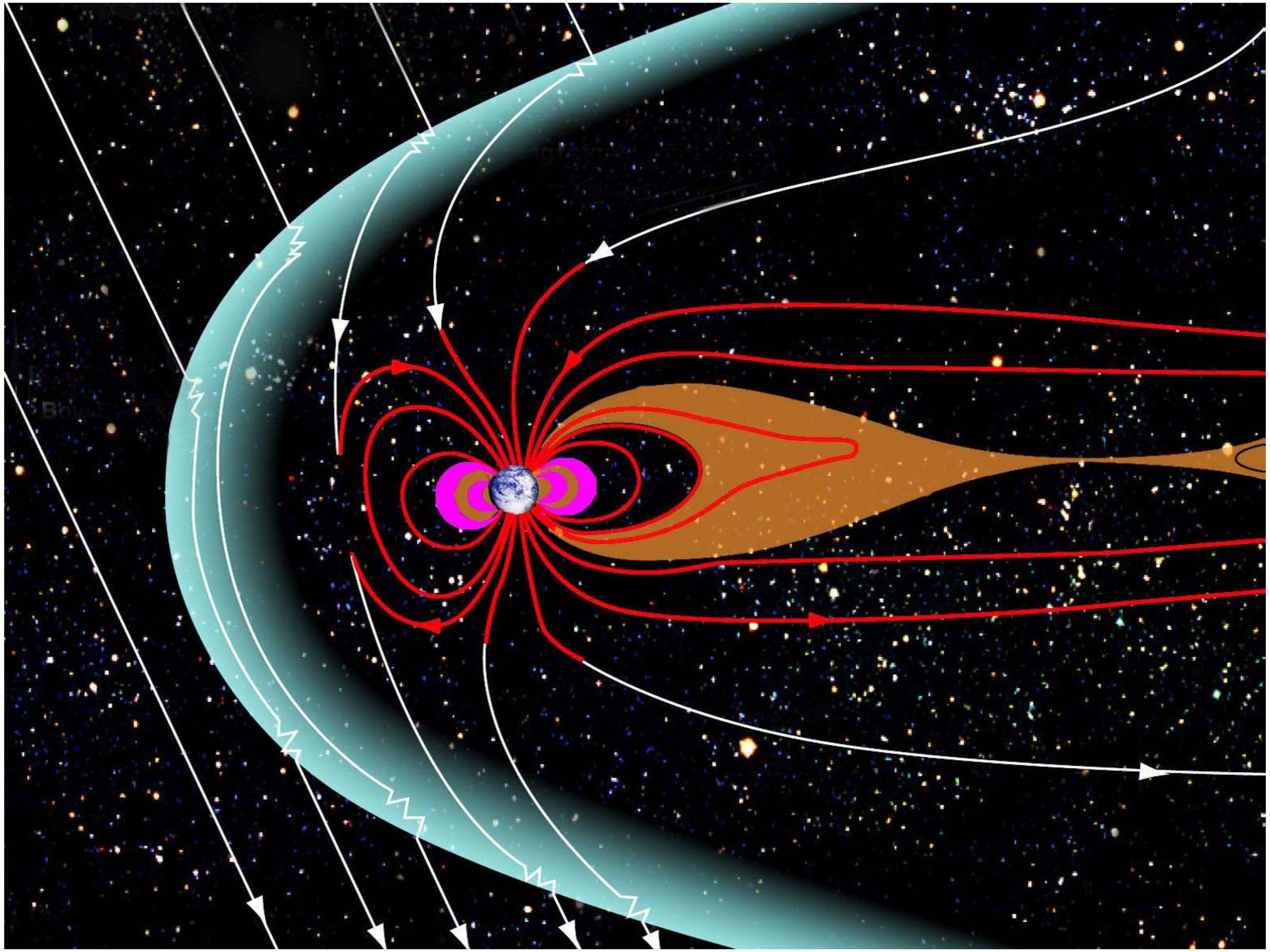
The Earth's Magnetosphere



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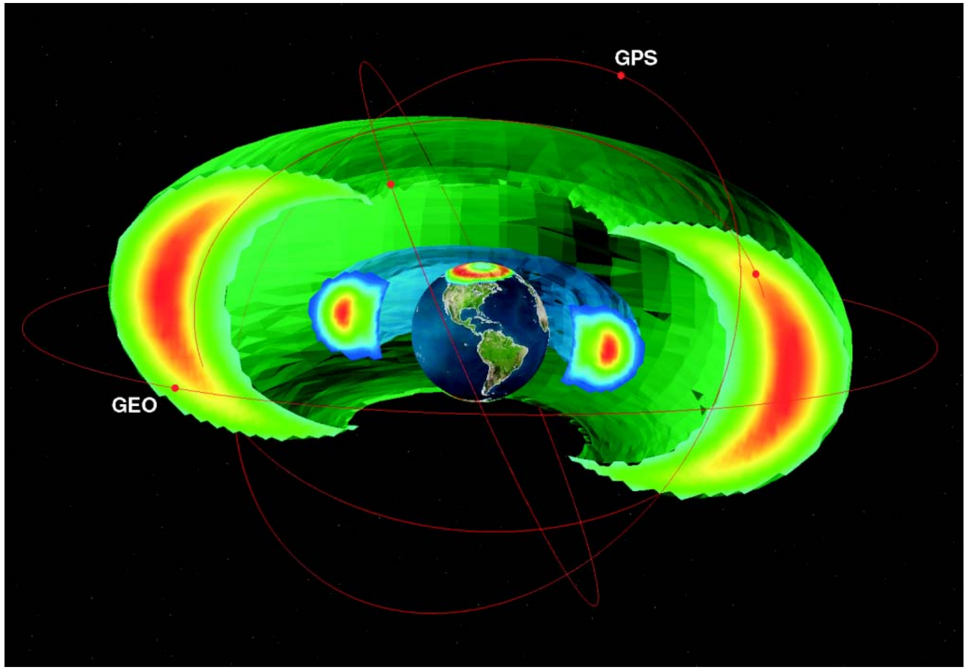
Earth's Radiation Belts

- Electrons and ions trapped inside the magnetic field
- Only one proton belt
- Two electron belts
  - Energies > 1 MeV
  - Peaks near 1.6 and 4.5 Re
- Outer electron belt highly variable
- Hazardous for spacecraft and humans



- Extend to Geostationary orbit
- GPS + Galileo satellites fly through the heart of the radiation belts

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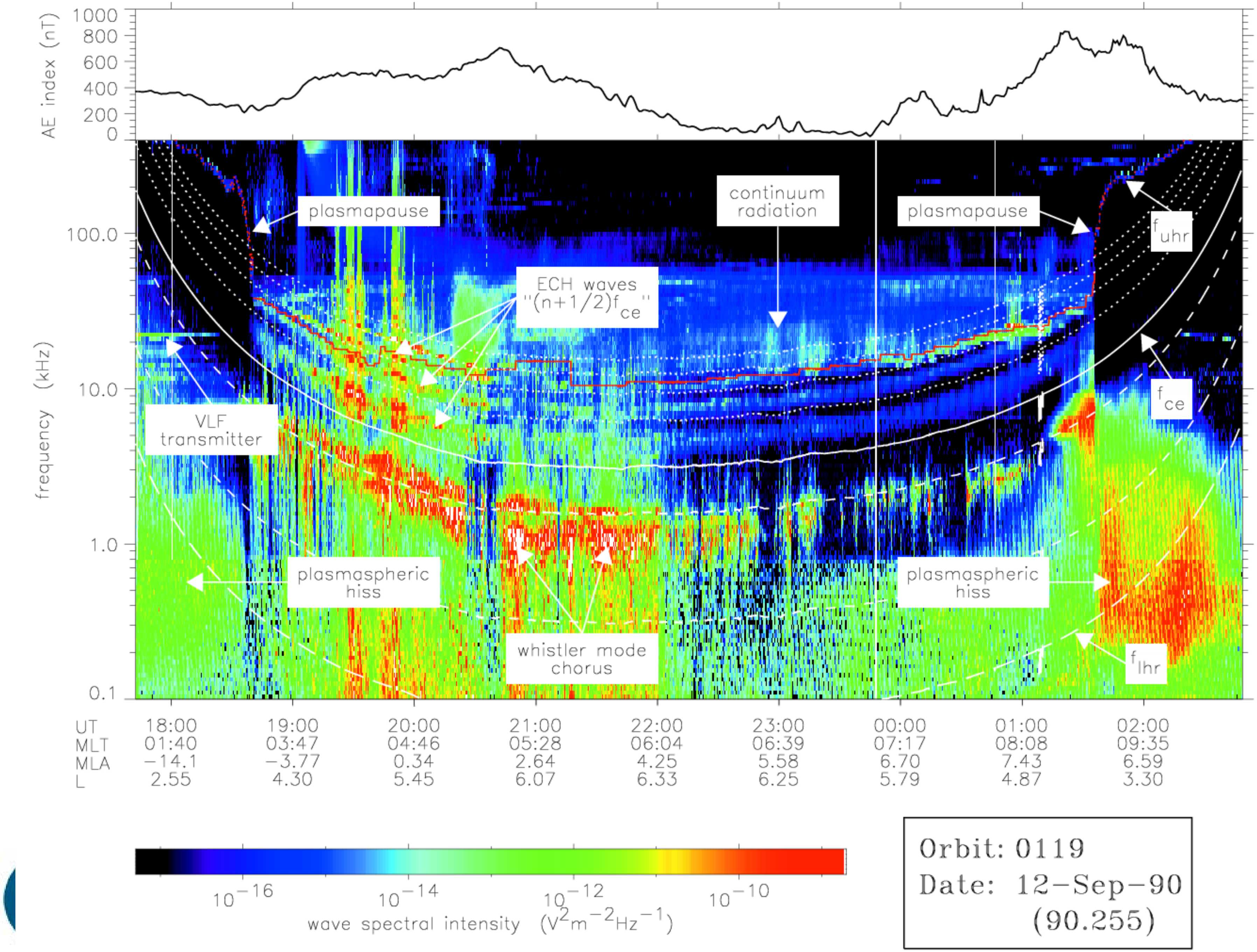
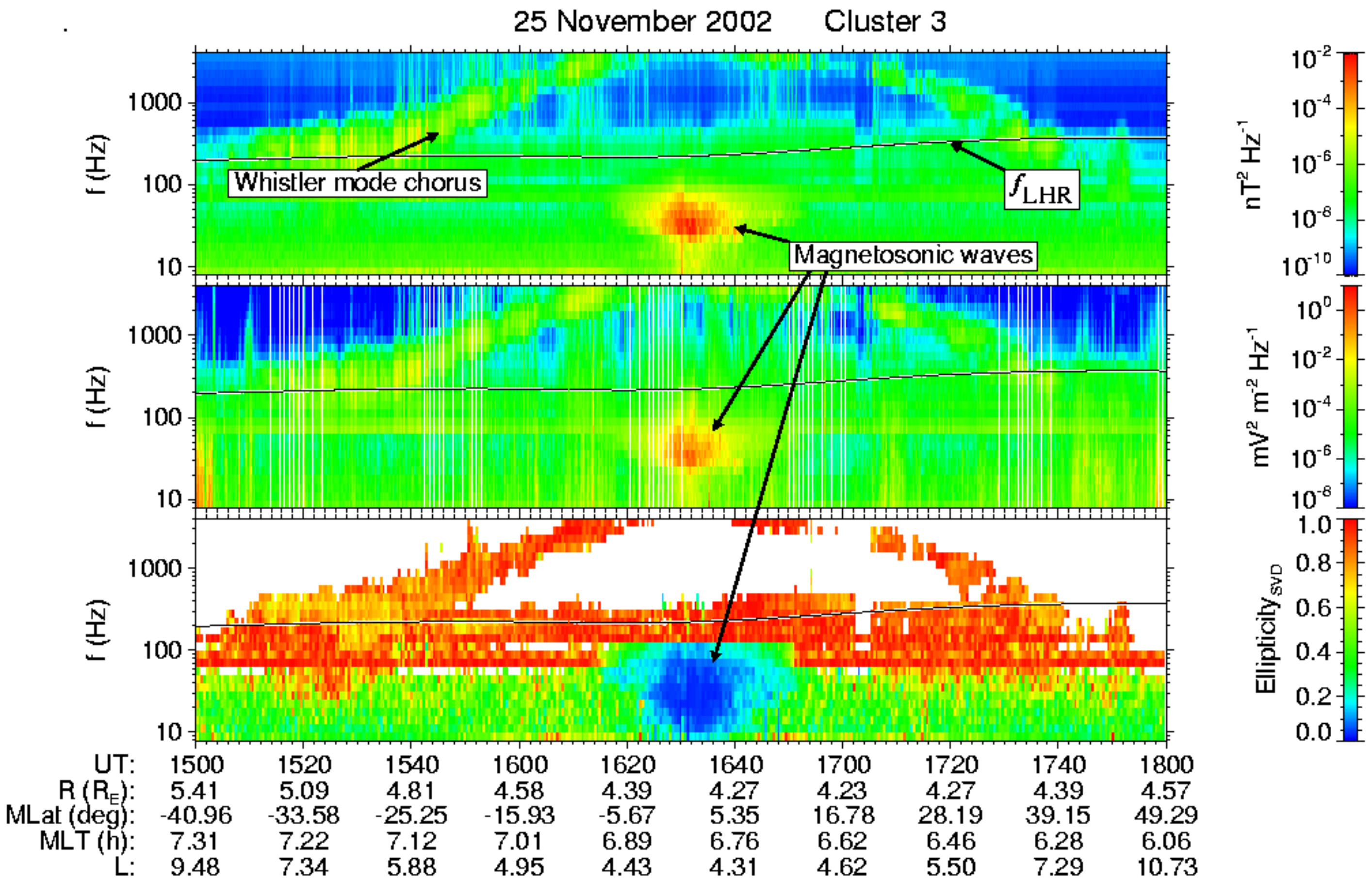


AE index (nT)
1000
800
600
400
200
0
frequency (kHz)
100.0
10.0
1.0
0.1
plasmapause
continuum radiation
plasmapause
ECH waves "(n+1/2)fce"
f uhr
VLF transmitter
f ce
plasmaspheric hiss
plasmaspheric hiss
whistler mode chorus
f lhr
UT 18:00 19:00 20:00 21:00 22:00 23:00 00:00 01:00 02:00
MLT 01:40 03:47 04:46 05:28 06:04 06:39 07:17 08:08 09:35
MLA −14.1 −3.77 0.34 2.64 4.25 5.58 6.70 7.43 6.59
L 2.55 4.30 5.45 6.07 6.33 6.25 5.79 4.87 3.30
10−16 10−14 10−12 10−10
wave spectral intensity (V2m−2Hz−1)
Orbit: 0119
Date: 12−Sep−90
(90.255)

Magnetosonic Waves



- **Propagate across Bo, fcH < f < fLHR**
- **Fine structure - harmonics of fcH+**
- **Generated by proton ring distributions**

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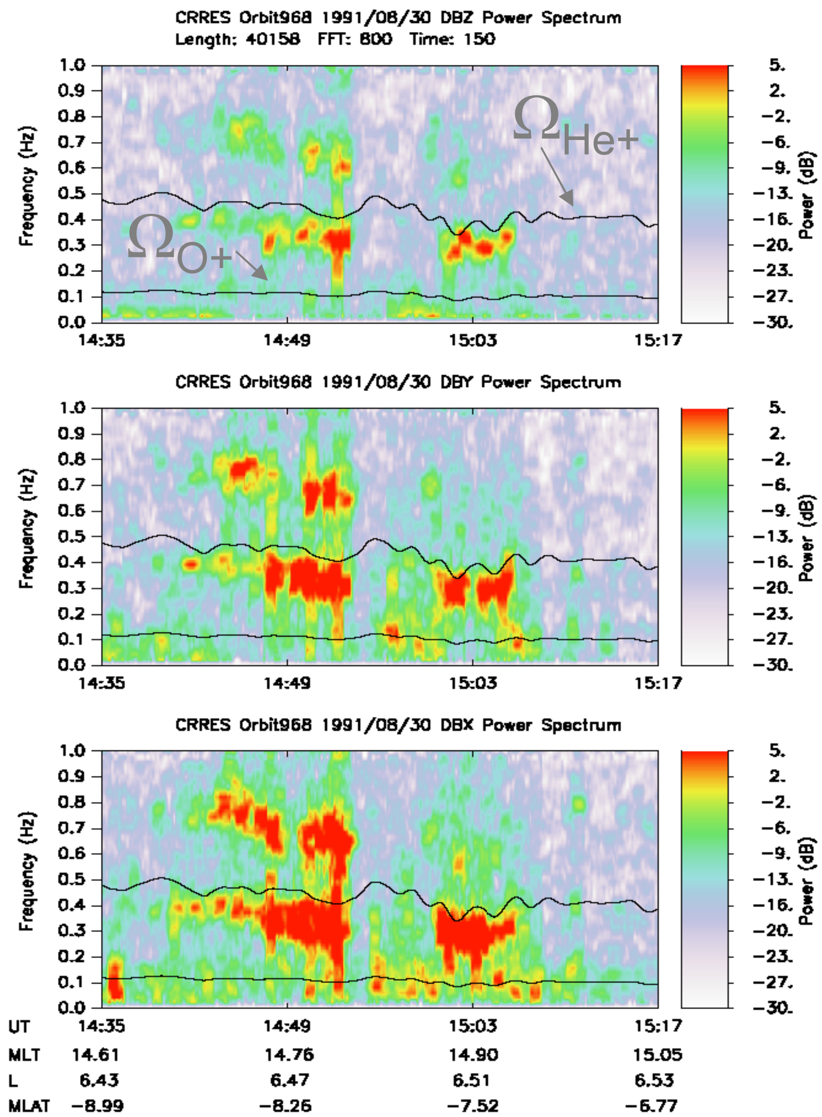
Electromagnetic Ion Cyclotron Waves

- Generated by unstable ion distributions, H+, He+, O+ of 1 – few hundred keV
- Associated with ring current injection
- Resonate with MeV electrons, causing precipitation
- Ion composition causes frequency stop bands, polarisation reversal, and unusual propagation



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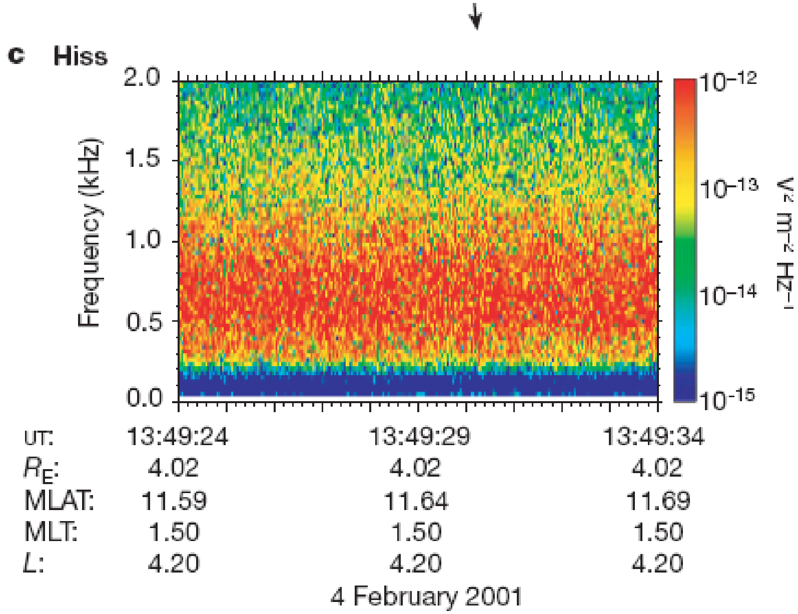
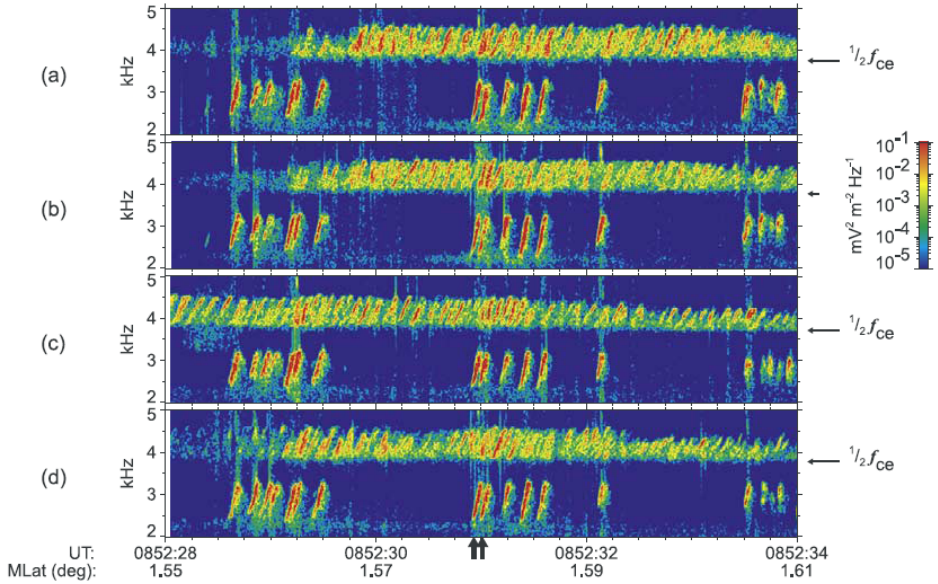
Whistler Mode Hiss and Chorus Waves





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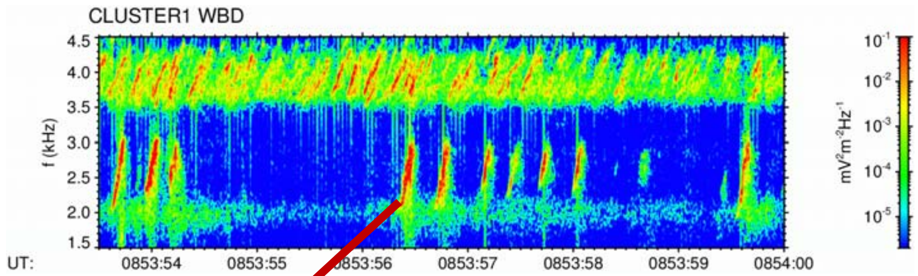
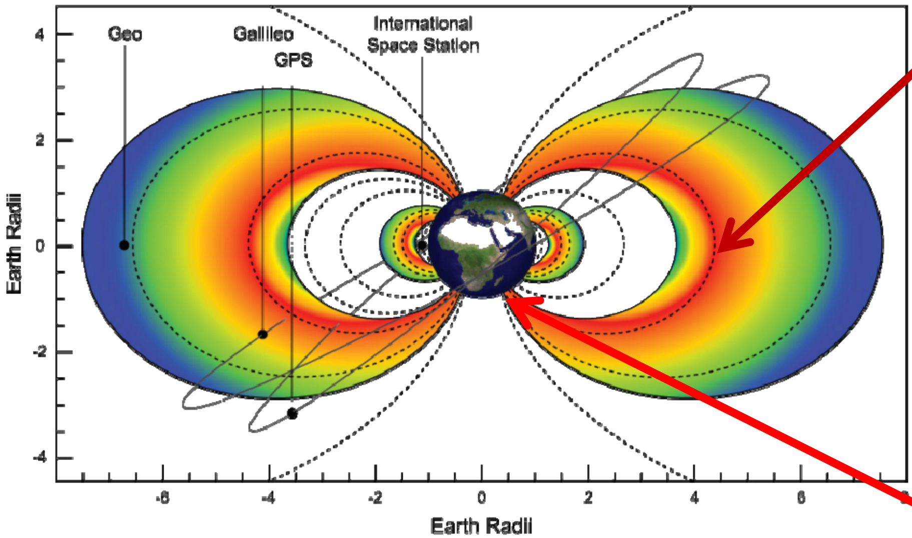
Antarctica - Space

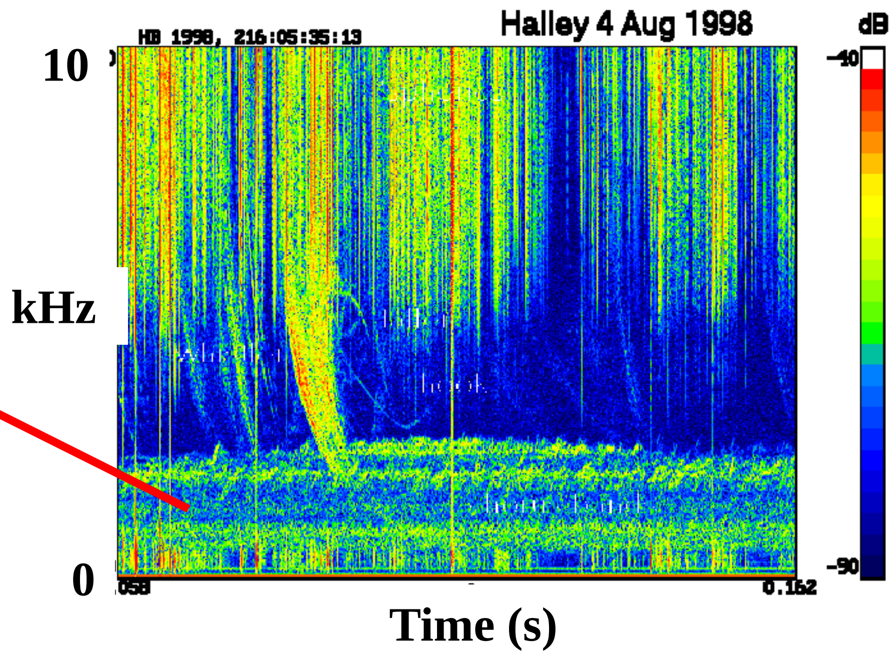
- Antarctica – observe very low frequency radio waves
- Most originate in space
- We have shown they accelerate electrons and form the radiation belts
- Changed ideas going back 40 years



Satellite observations



Antarctic observations



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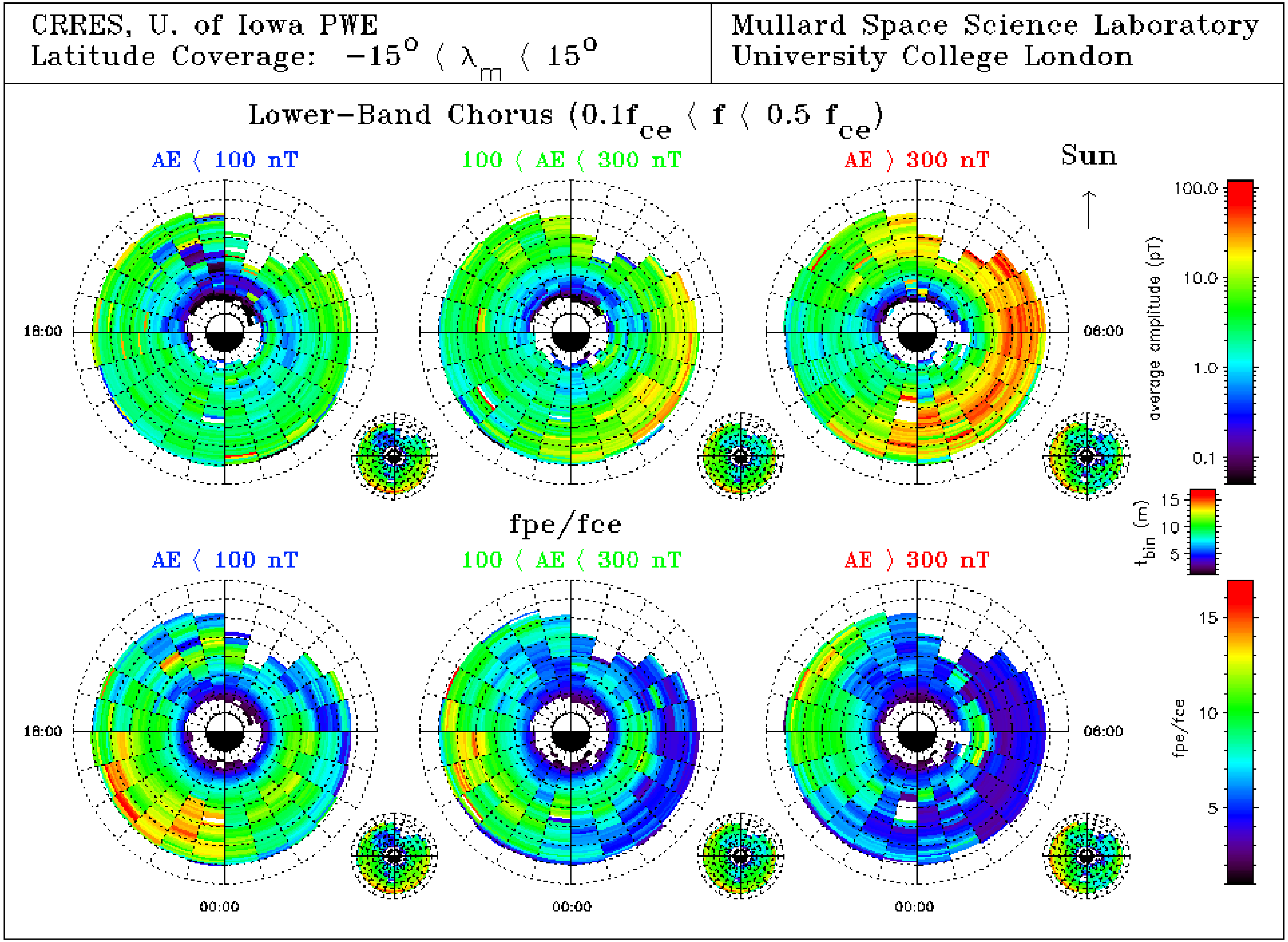

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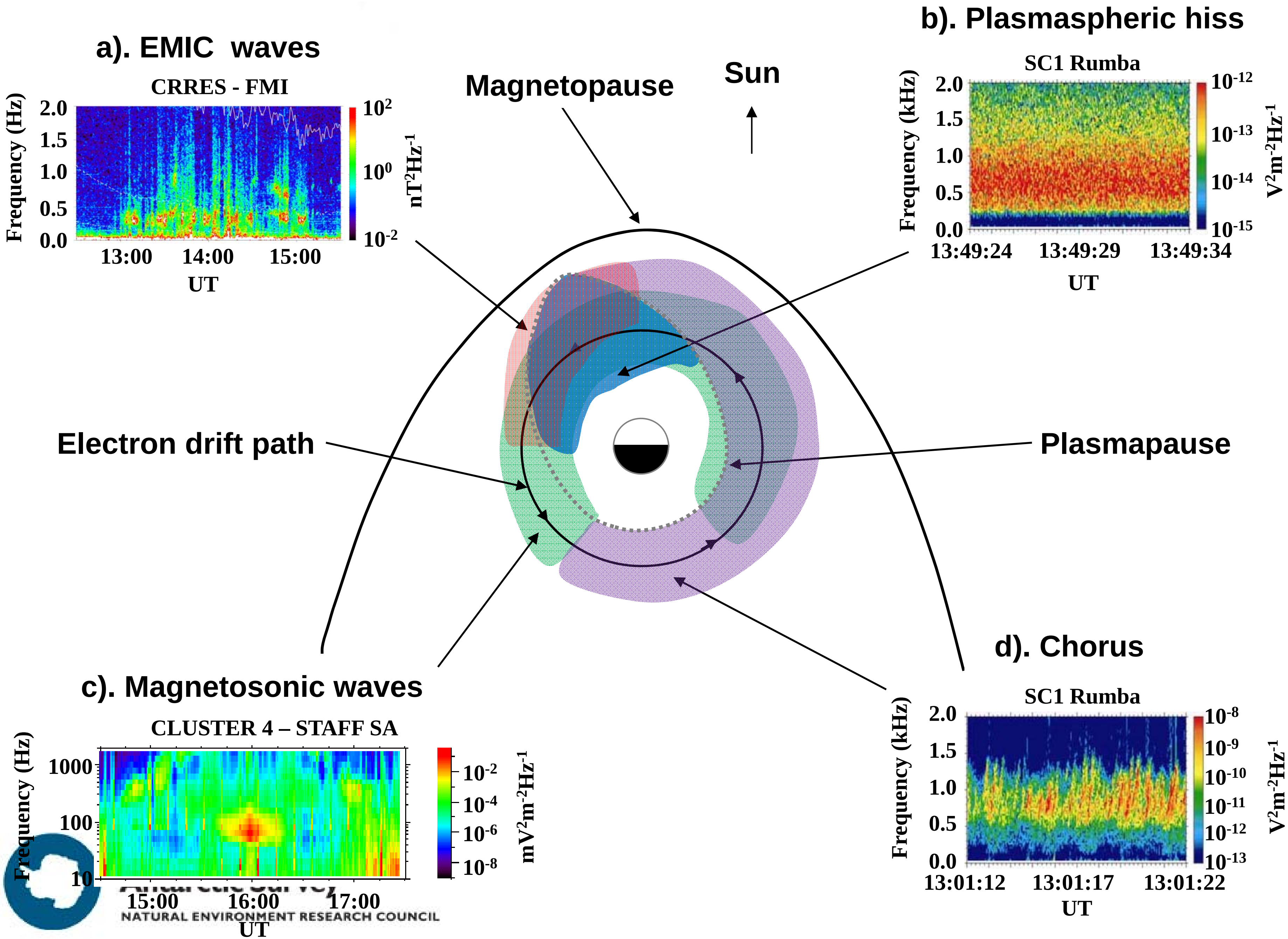
Meredith et al. [2002]


a). EMIC waves
CRRES - FMI
Frequency (Hz)
2.0
1.5
1.0
0.5
0.0
13:00
14:00
15:00
UT
nT²Hz⁻¹
b). Plasmaspheric hiss
SC1 Rumba
Frequency (kHz)
13:49:24
13:49:29
13:49:34
UT
V²m⁻²Hz⁻¹
Magnetopause
Sun
Electron drift path
Plasmapause
c). Magnetosonic waves
CLUSTER 4 – STAFF SA
1000
100
10
15:00
16:00
17:00
UT
mV²m⁻²Hz⁻¹
d). Chorus
SC1 Rumba
13:01:12
13:01:17
13:01:22
UT
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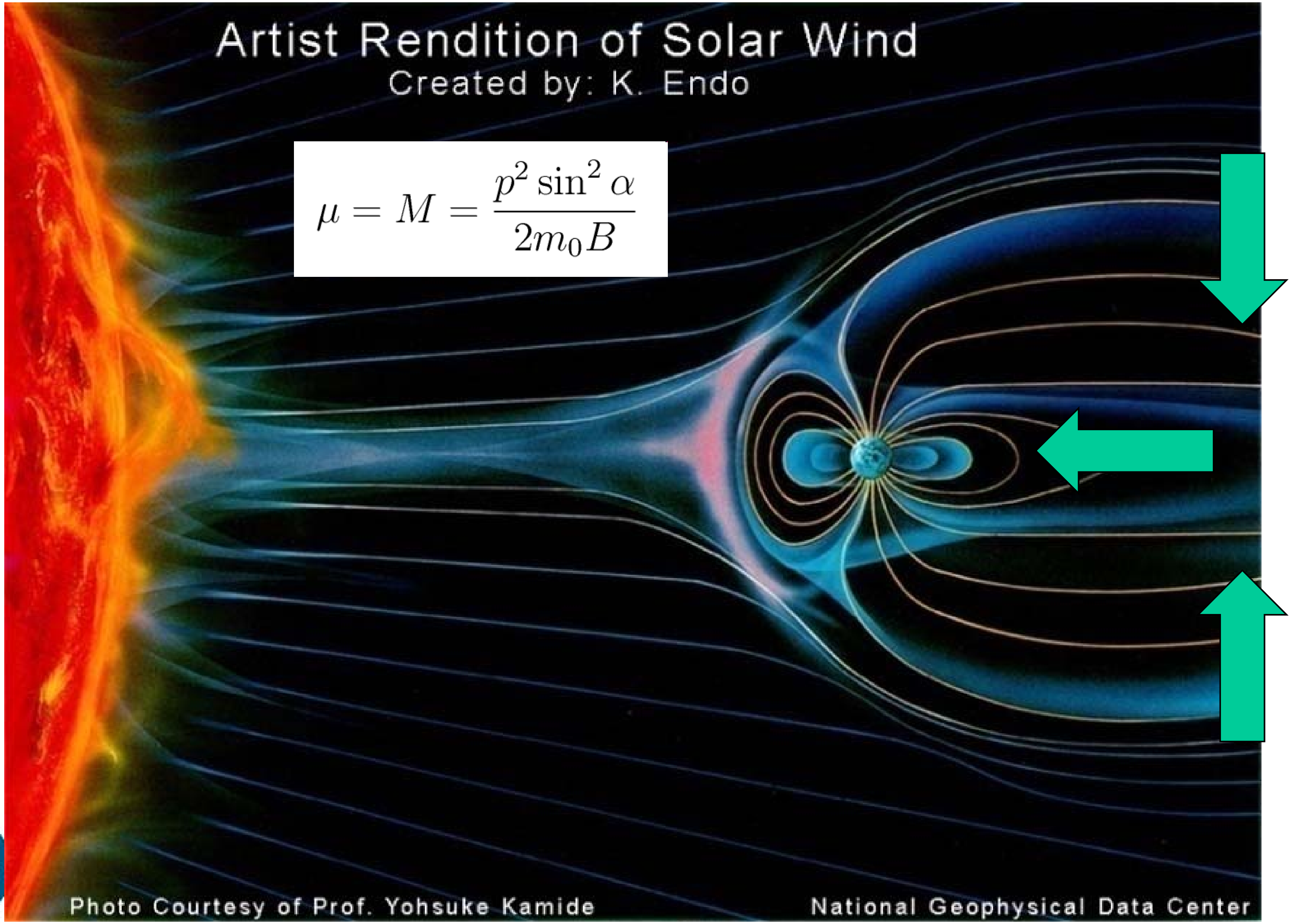
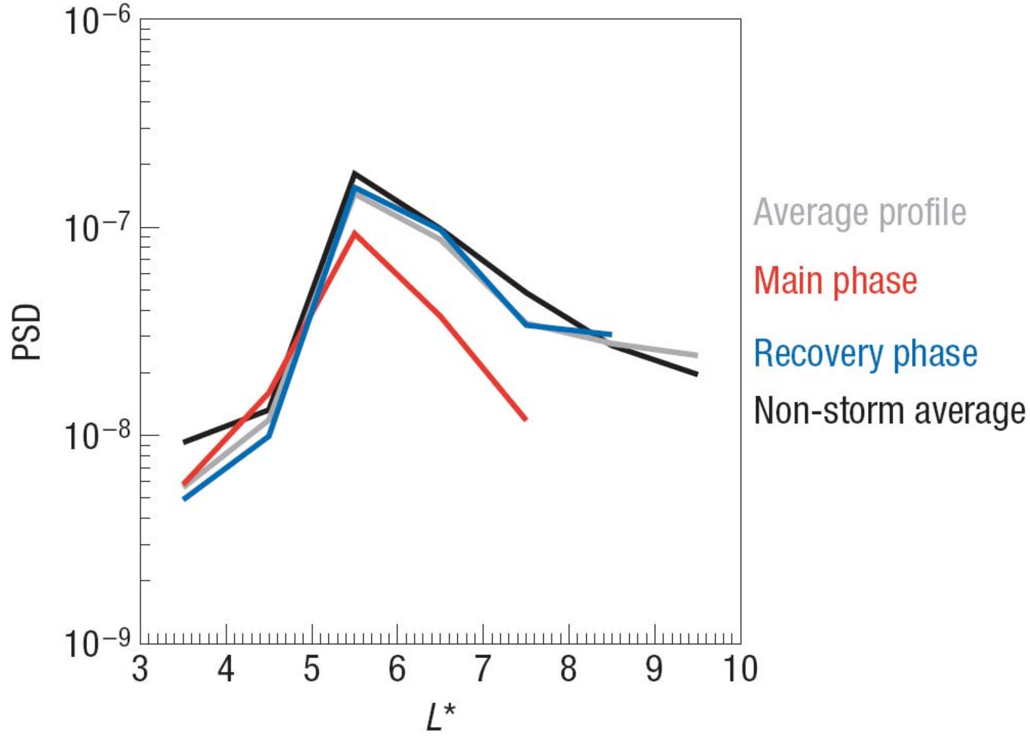
Radiation Belt Formation – Original Idea



$$\mu = M = \frac{p^2 \sin^2 \alpha}{2 m_0 B}$$

Electron Phase Space Density

M = 2083 MeV/Gauss



- BUT
- Peak does not support radial diffusion from a source in the outer magnetosphere
- Suggests a new "local" acceleration mechanism

Chen et al., *Nature Physics,* [2007]

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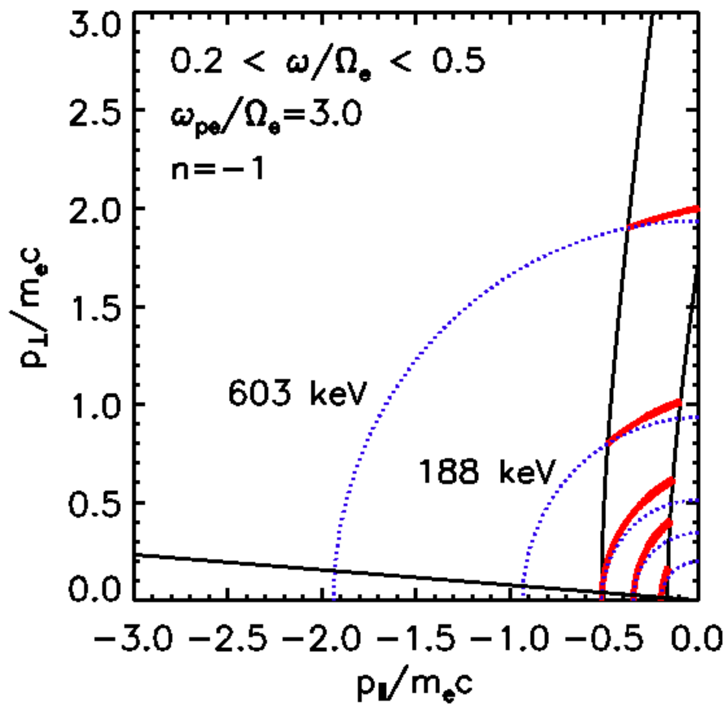
Acceleration by Whistler Mode Waves

$$v_{\parallel} = v_{\parallel res} = \frac{\omega}{k_{\parallel}}\left(1 - \frac{n\Omega_{\sigma}}{\gamma\omega}\right)$$

- Solve Doppler shifted cyclotron resonance with dispersion relation
- Diffusion into loss cone E > ~10 keV
  - Whistler wave growth
- Diffusion at large pitch angles ~ MeV
  - Acceleration
  - Trapping

Horne and Thorne, [1998, 2003, 2005a,b]



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BAS Radiation Belt Model

- Fokker-Planck Equation

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f}{\partial L}\right)\Bigg|_{\mu J} + \frac{1}{g(\alpha)}\frac{\partial}{\partial \alpha}\left(g(\alpha) D_{\alpha\alpha}\frac{\partial f}{\partial \alpha}\right)\Bigg|_{EL} + \frac{1}{A(E)}\frac{\partial}{\partial E}\left(A(E) D_{EE}\frac{\partial f}{\partial E}\right)\Bigg|_{\alpha L} - \frac{f}{\tau(\alpha, E)}$$

Radial transport | Pitch angle diffusion | Energy diffusion | Losses

- Drift & bounce averaged diffusion coefficients D_{LL}, $D_{\alpha\alpha}$, D_{EE} are activity, location and energy dependent

- Details in: Glauert et al. [2014]

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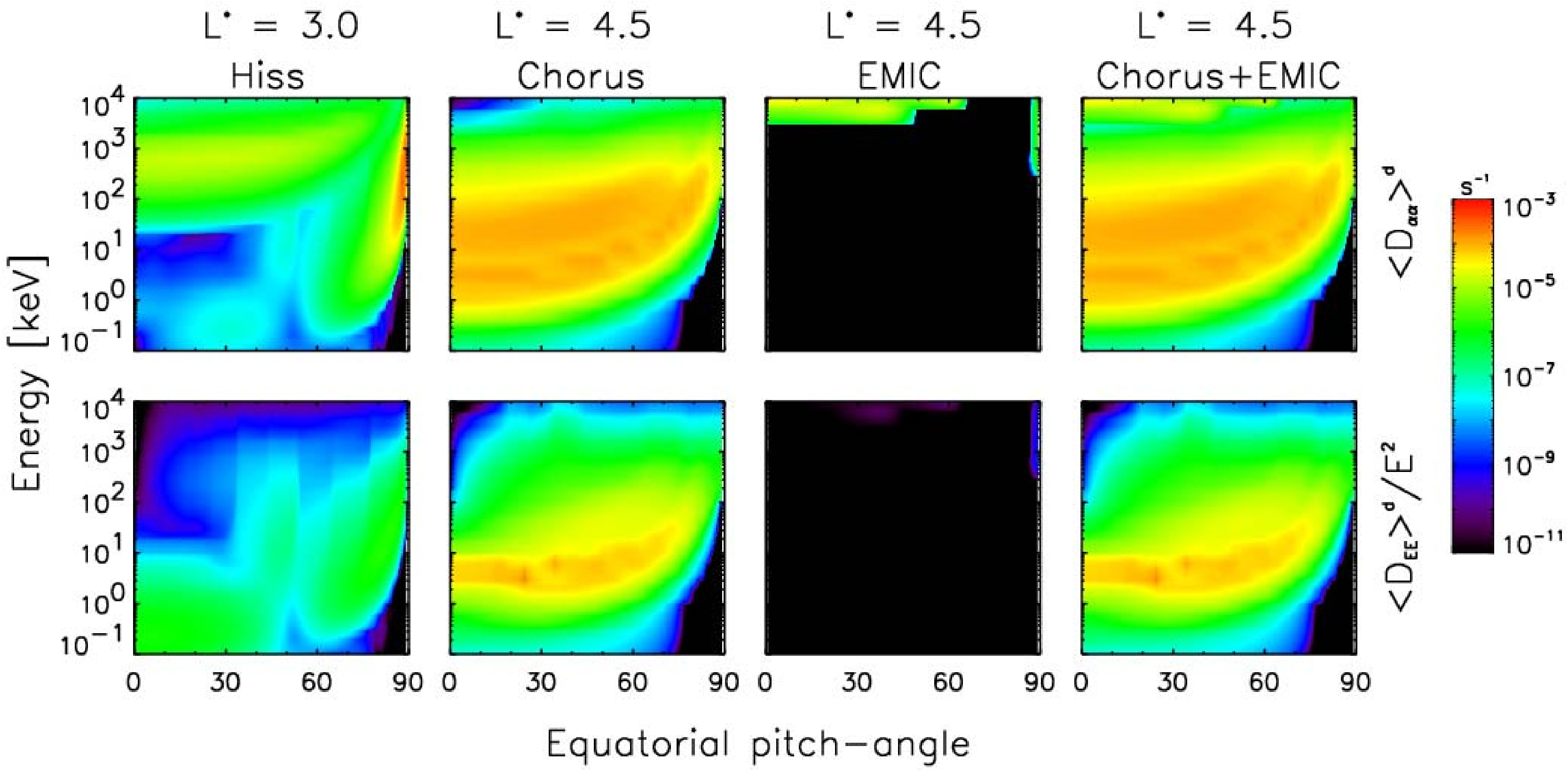
Pitch Angle and Energy Diffusion Rates



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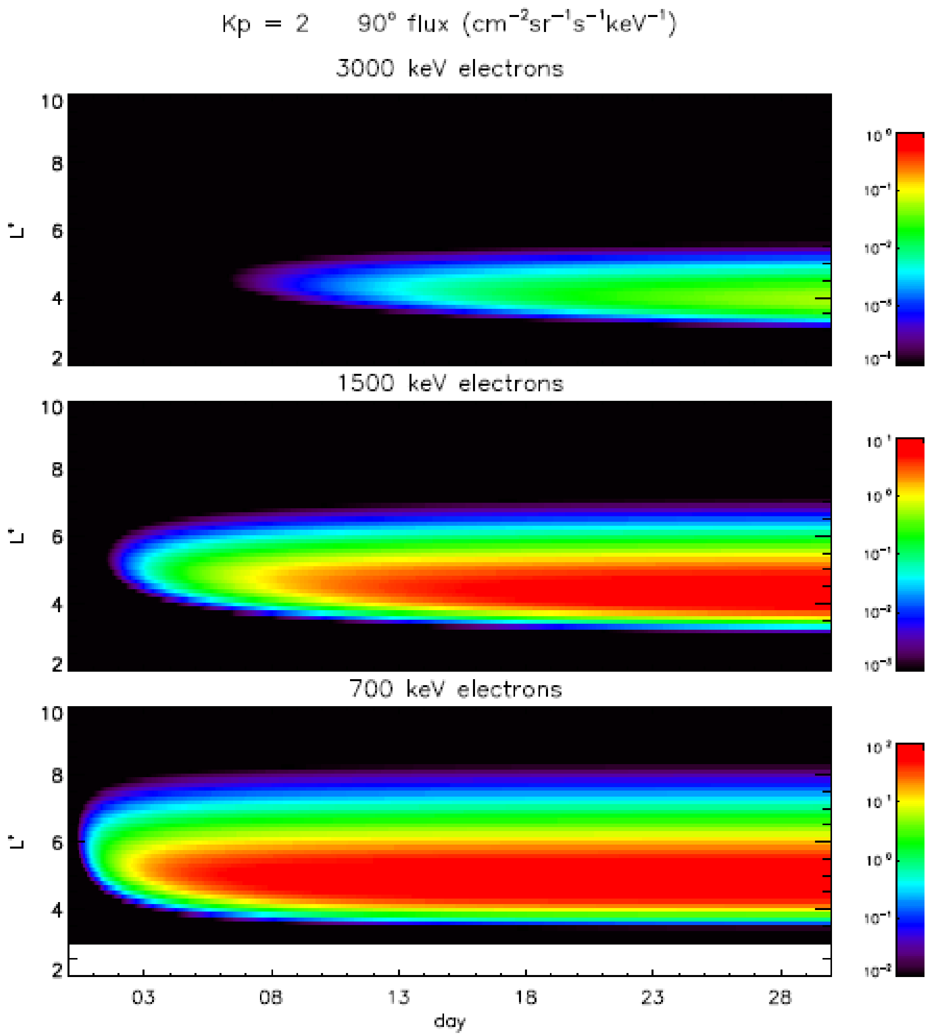
Radiation Belt from Chorus Alone



- Initial soft electron spectrum (~ 10 keV) along the low energy boundary
- Chorus wave diffusion only
- Kp = 2
- Time delay for higher energies
- Glauert et al., JGR [2014]

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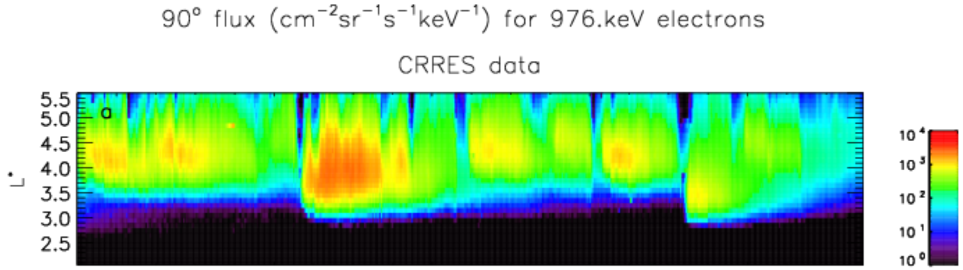
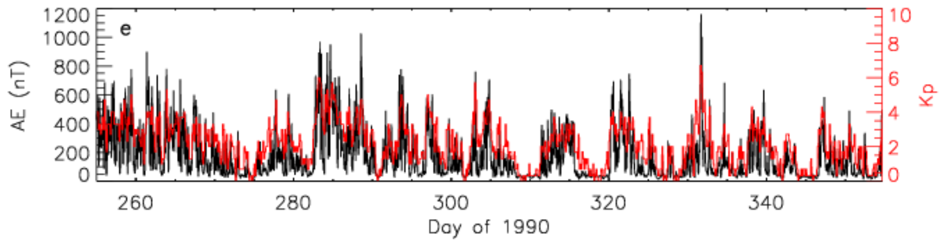
Importance of Wave-Particle Interactions

Satellite data - Electrons





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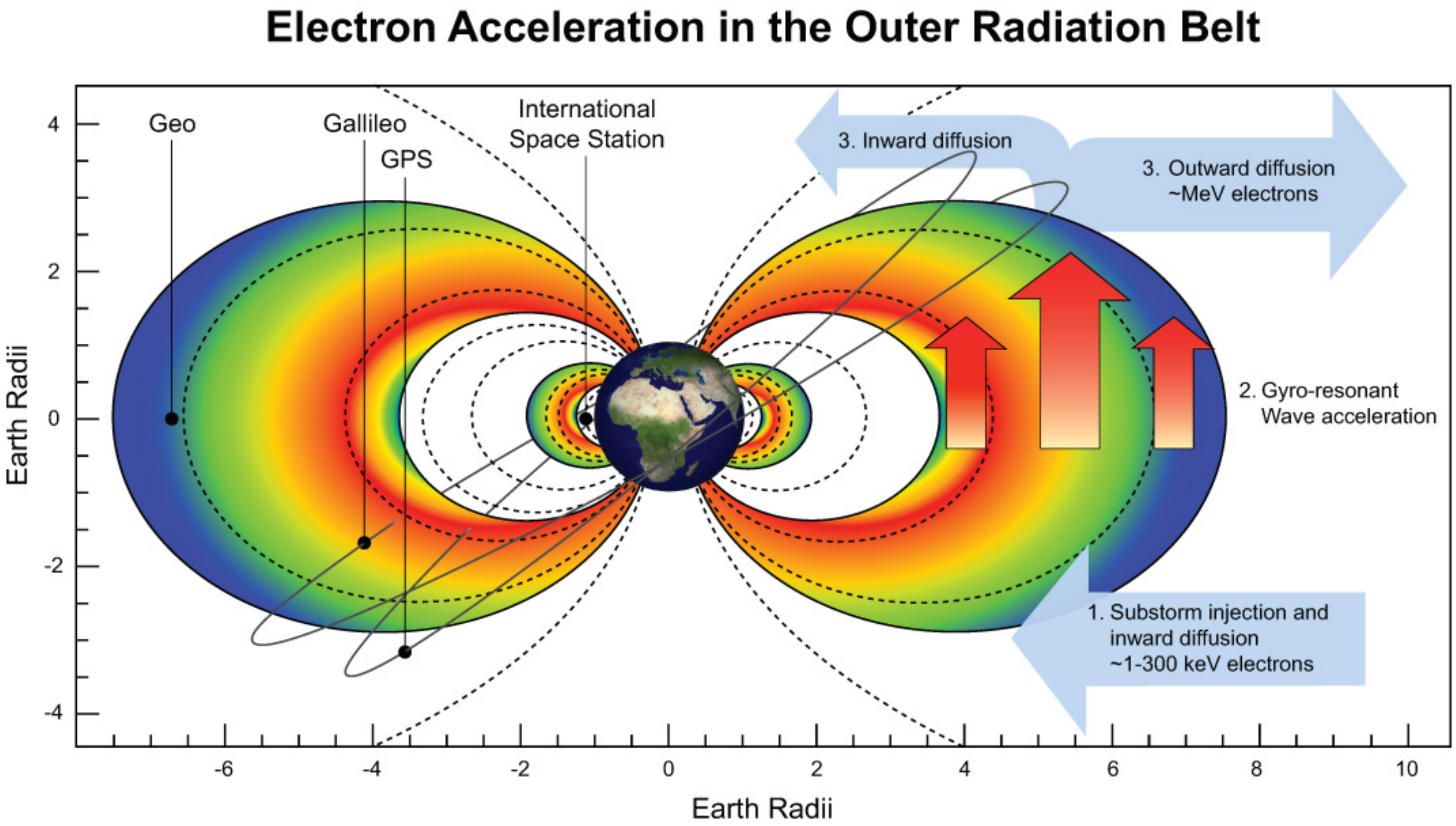
New Wave Acceleration Concept



Horne, *Nature Physics* [2007]

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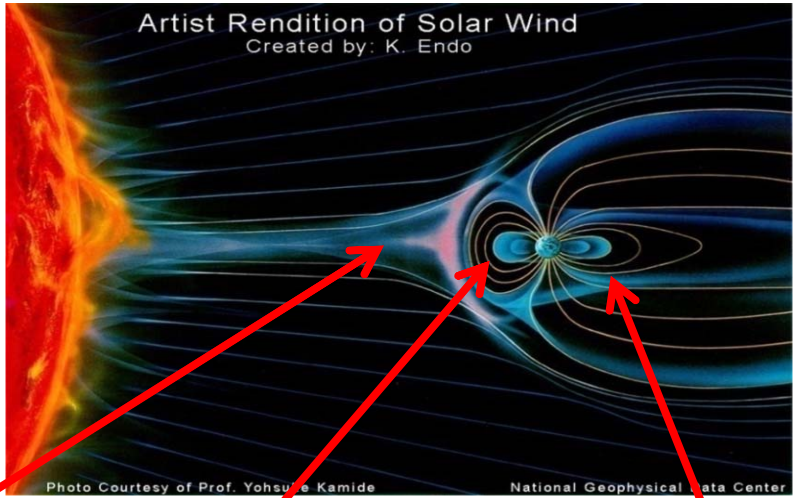
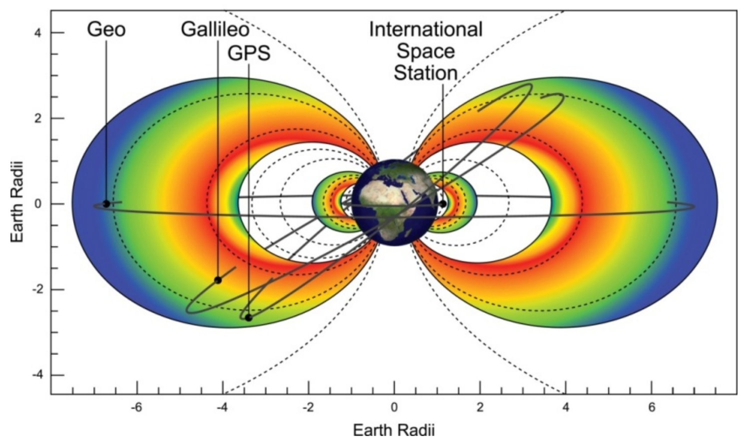
Space Weather - Forecasting Concept

- It takes ~ 40-60 minutes for the solar wind to flow from the ACE satellite to the Earth
- Access ACE satellite data in real time and use it to drive our forecasting models



ACE satellite

Satellite orbits and the van Allen radiation belts



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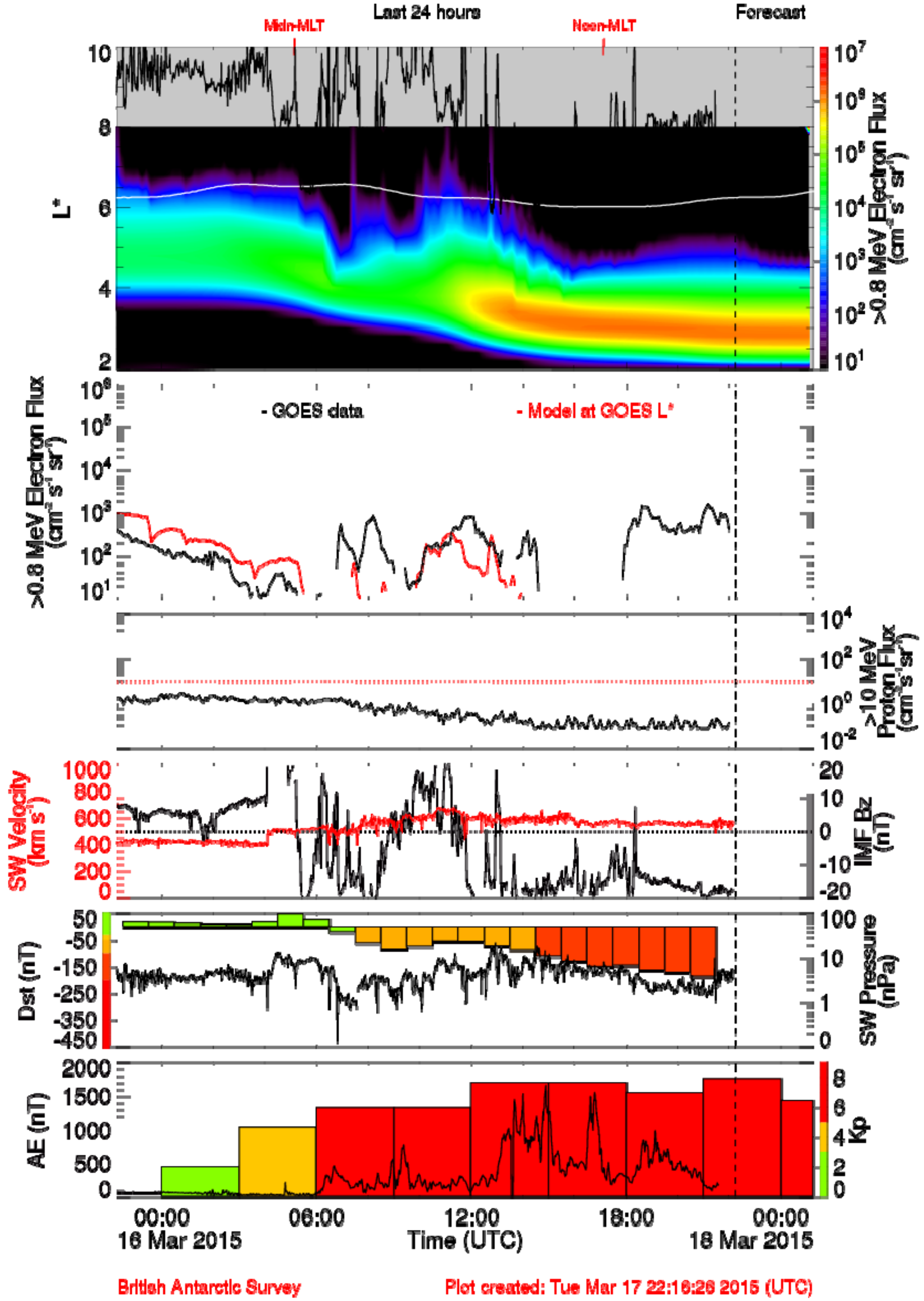
Space Weather

- Forecast the radiation belt flux
- Turn into a risk index
- Risk of satellite charging
- Satellite operators
- Space Insurance
- Satellite design and construction
- www.spaceweather.ac.uk



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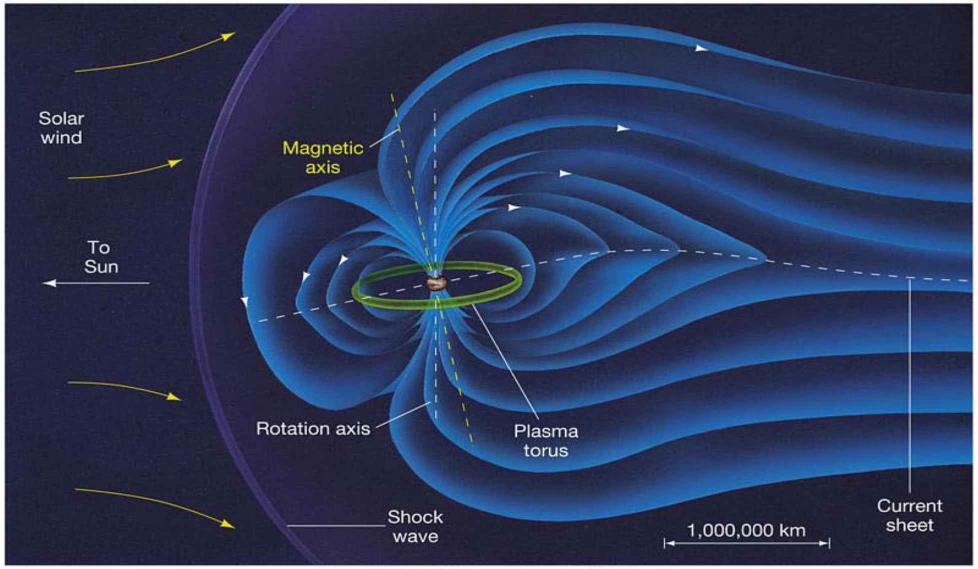
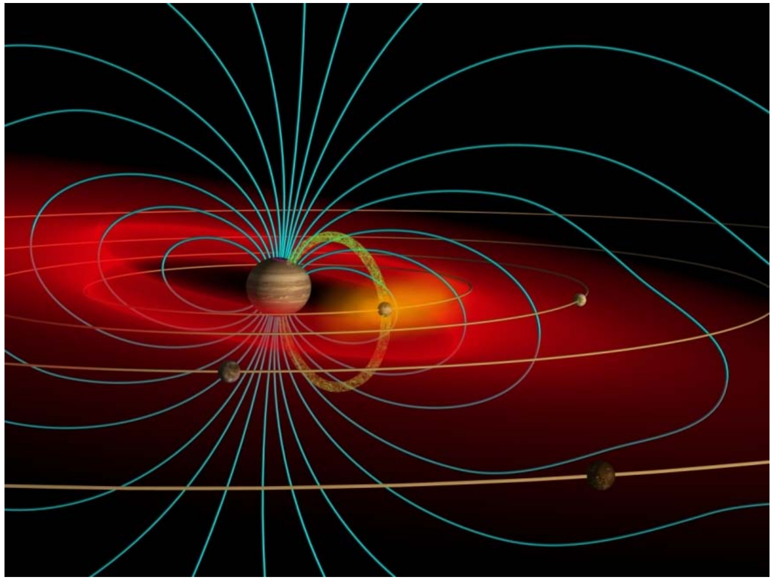
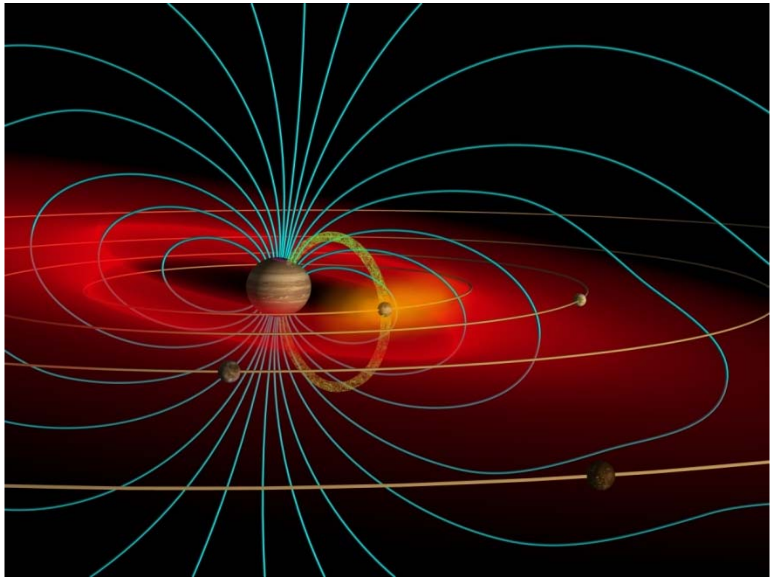
Jupiter

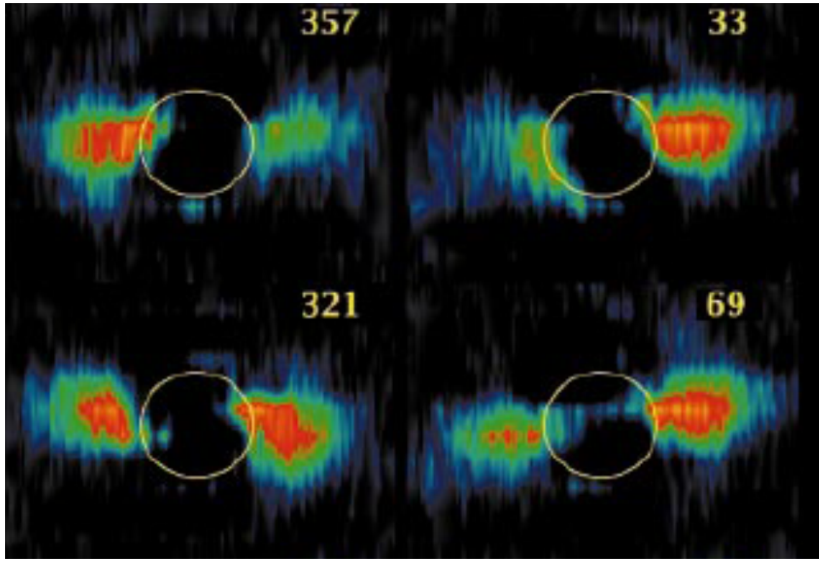




- Largest magnetosphere in the solar system
- Volcanoes on the moon Io emit gasses – becomes ionised – main source of plasma – torus
- Rapid rotation – 9.8 hours – centrifugal force – cold plasma flows out – hot plasma in - flux interchange
- Dust and rings – absorption of plasma

Jupiter - The Problem





[Bolton et al., *Nature*, 2002]

- Synchrotron radiation indicates intense radiation belt:
  - 50 MeV electrons at L=1.4

- Could gyro-resonant electron acceleration apply to Jupiter?

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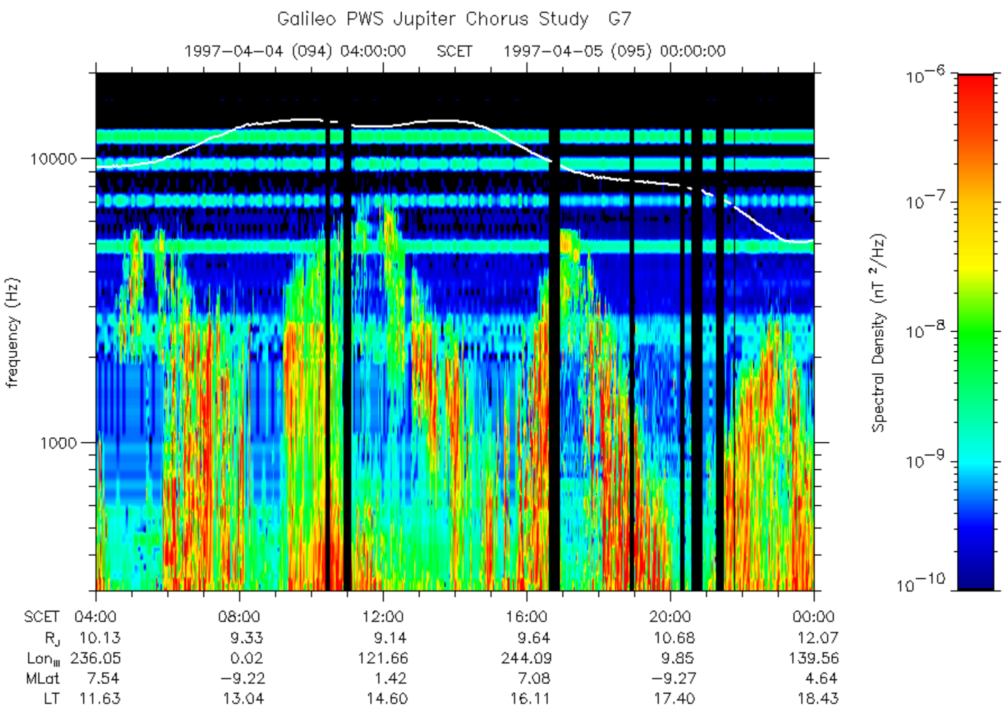
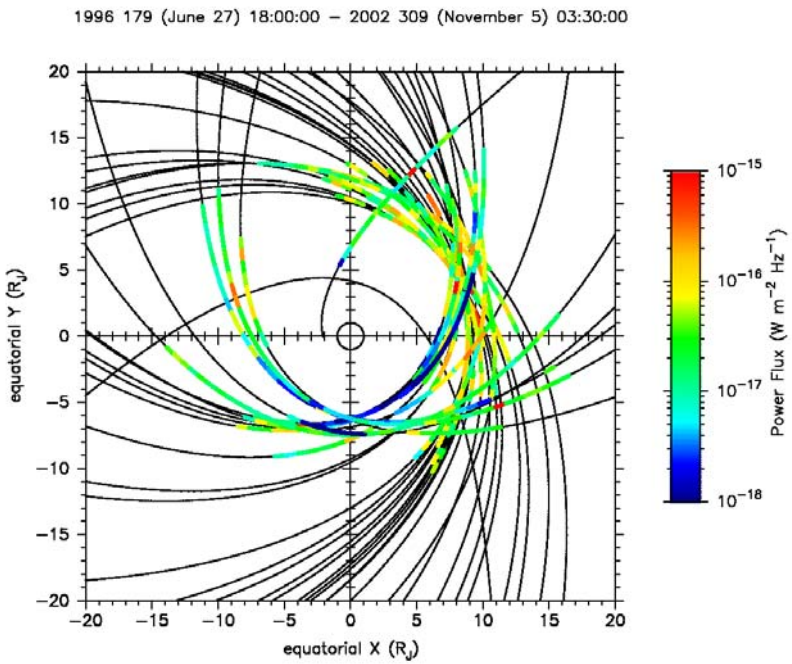
Whistler Mode Waves Observed at Jupiter





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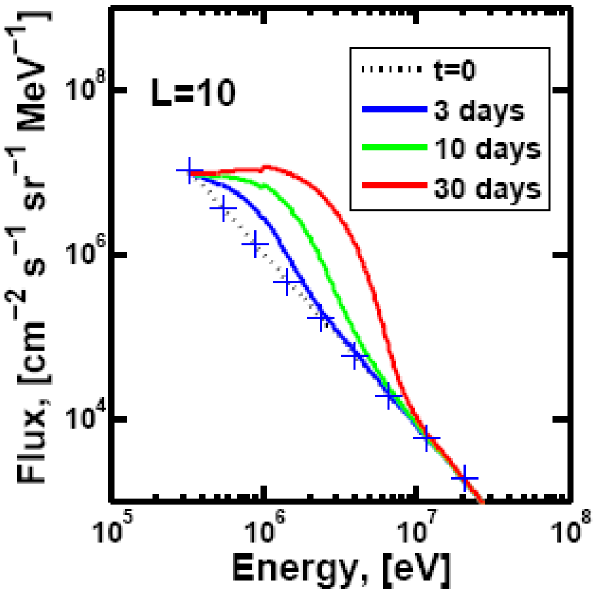
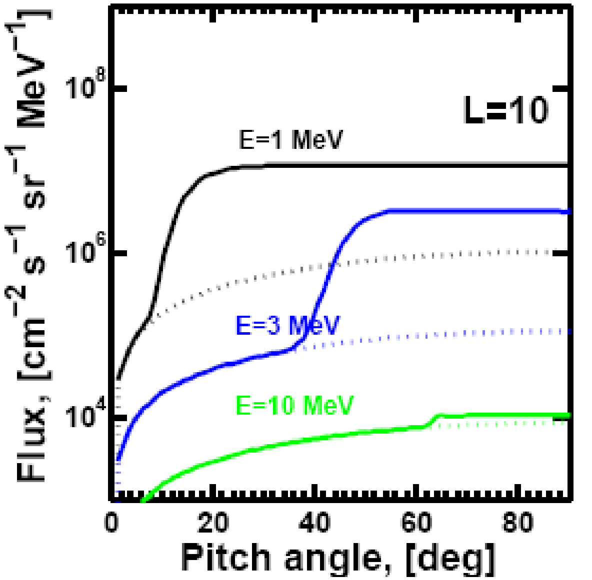
Gyro-resonant Electron Acceleration at Jupiter

- 2d Fokker-Planck
- Timescale ~ 30 days for flux to increase by a factor of 10
- Timescale is comparable to transport timescale (20 - 50 days) for thermal plasma
- Predict anisotropic pitch angle distribution





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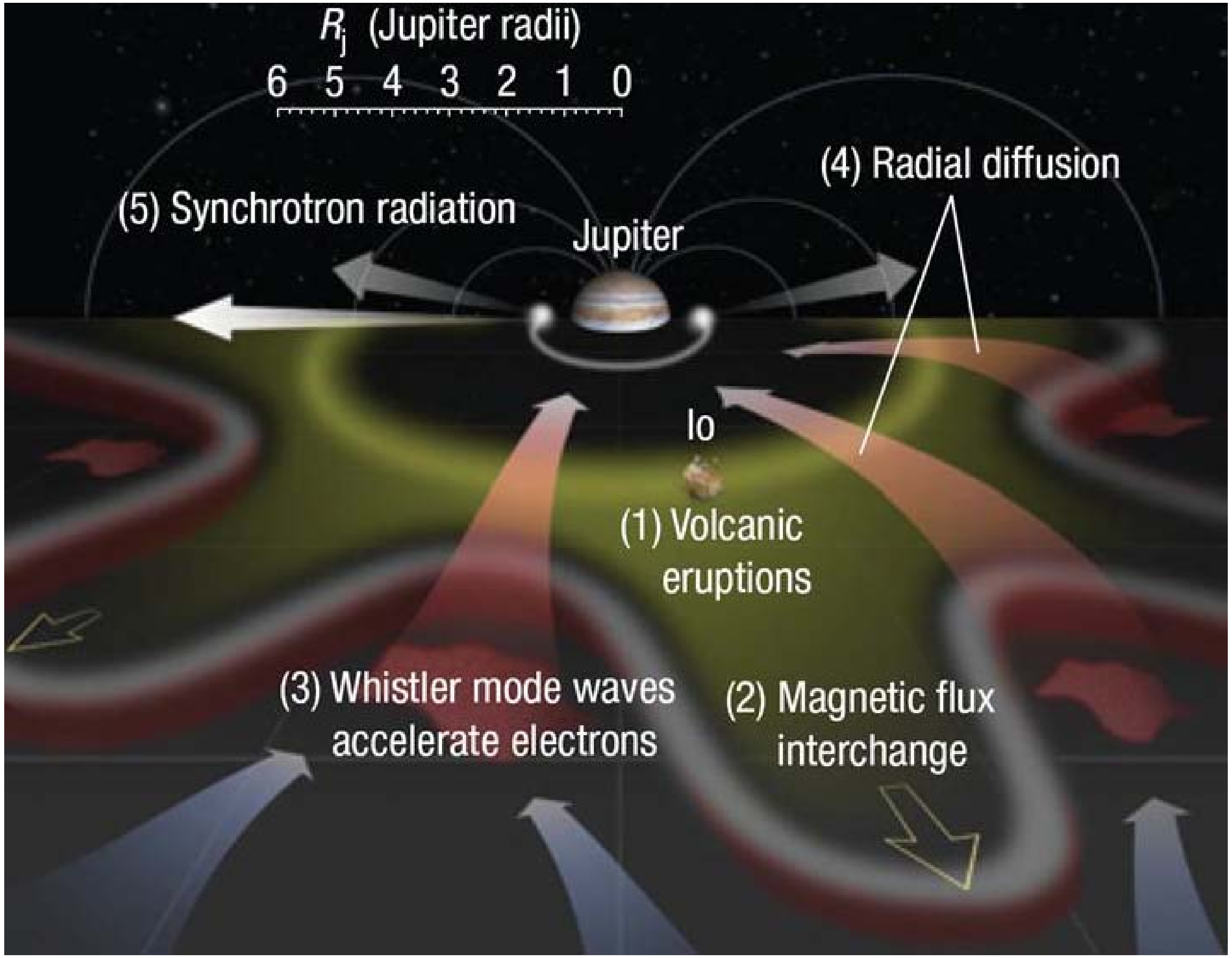
Production of Synchrotron Radiation

- Suggest Gyro-resonant electron acceleration provides the missing step



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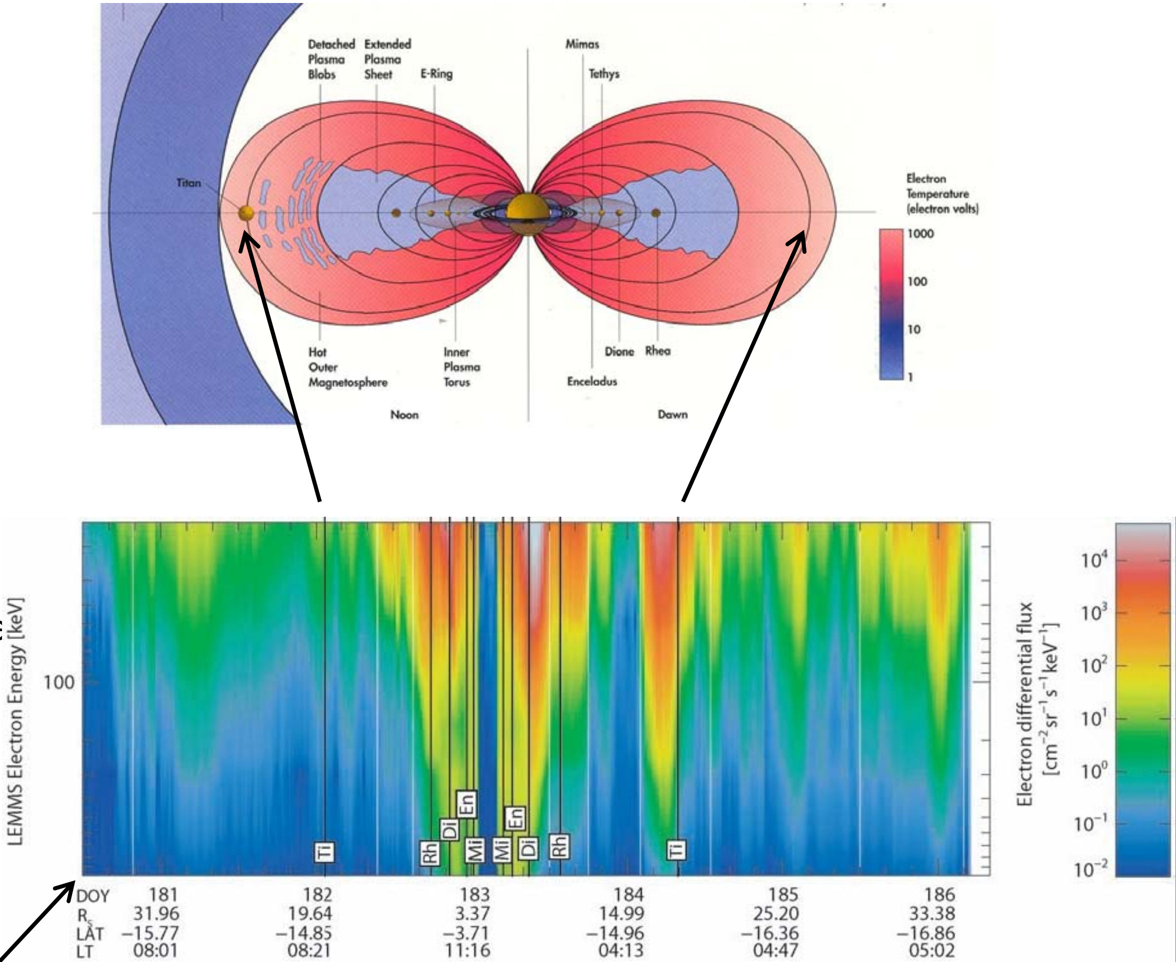
Horne et al., *Nature Physics*, [2008]

Saturn



- Weak synchrotron radiation
  - Absorption by dust L < 2.3
- Radiation belt intensity comparable to the Earth, weaker than Jupiter
- Rapid rotation
- Moon Enceladus source of plasma
  - Flux interchange

1 MeV

Krimigis et al. [2005]

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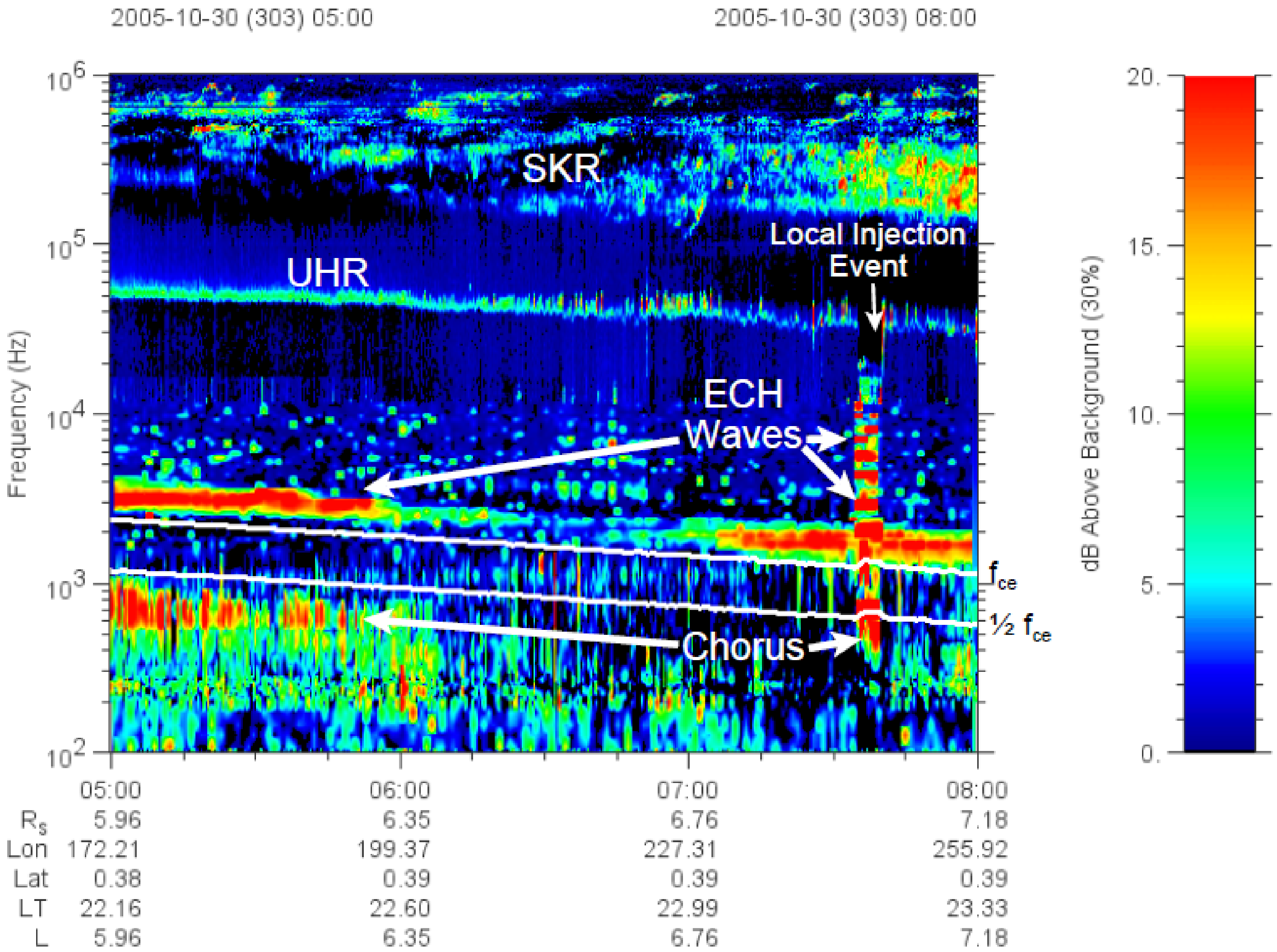
Saturn



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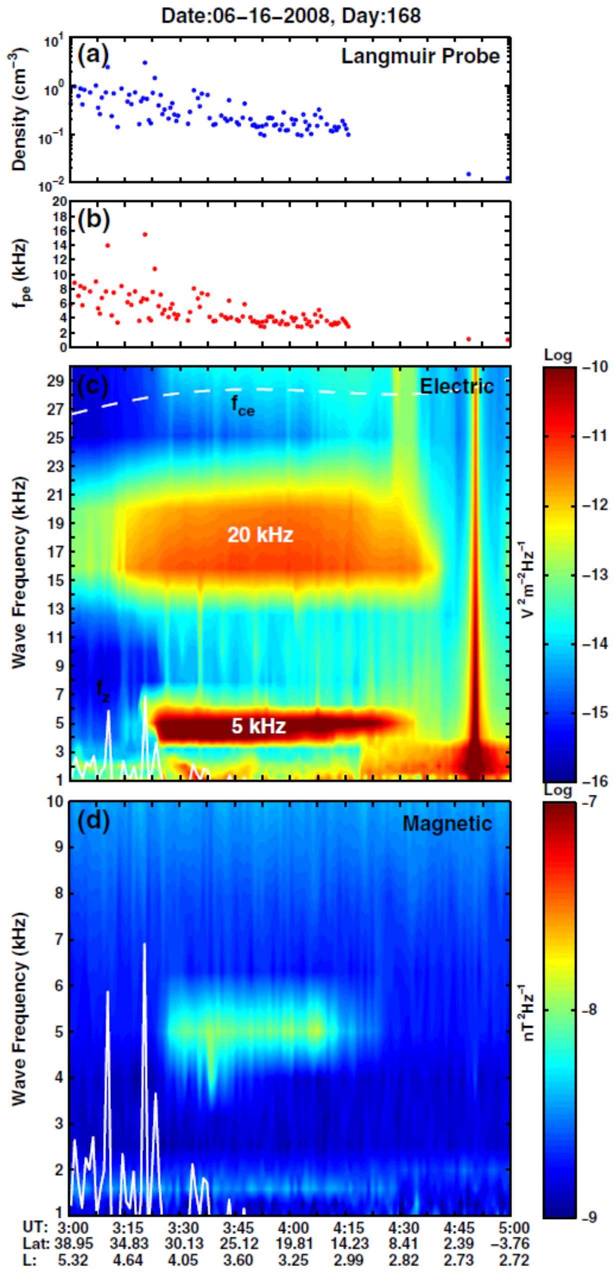
- Chorus observed – but too weak to form radiation belts [Menietti et al., 2014; Shprits et al. 2012]

Z mode waves

- fpe < f < fce
- Observed inside the orbit of the moon Enceladus
- Generation?
  - Local instability?
  - Mode conversion?
  - Other?



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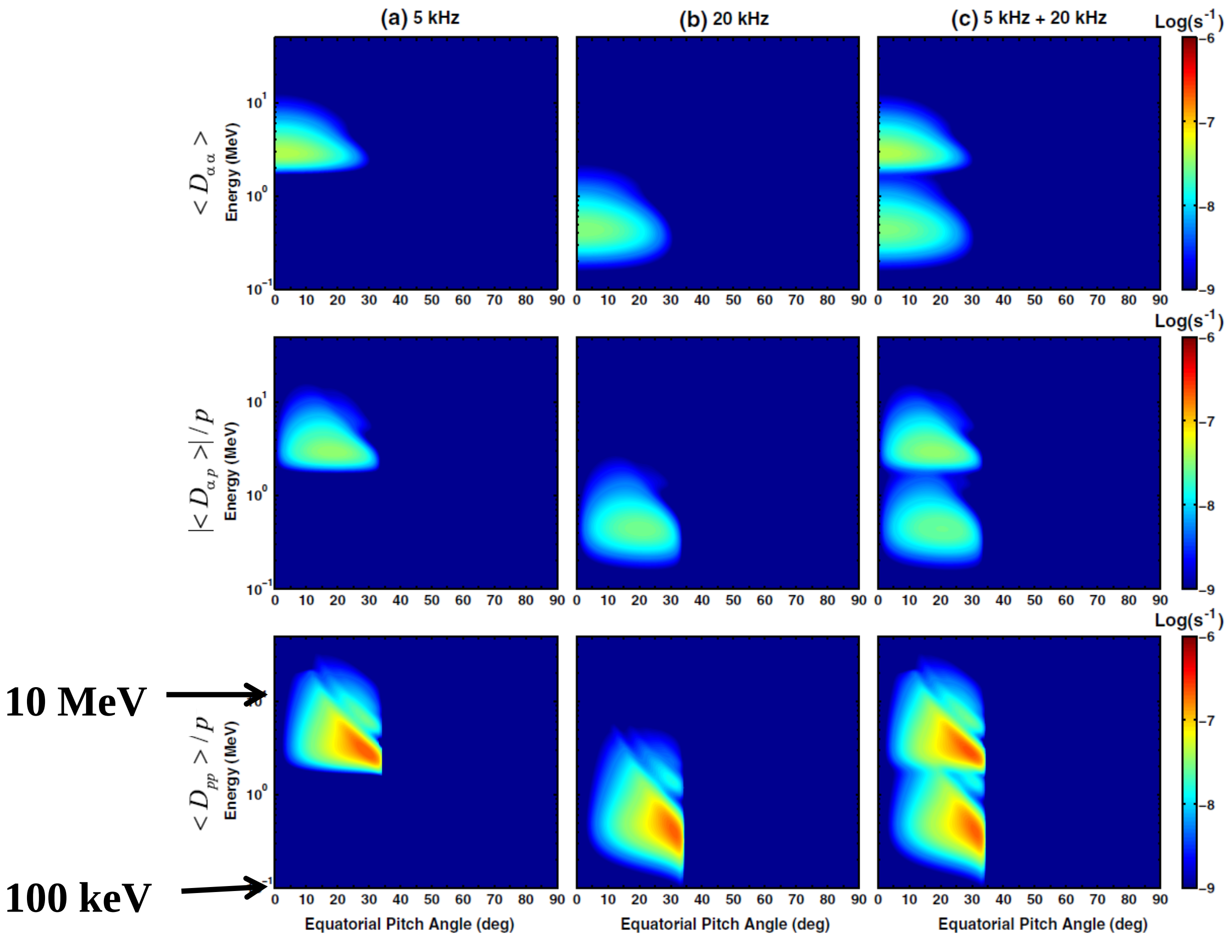
Z mode waves – Resonant Energy

- Gu et al., [2013]
- They assume a wave normal angle of 90°
- Unlikely
- Wider range of resonant energies if field aligned
- Subject of on-going analysis



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Summary

- Electron acceleration up to MeV energies by whistler mode chorus waves are a major source of the Earth's electron Van Allen radiation belts

- Wave-particle interactions play a major role in radiation belt variability – via acceleration and precipitation (loss) into the atmosphere

- Including wave-particle interactions enables better Space Weather forecasting

- Jupiter – chorus waves can accelerate electrons to MeV energies outside the orbit of the moon Io – and provide the missing step in the formation of Jupiter's radiation belts

- Saturn – chorus is too weak to cause substantial electron acceleration. However, Z mode waves could be important, inside the orbit of Enceladus

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The End

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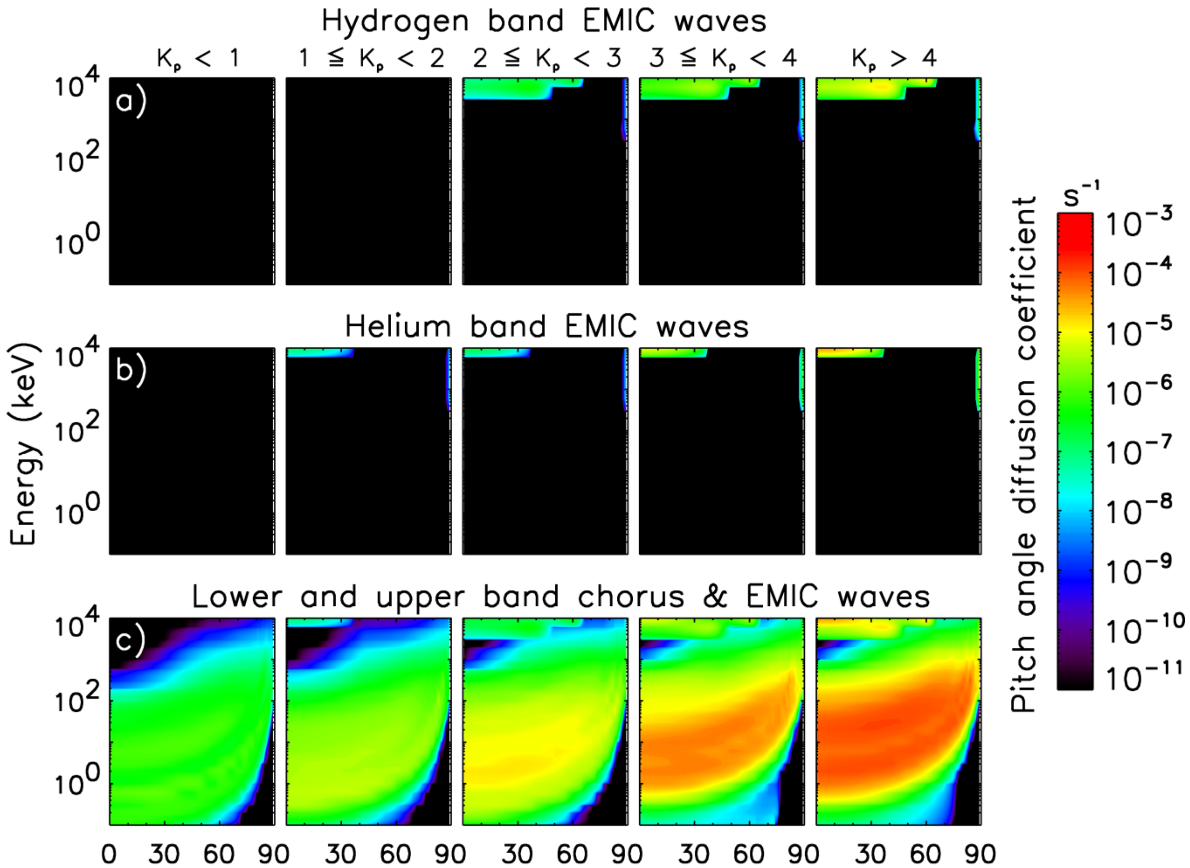
EMIC diffusion rates L* = 4.5

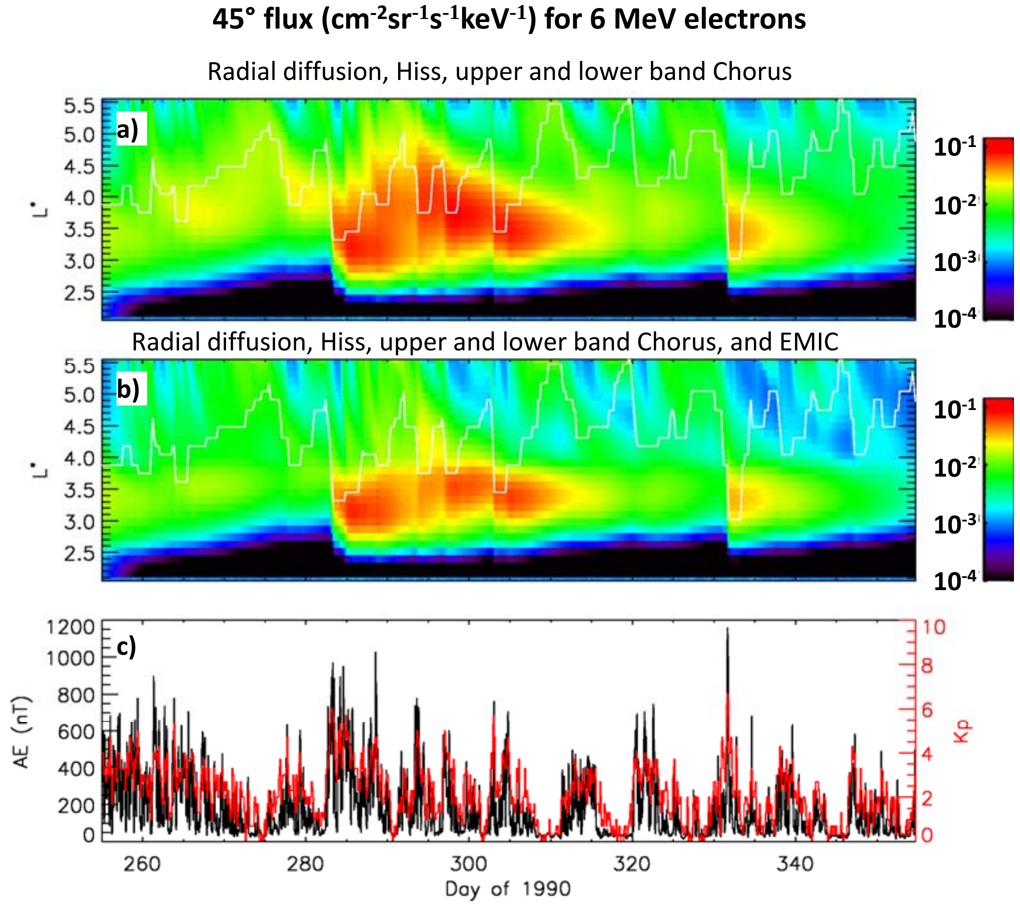


- Pitch angle diffusion becomes significant only at high energies (E > 3 MeV) and low pitch angles (α < ~60°)
- Energy diffusion is insignificant at all energies and pitch angles

Electron flux: 100 day simulation – 45°

Without EMIC

With EMIC



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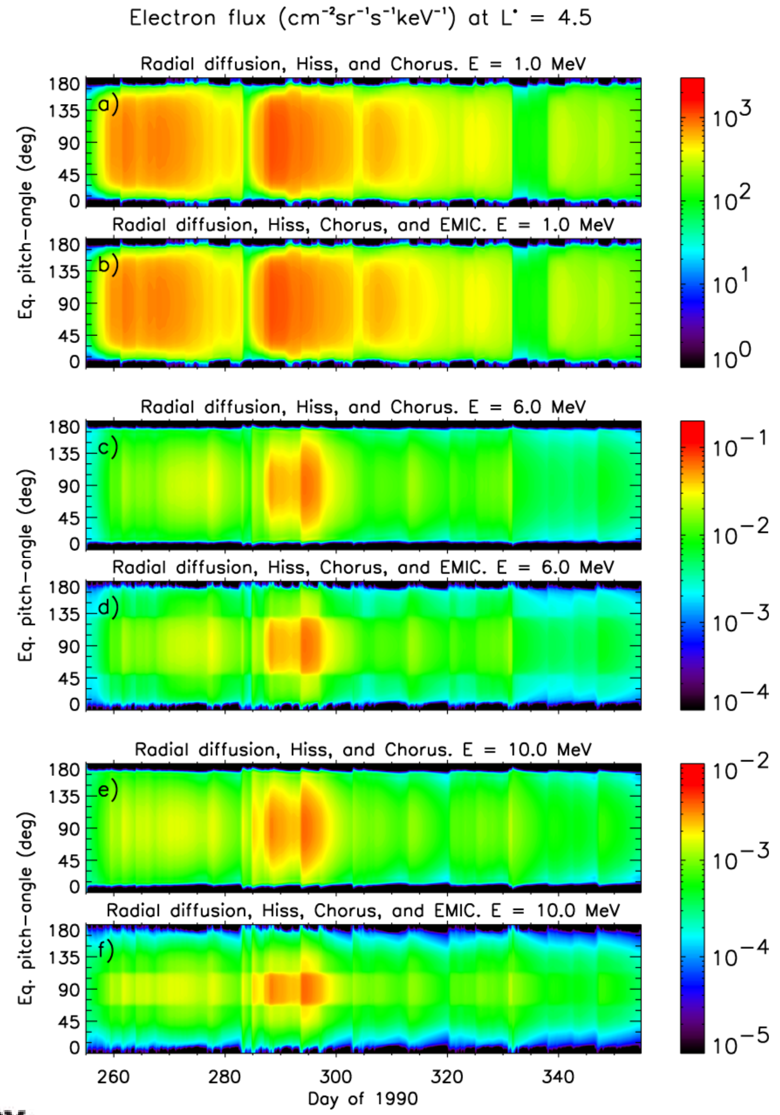
Electron Pitch Angle Distribution



- Pitch angle distribution becomes narrower with increasing energy
- Test for in VAP data
- Kersten et al., [2014]

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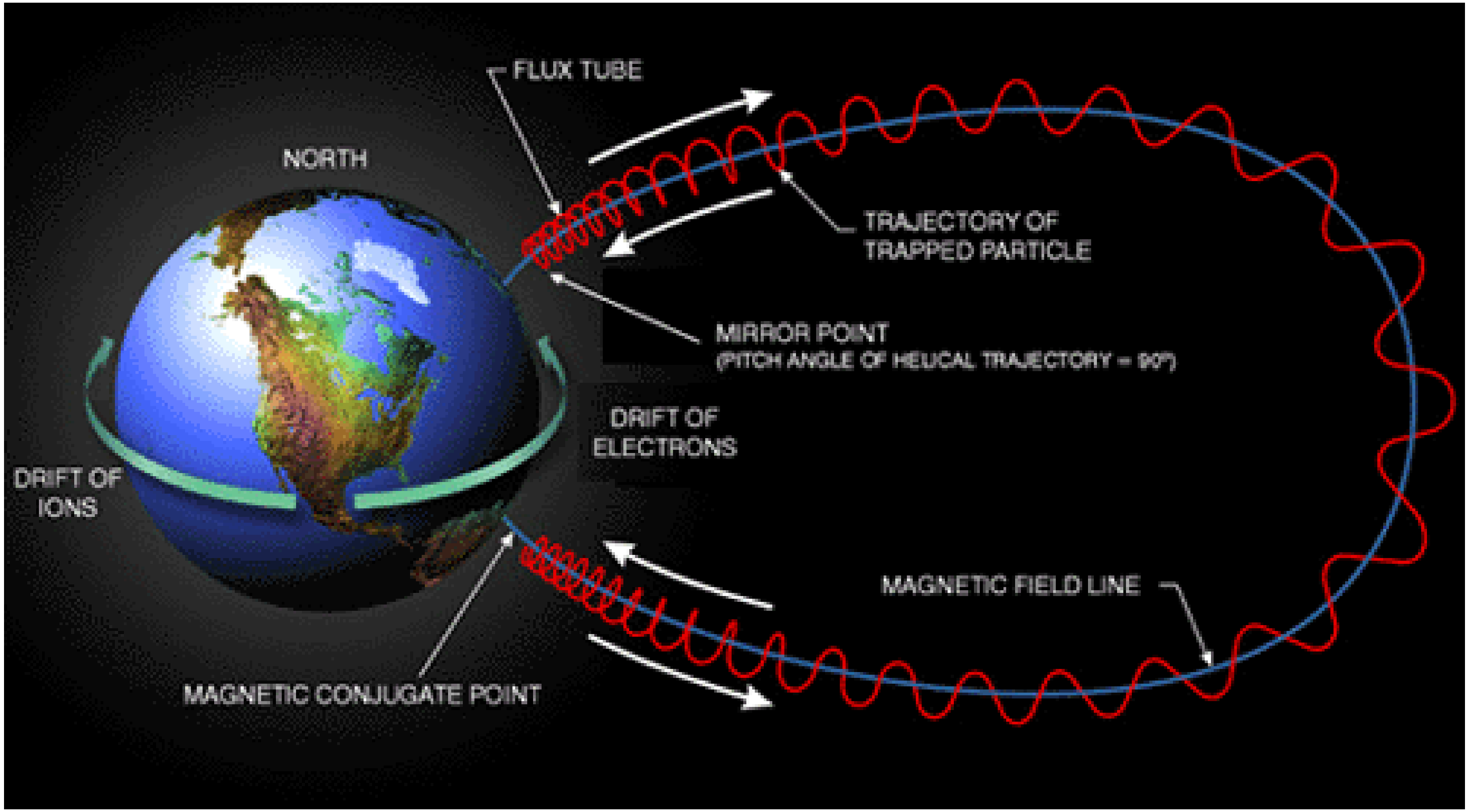
Cyclotron, bounce and drift motion



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Doppler Shifted Cyclotron Resonance

- Whistler waves propagating along the magnetic field have right hand circular polarization

- $\omega < \Omega$

- For resonance, the wave frequency is Doppler shifted up to the cyclotron frequency by relative motion of electrons and waves along B.

$$\omega - k_{\|} v_{\|} - n\Omega_{\sigma}/\gamma = 0$$

- Efficient exchange of energy

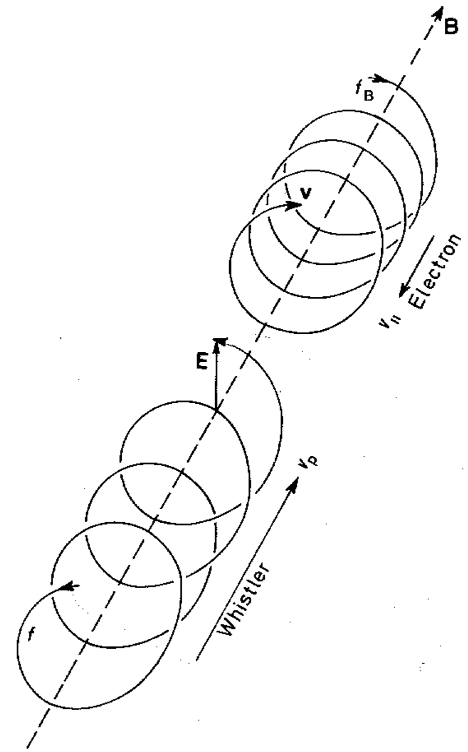

Figure 9.2 Spiral motions of electron and whistler about the geomagnetic field. For effective interaction the electric vector of the whistler must be maintained parallel to the velocity of the electron.

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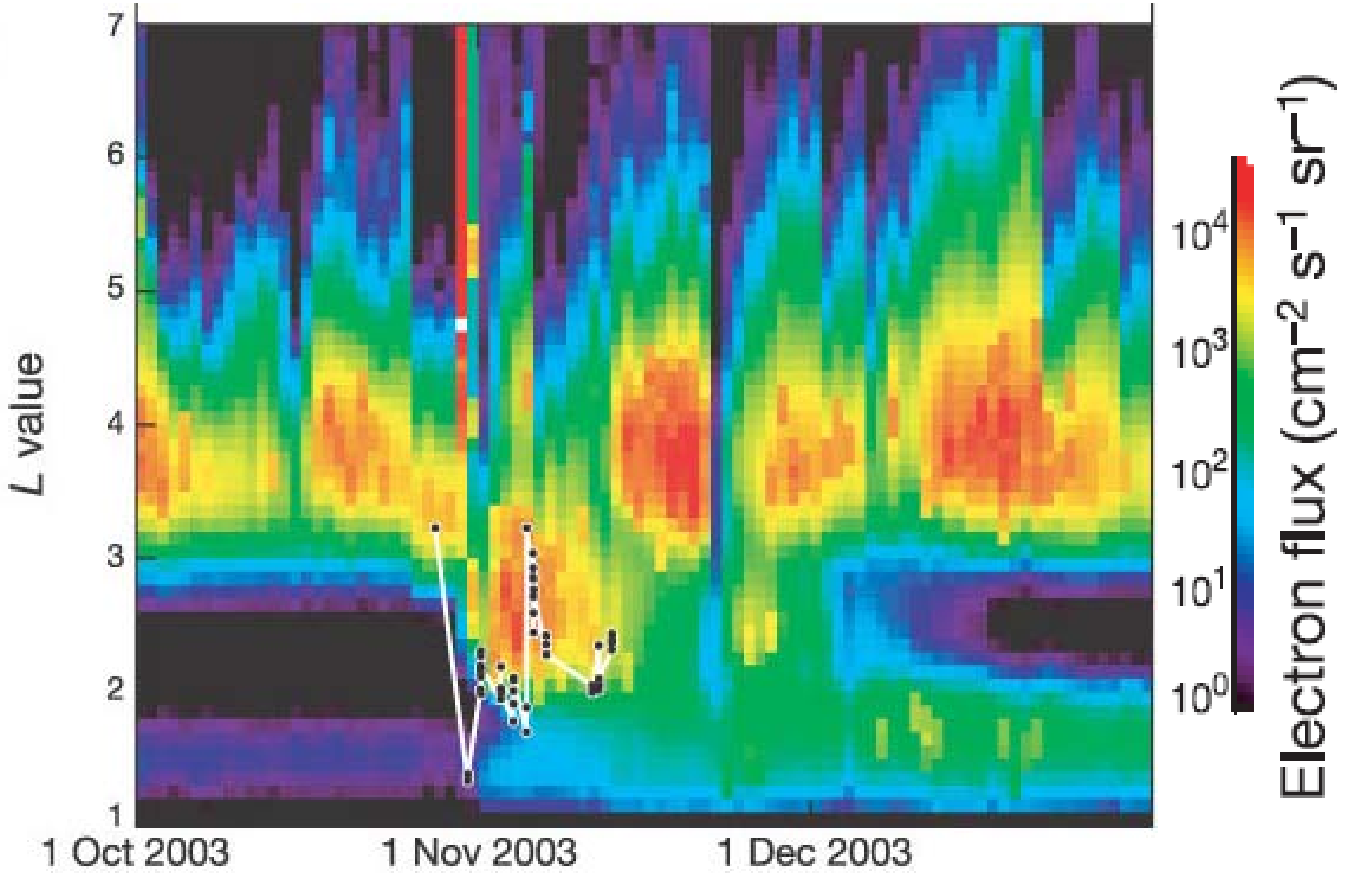
Electron Radiation Belts – The Haloween 2003 Magnetic Storms



Baker et al. Nature [2004]

- 23rd Oct to 6th Nov 2003
  - 47 satellites reported malfunctions – 1 total loss
  - 10 satellites – loss of service for more than 1 day

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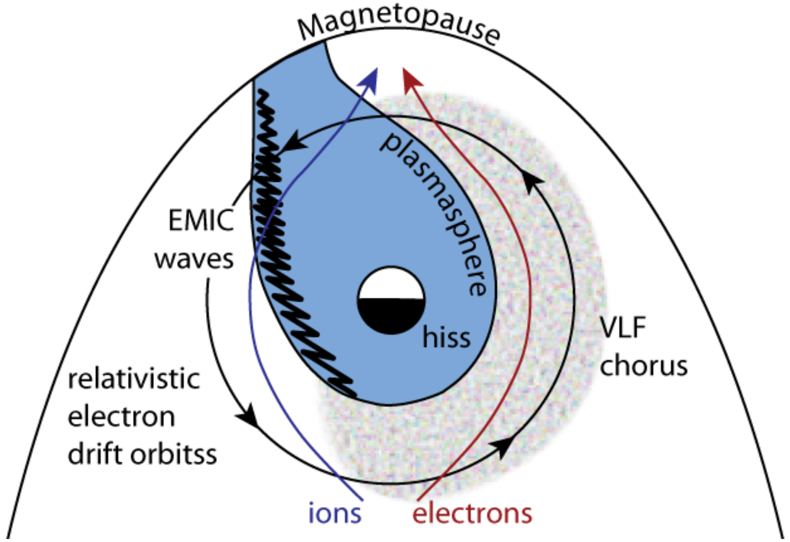
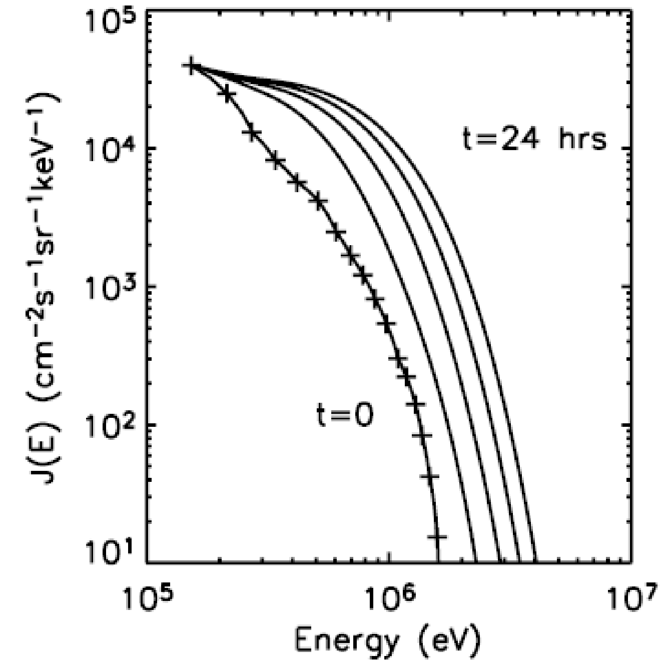
Concept

Summers et al. [1998]





Horne et al. [2005]

- Injection of ~1 - 100 keV electrons excites whistler mode chorus waves
- Whistler mode chorus accelerates fraction of population to ~ MeV energies
- Solve Fokker-Planck equation to get timescale

$$\frac{\partial f}{\partial t} = \frac{1}{A(E)}\frac{\partial}{\partial E}\left[A(E)\langle D_{EE}\rangle \frac{\partial f}{\partial E}\right]$$

$$A = (E+E_0)(E+2E_0)^{\frac{1}{2}}E^{\frac{1}{2}}$$

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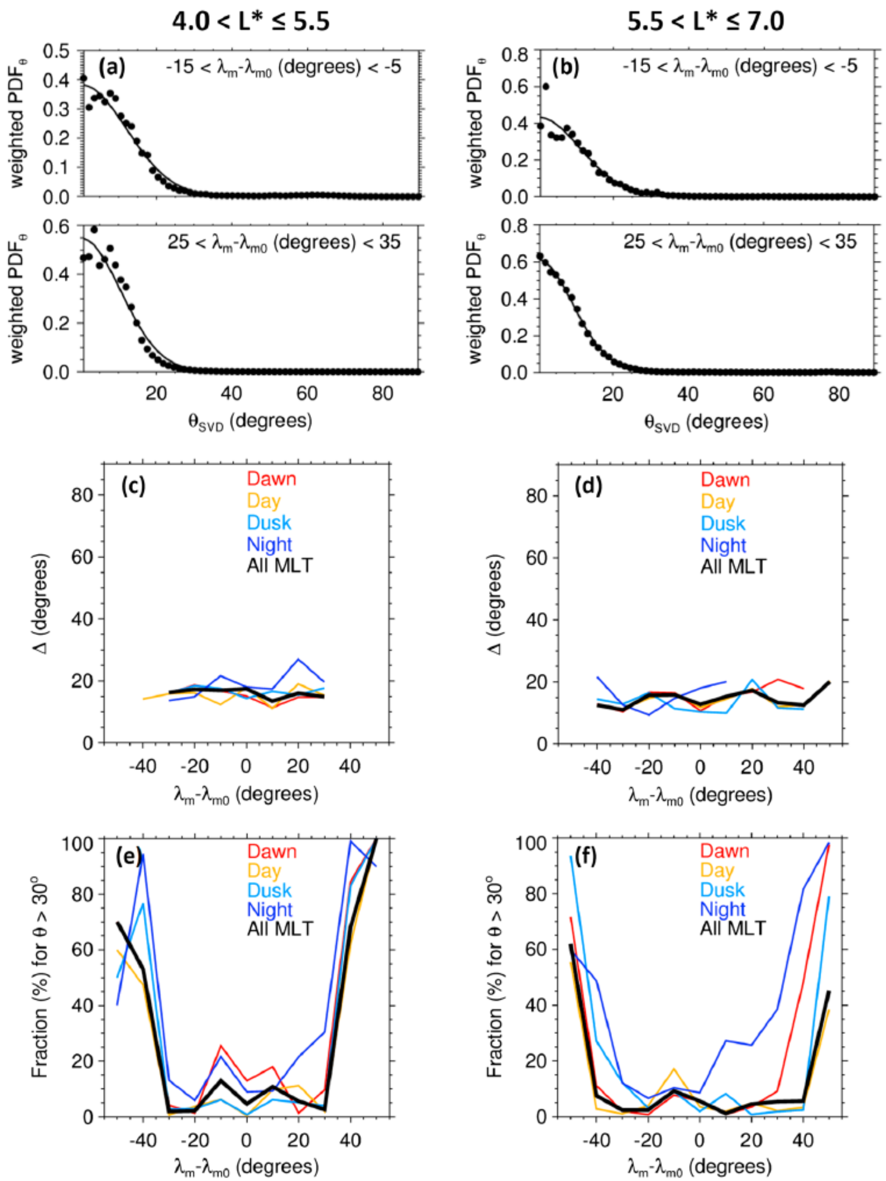
Chorus Wave Normal Angle



- Santolik et al., [2014]
- Angular width ~ 15^{o}

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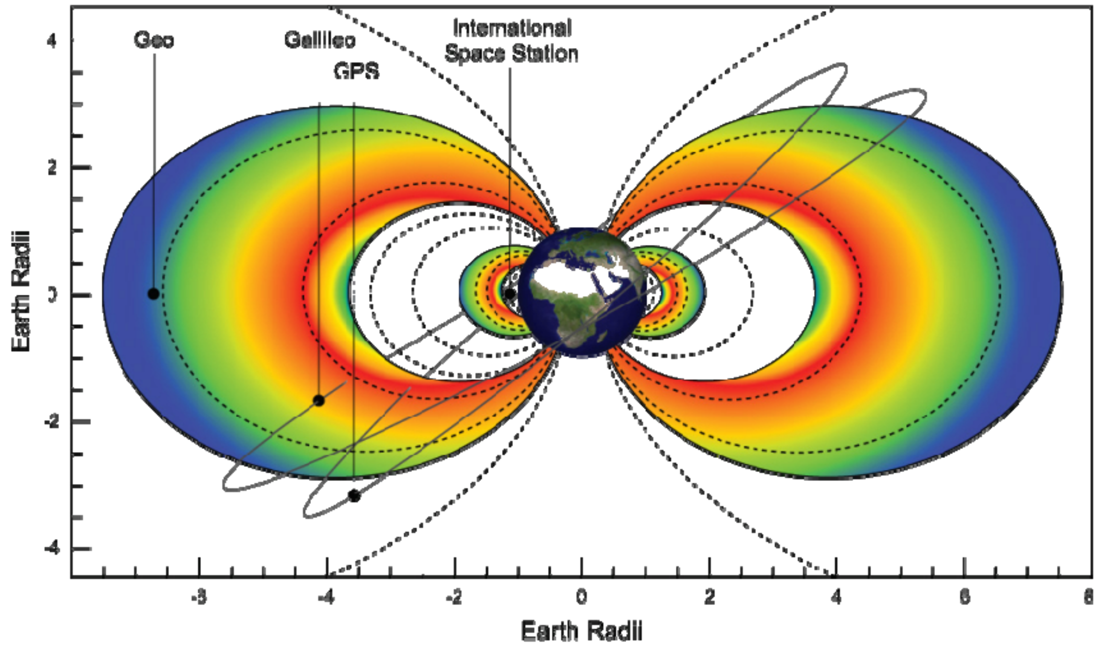
Satellite Orbits and the Earth's Radiation Belts

The Earth's Electron Radiation Belts



- About 1000 satellites in orbit:
  - 420 in geosynchronous orbit GEO — 470 in low Earth orbit LEO
  - 70 in medium Earth orbit MEO — 35 in highly elliptical orbit HEO

- Earth's radiation belts contain very high energy electrons and ions that damage satellites

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SPACESTORM

Hiss Waves – Inside High Density Plasmasphere