

# The Properties of Large Amplitude Whistler Mode Waves in the Magnetosphere: Propagation and Relationship with Geomagnetic Activity

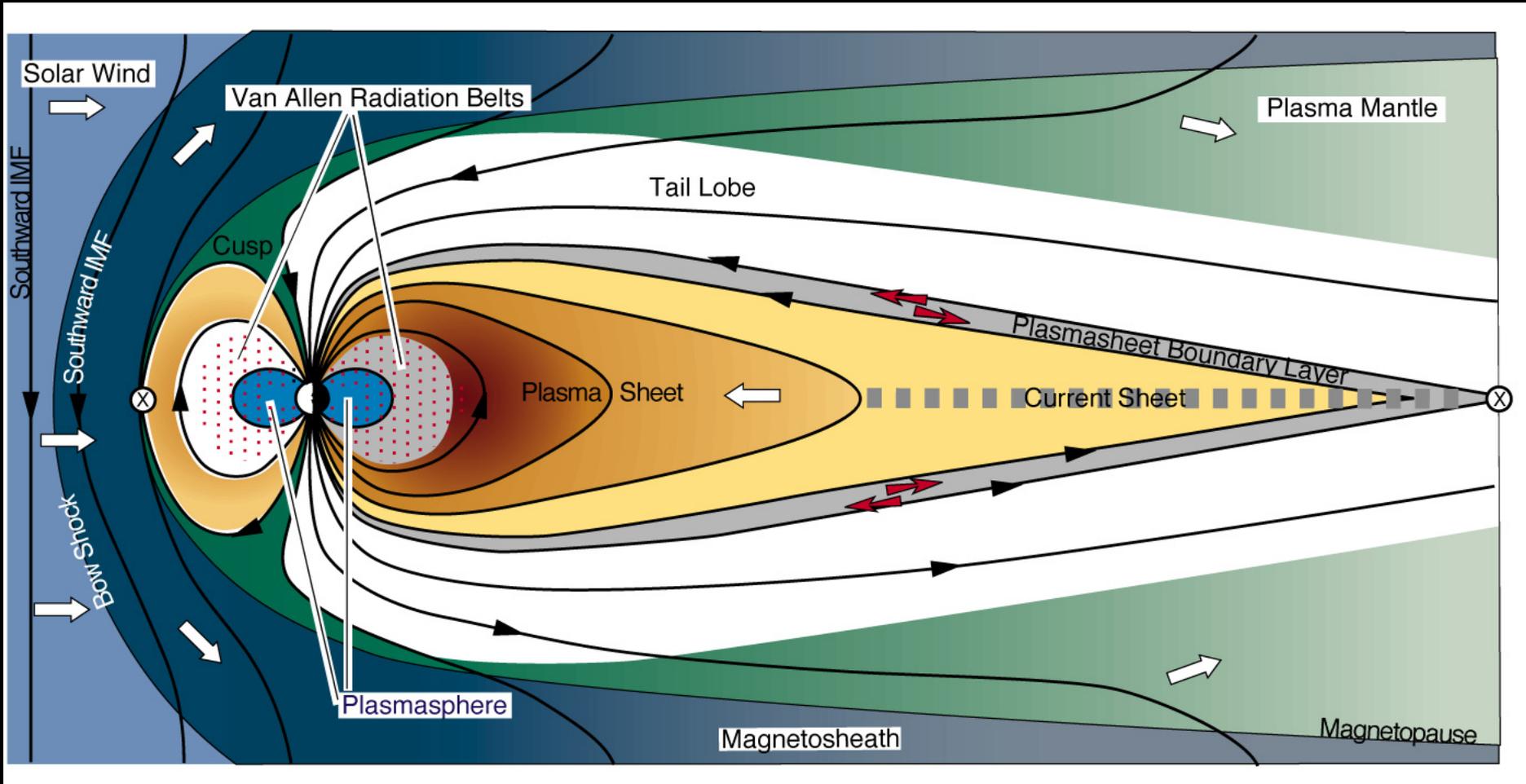
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K. Kersten<sup>2</sup>, J.R. Wygant

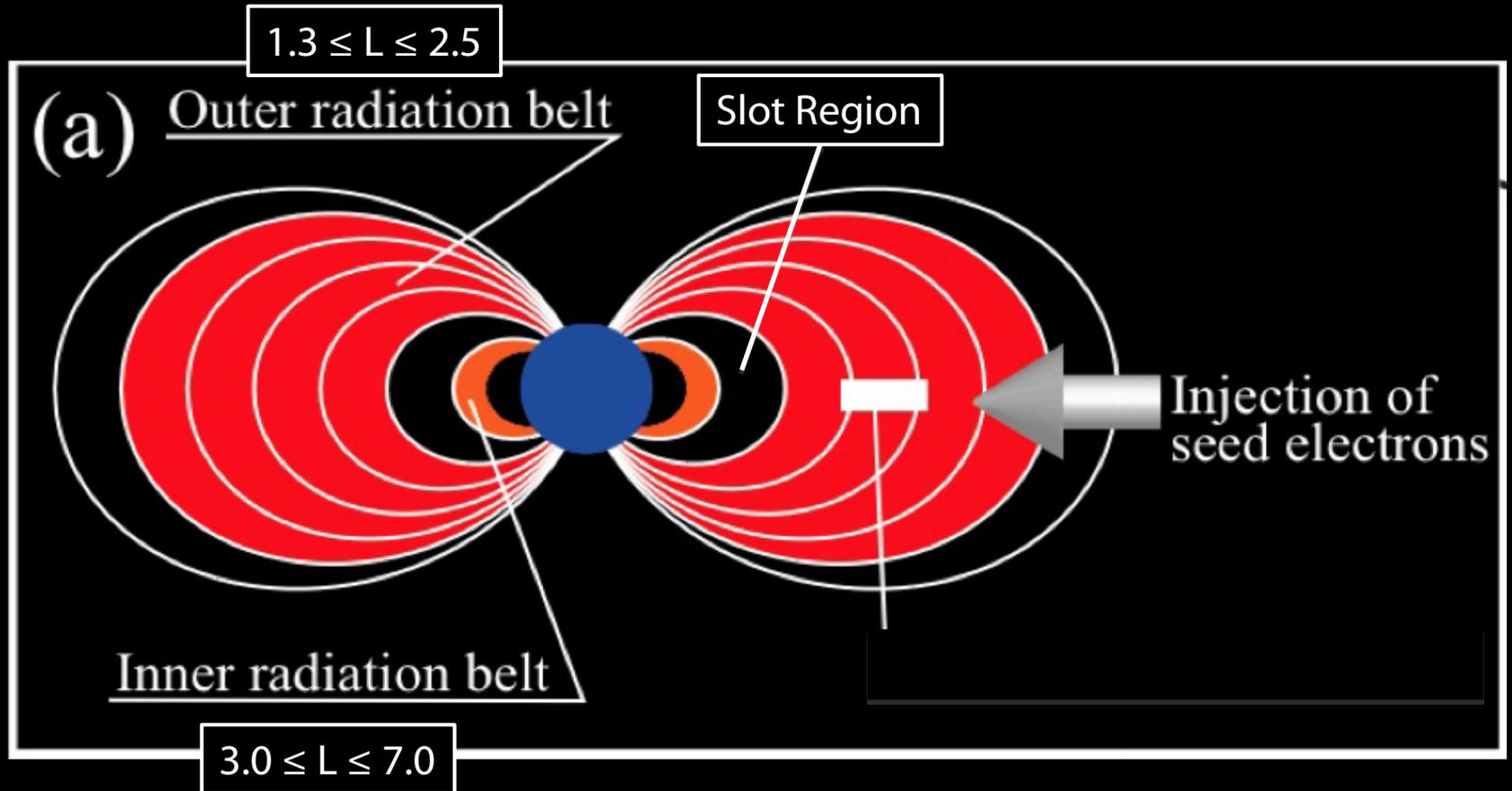
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# The Earth's Magnetosphere



# The Earth's Radiation Belts



*Katoh et al., 2008*

Figure 1a (Modified)

# Outline



- **Definitions/Background**
- Discuss previous observations
- Introduce spacecraft and instruments
- Motivate study
- Results
- Conclusions

# Whistler Mode Waves: Description

Whistler = generic term used to describe a broad range of waves with an even broader range of properties

Dispersive

$$n^2 = \frac{\omega_{pe}^2}{\omega(\Omega_{ce} \cos\theta - \omega)}$$

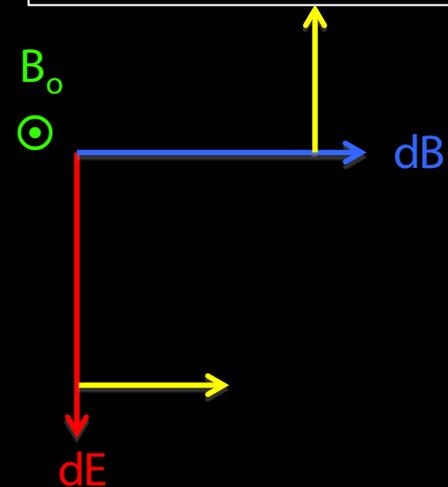
$$\omega_{pe} = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$$

$$\Omega_{ce} = \frac{eB_0}{m_e}$$

Broad Range of  
Frequencies

$$\Omega_{ci} \leq \omega \leq \Omega_{ce}$$

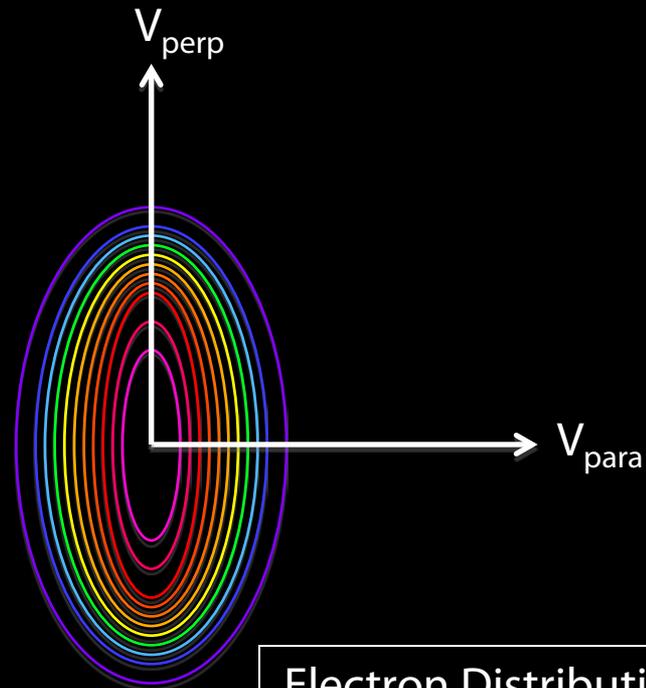
Right-hand polarized  
(with respect to  $B_0$ )



Can interact with both electrons and ions by: (1) Landau resonance, (2) cyclotron resonance [*Kennel and Petschek, 1966*], (3) nonlinear trapping [*Kellogg et al., 2010*], etc.

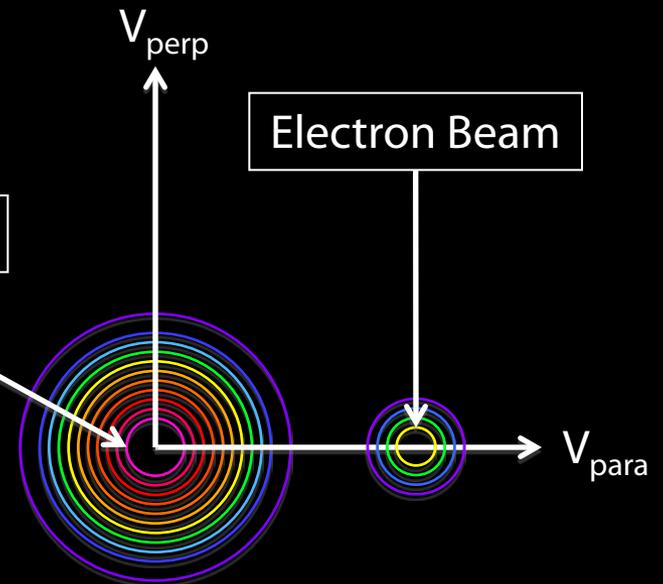
# Whistler Mode Waves: Generation

$T_{\text{perp}} > T_{\text{para}}$  : Temperature Anisotropy  
[*Kennel and Petschek, 1966*]



Electron Beam :  
[e.g. *Sauer and Sydora, 2010*]

Main Distribution



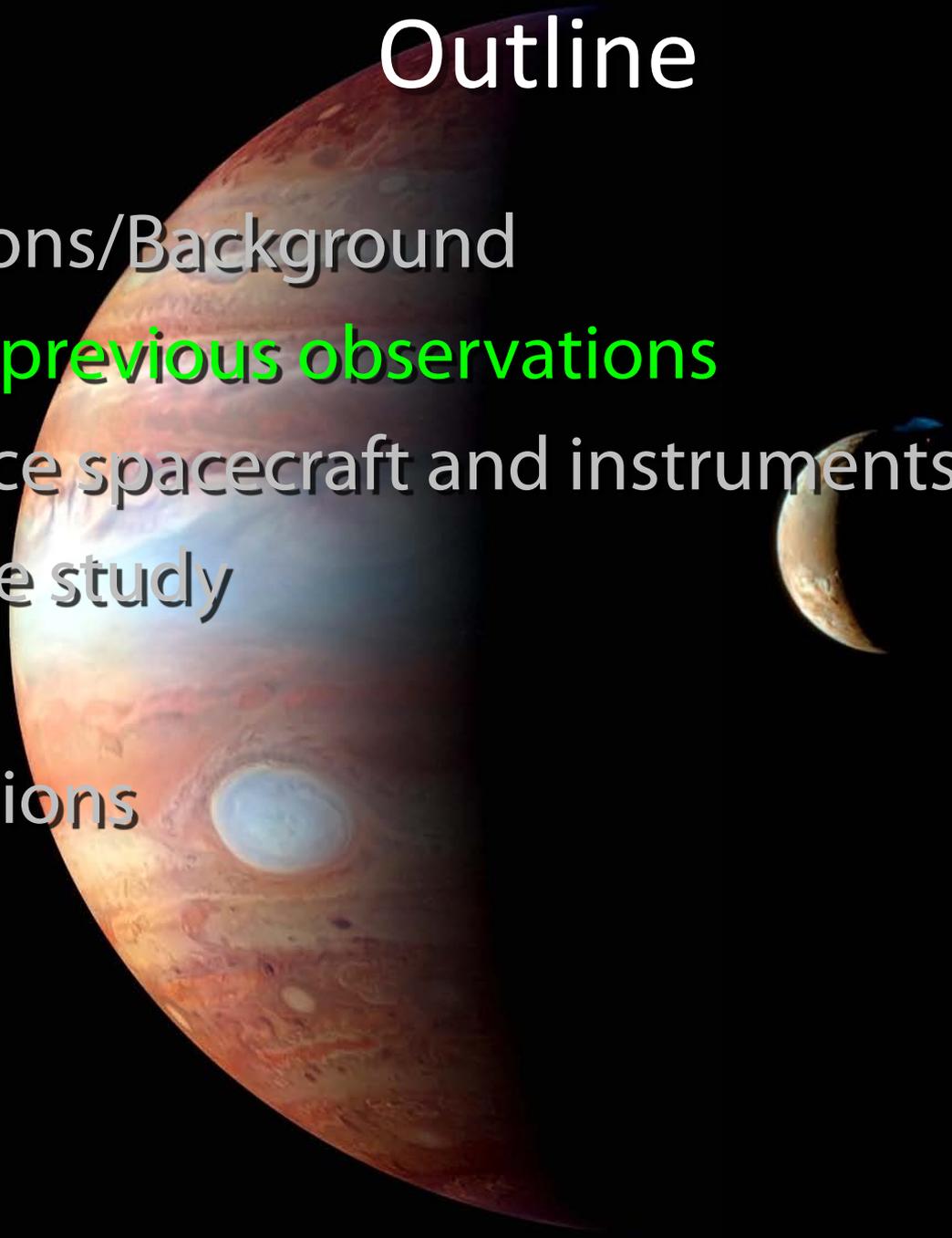
Para/Perp : With respect to  $B_0$

# Whistler Mode Waves: History

- Whistler mode waves were first discovered by Barkhausen in 1919 while listening to signals from an antenna connected to a simple vacuum tube [*Barkhausen, 1919*]
- Over 30 years later, *Storey [1953]* explained these “strange signals” as resulting from lightning strikes
- Since the advent of spacecraft, these ubiquitous wave modes have been observed in every space plasma environment including: **magnetosphere** [e.g. *Burtis and Helliwell, 1969*]; **solar wind** [e.g. *Neubauer and Musmann, 1977*]; **upstream of interplanetary shocks** [e.g. *Wilson III et al., 2009*, and ref. therein]; **upstream of planetary bow shocks** [e.g. *Hoppe et al., 1981*]; **upstream of cometary bow shocks** [e.g. *Tsurutani et al., 1987*]; and in **extraterrestrial magnetospheric environments** [*Sonnerup et al., 1981*]

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# Time-Averaged Spectral Intensity

*Gurnett et al., [2005]*

Note:  $10^{-6} \text{ (mV/m)}^2/\text{Hz}$  at 1 kHz =  $\sim 0.03 \text{ mV/m}$

Previous studies primarily focused on **time-averaged spectral intensity** data, with typical wave zero-to-peak amplitudes of  $dE \sim 0.5 \text{ mV/m}$  [e.g. *Meredith et al., 2001*], and  $\text{dB} \sim 0.01\text{-}0.1 \text{ nT}$  [e.g. *Horne et al., 2003; 2005*]

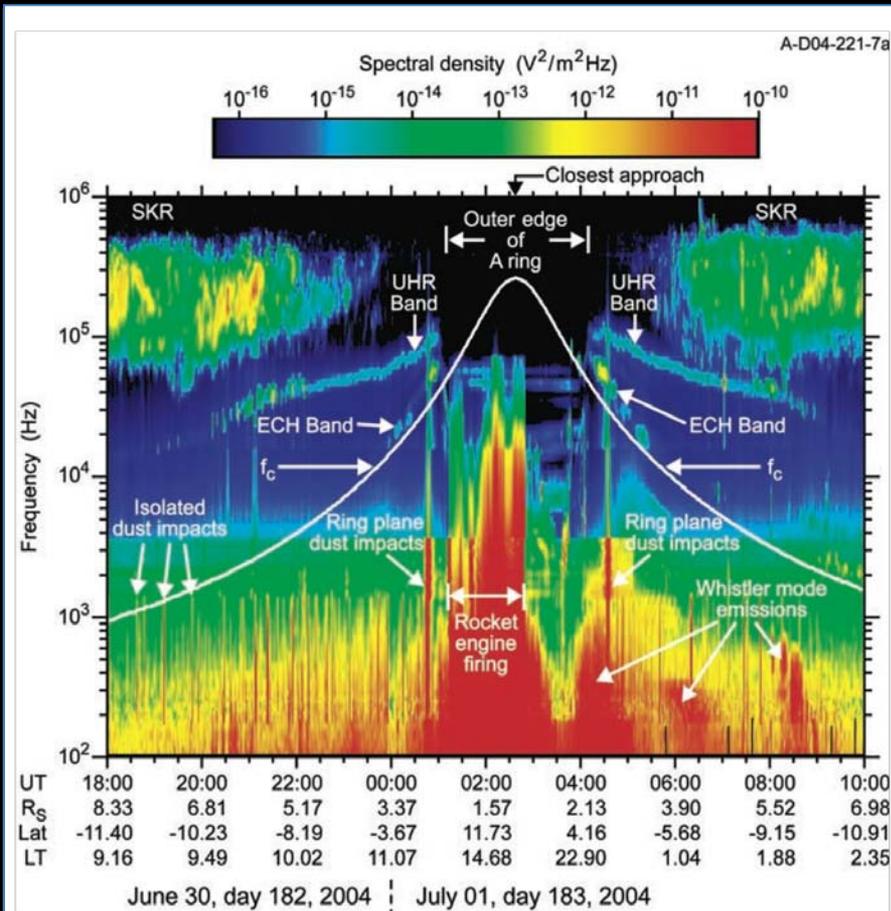


Fig. 3. A color frequency-time spectrogram showing the electric field intensities detected by the RPWS during the Cassini pass through the inner region of the saturnian magnetosphere. The intensities are coded according to the color scale at the top of the spectrogram. The white line is the  $f_c$  computed from Cassini magnetic field measurements (21). Lat., latitude; LT, local time.

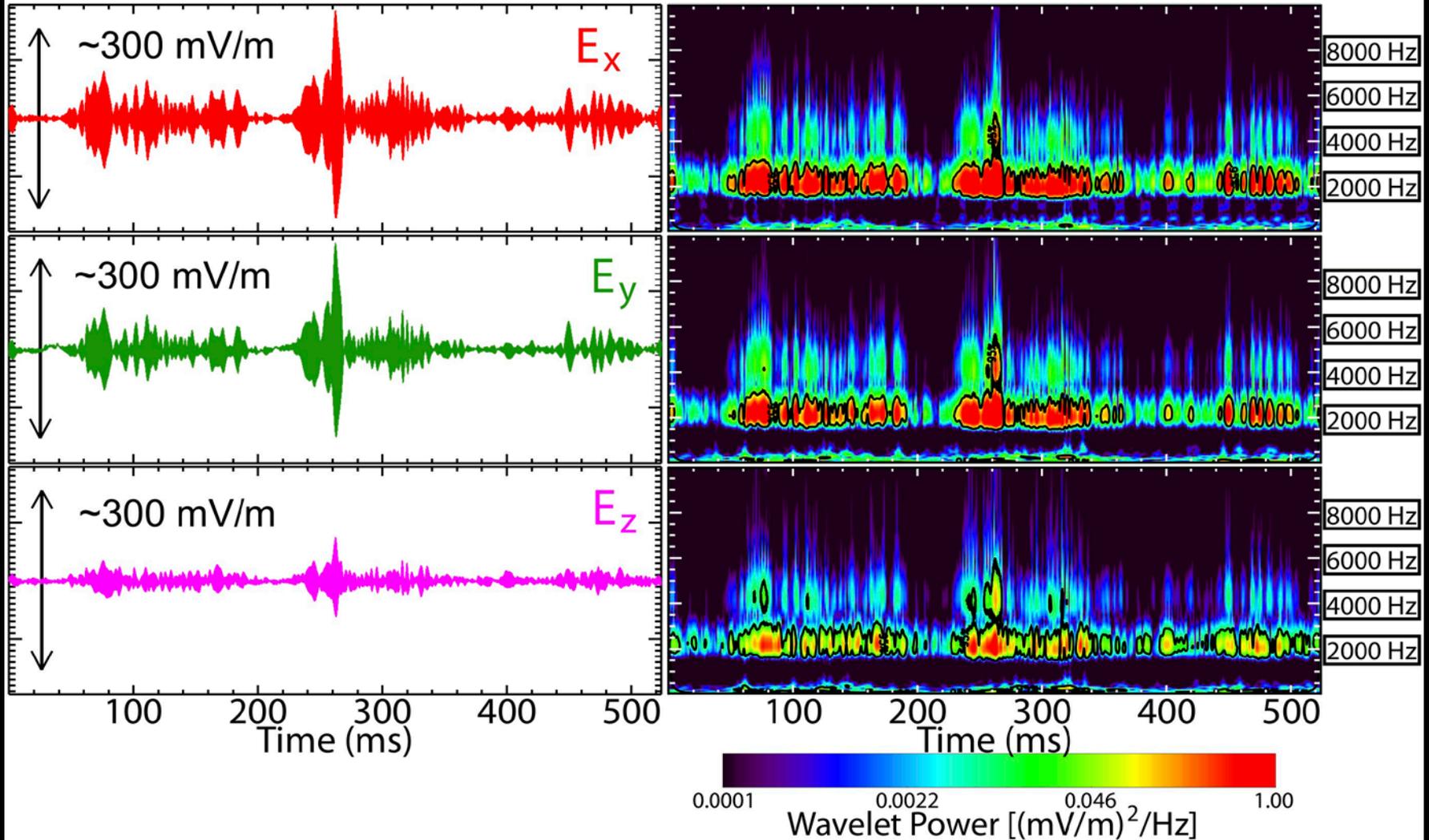
*Tsurutani et al., [2009]* showed that time-averaged spectral intensity data can severely underestimate the instantaneous wave amplitudes, shown by example in *Cully et al., [2008]*

# Waveform Captures

*Cattell et al., [2008]*

Recall Spectral Intensity Amplitudes =  $\sim 0.03\text{-}0.5$  mV/m

STB WAVES Electric Fields for 11:22:02.113 UT on 12/12/2006



# Previous Observations of Whistler Mode Waves

- *Cattell et al., [2008], Kersten et al., [2011], and Breneman et al., [2011]*, using test particle simulations, found the waves capable of producing MeV electrons in fractions of a second

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# Wind Spacecraft

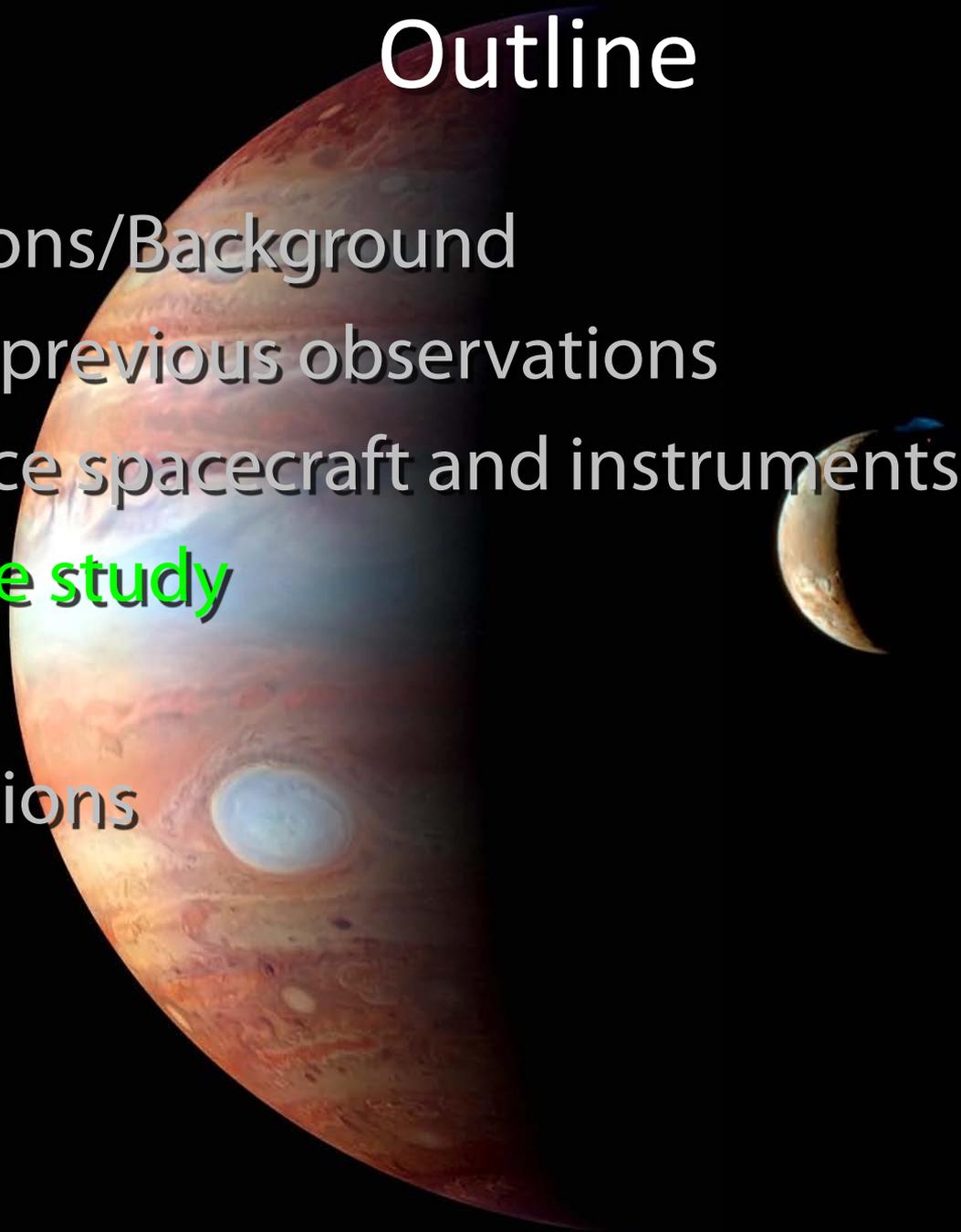


# Wind Spacecraft Instruments

Instrument Name	Instrument Type	Data Product	Time Resolution
Time Domain Sampler (TDS) [ <a href="#">Bougeret et al., 1995</a> ]	Electric: 2 orthogonal dipole wire (X,Y) and 1 stacer antenna (Z) Magnetic: 3 orthogonal search coil magnetometers	2-4 Electric and Magnetic field components vs. time	1875-120,000 samples per second
Magnetic Field Instrument (MFI) [ <a href="#">Lepping et al., 1995</a> ]	dual triaxial fluxgate magnetometers	3 component vector magnetic field	~0.33-22 samples per second
3DP [ <a href="#">Lin et al., 1995</a> ]	Low Energy: top-hat spherical section electrostatic analyzers High Energy: three arrays of double-ended solid state telescopes	full 4 $\pi$ steradian particle distributions from ~3 eV to >500 keV for electrons and ~80 eV to > 6 MeV for ions	Burst Mode: 3 second Survey Mode: 24 seconds and up

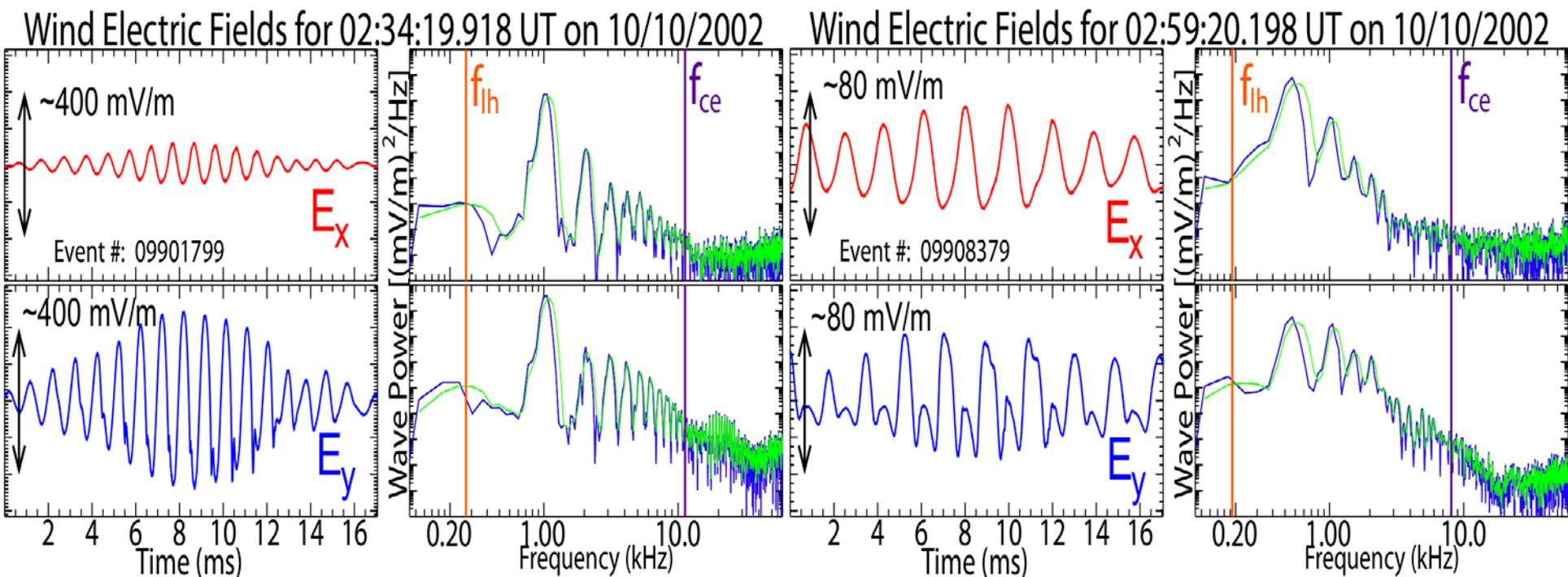
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# Whistler Mode Waves in the Radiation Belts: New Motivations

*Kellogg et al., [2010]* showed evidence for electron trapping



# Whistler Mode Waves in the Radiation Belts: New Motivations

- *Cattell et al., [2008]*, *Kersten et al., [2011]*, and *Breneman et al., [2011]*, using test particle simulations, found that large amplitude whistler mode waves are capable of producing MeV electrons in fractions of a second
- *Breneman et al., [2011]* found lightning- and transmitter-generated whistler mode waves in the inner plasmasphere ( $L < 2$ ) with amplitudes  $\sim 2$ - $3$  orders of magnitude larger than previous observations in this region
- *Kersten et al., [2011]* using STEREO, SAMPEX, and Wind observations found evidence for electron microburst production by large amplitude whistler mode waves.

# Outline



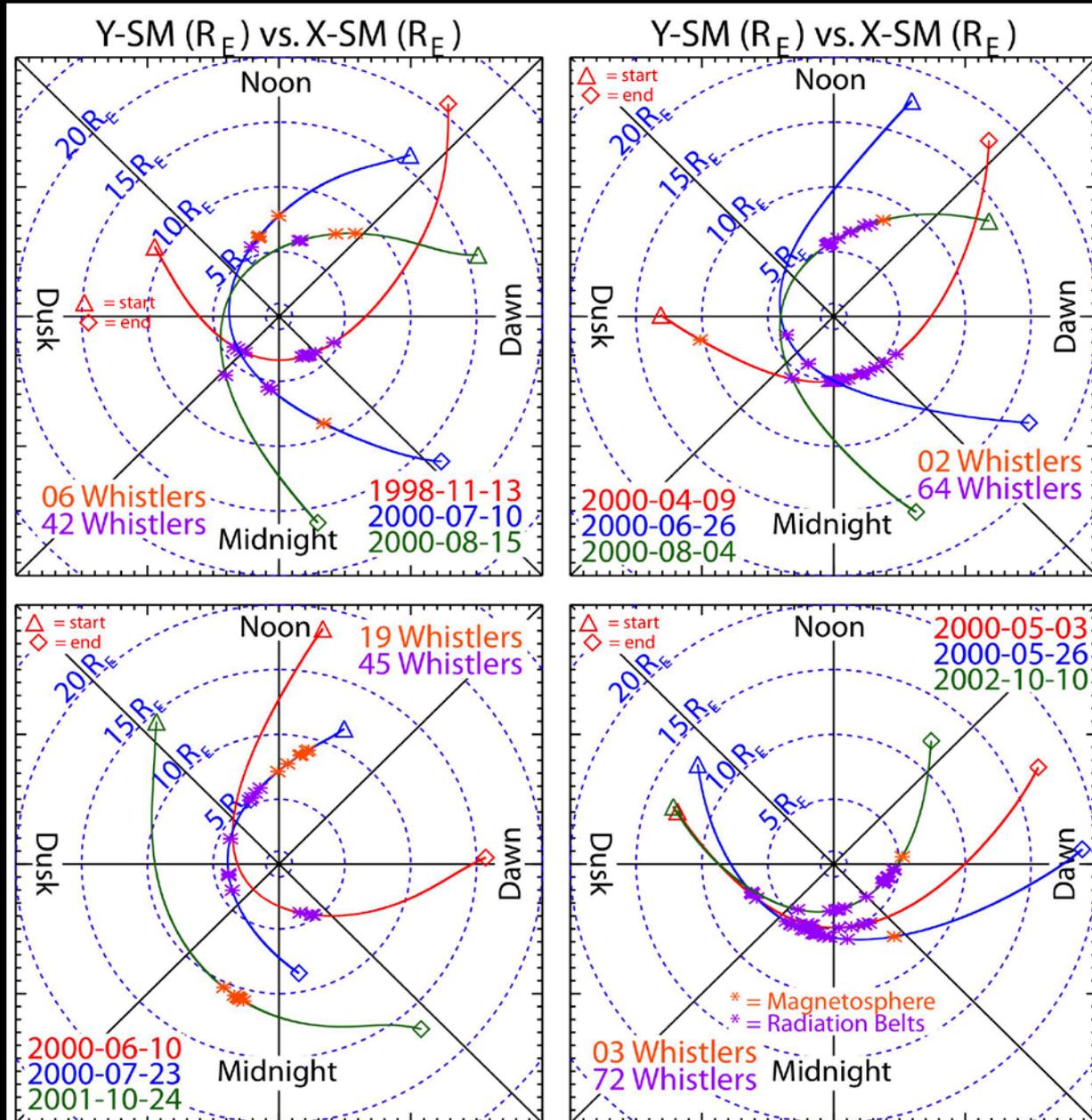
- Definitions/Background
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# Summary of Wind Observations

TDS Sample Statistics [= 247 Whistlers]  
[13 Orbits over 4 Years]

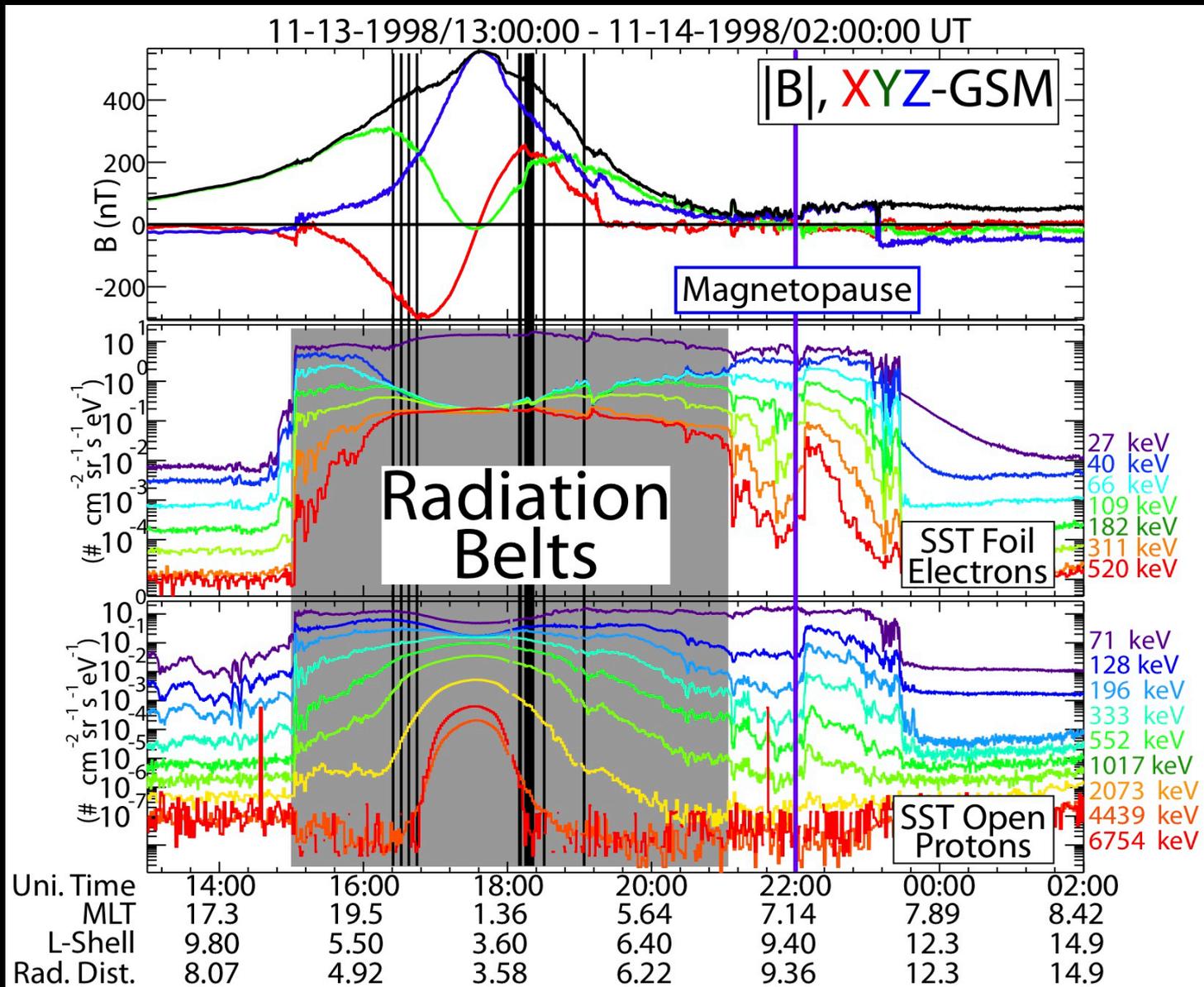
	Whistlers	Other	Hours Spent in Region
Radiation Belts	217	121	~60
Magnetosphere	30	416	~100

# Wind Petal Orbits



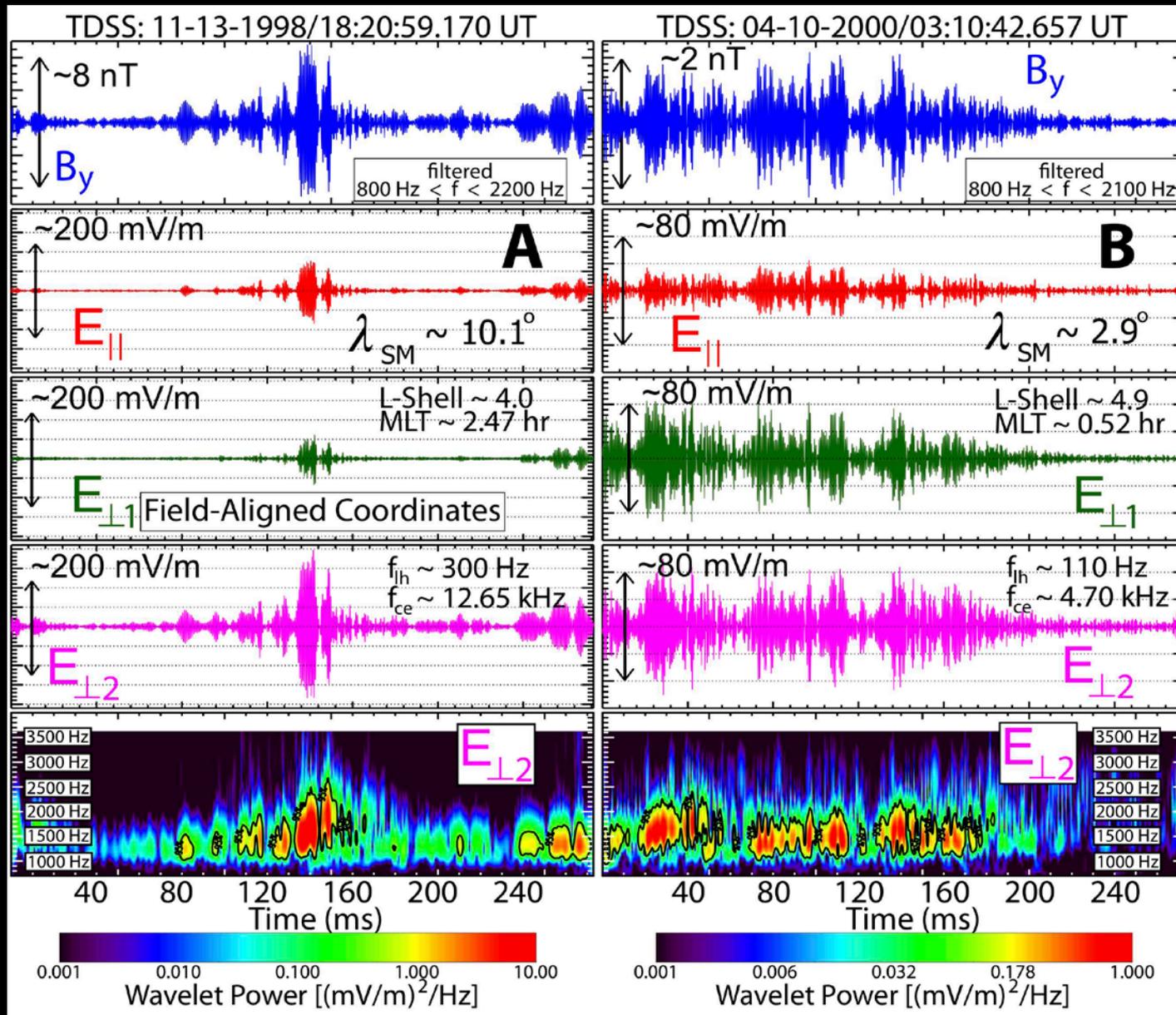
# Example Petal Orbit: Wind Observations

## *Wilson III et al., [2011]*



# Search Coil Observations (TDSS)

*Wilson III et al., [2011]*



Recall Spectral Intensity Amplitudes =  $\sim 0.03\text{-}0.5$  mV/m ( $\sim 0.01\text{-}0.1$  nT)

# Search Coil Observations

*Wilson III et al., [2011]*

## Search Coil Results:

- lower bound on Poynting flux  $\geq 300 \text{ mW/m}^2$ ,  $\sim 4$  orders of magnitude above previous estimates [e.g. *Santolik et al., 2010*]
- Use of minimum variance analysis (MVA) produced propagation direction angles (or wave normal angles) with respect to the magnetic field,  $q_{\text{kB}}$ , up  $\sim 50^\circ$ , much more oblique than predicted by theory
- $\geq 8 \text{ nT}$  peak-to-peak wave amplitudes,  $\sim 2$  orders of magnitude above previous observations [e.g. *Horne et al., 2003; 2005*]
- No relationship between GSM latitude,  $I_{\text{GSM}}$ , and  $q_{\text{kB}}$  a relationship predicted by theory [e.g. *Bortnik et al., 2007; 2008*]

# Relationship to Geomagnetic Activity

## *Wilson III et al., [2011]*

### Wind Results:

- 162/247 of the whistlers are observed during magnetically active periods ( $AE > 200$  nT)
- cursory examination of LANL geosynchronous low energy ( $\sim 30$ -300 keV) electrons show substorm injections prior and/or during each petal orbit, consistent with substorm related free energy sources [e.g. *Li et al., 2009*]
- We observe 114/247 when  $|I_{GSM}| \leq 5^\circ$ , 166/247 when  $|I_{GSM}| \leq 10^\circ$ , and 188/247 when  $|I_{GSM}| \leq 15^\circ$
- 154/247 of the whistlers are observed  $21 \text{ hrs} \leq \text{MLT} \leq 3 \text{ hrs}$  (i.e., nightside) while only 39/247 were between  $6 \text{ hrs} \leq \text{MLT} \leq 18 \text{ hrs}$  (i.e., dayside)
- The observation of waves between  $21 \text{ hrs} \leq \text{MLT} \leq 24 \text{ hrs}$  suggests that some of the waves are not driven by the standard model of substorm injection [*Thomsen, 2004*]  
{limited coverage of Wind observations make MLT and  $I_{GSM}$  distributions impossible to determine}

# Amplitude Statistics

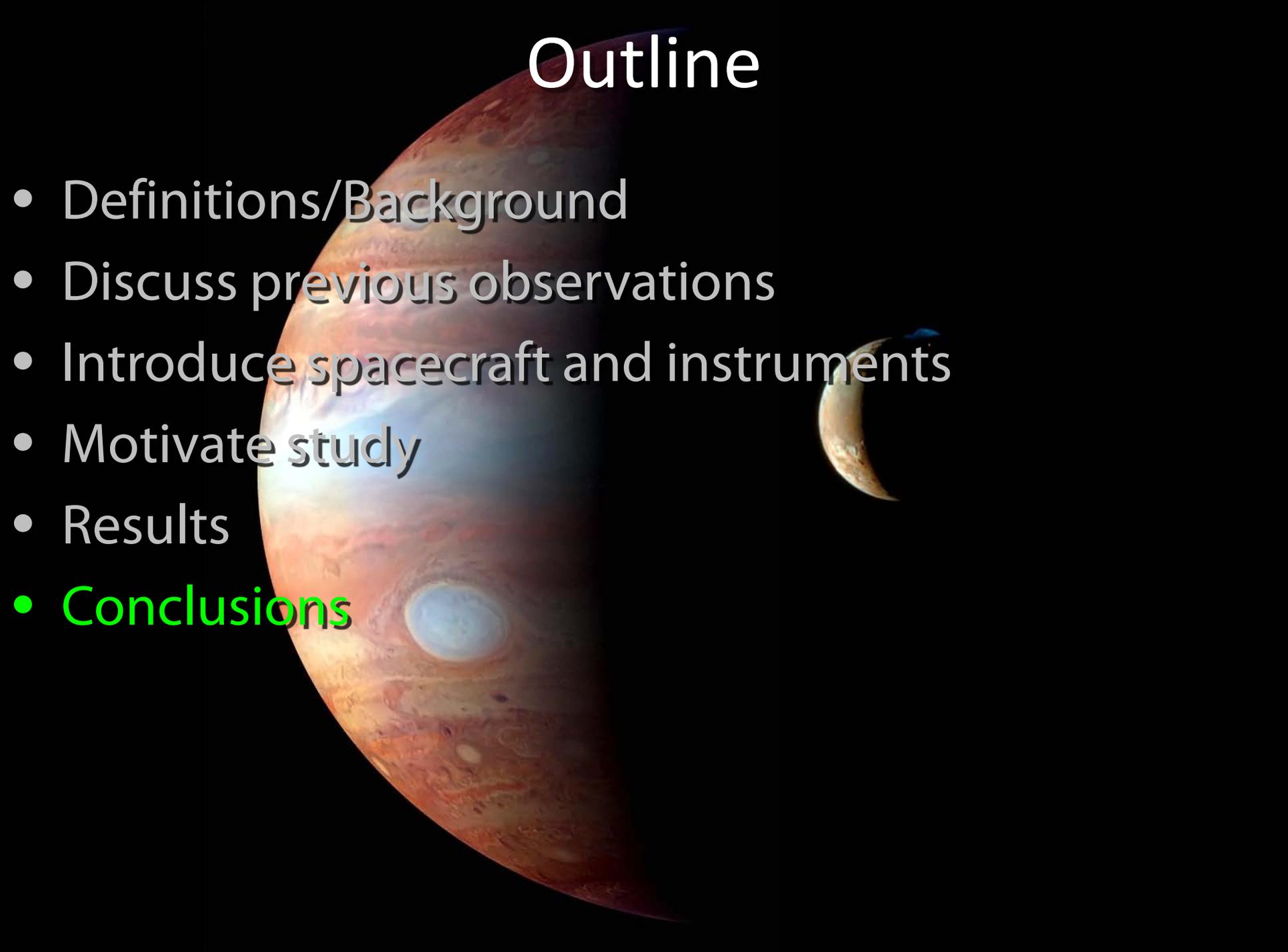
*Wilson III et al., [2011]*

TDS Results:

- 1) 191/247 of the whistlers were measured with at least 2 (TDSF) or 3 (TDSS) dE
- 2) 56/247 of the whistlers were measured with at least 3 (TDSS) dB
- 3) 247/247 had at least 1 dE and 66/247 had at least 1 dB

Amplitude Statistics [peak-to-peak]			
$ dE  \geq 80 \text{ mV/m}$	$ dB  \geq 0.8 \text{ nT}$	$ dE  \geq 160 \text{ mV/m}$	$ dB  \geq 1.6 \text{ nT}$
104/191	28/56	53/191	8/56
105/247	38/66	53/247	18/66

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# Conclusions: Amplitudes

- $\geq 8$  nT peak-to-peak ( $\geq 300$  mV/m peak-to-peak) wave amplitudes are the largest search coil whistler mode wave observations in the radiation belts {~1-2 orders of magnitude above previous observations}
- Poynting flux estimates ( $\geq 300$  mW/m<sup>2</sup>) are consistent with rapid electron energization {~4 orders of magnitude above previous estimates [e.g. Santolik et al., 2010]}
- Large Poynting flux estimates combined with test particle simulations by Cattell et al., [2008] and Kersten et al., [2011] suggest these very large amplitude waves affect local radiation belt dynamics on time scales of hours or even minutes {~1-2 orders of magnitude faster than previous estimates}

# Conclusions

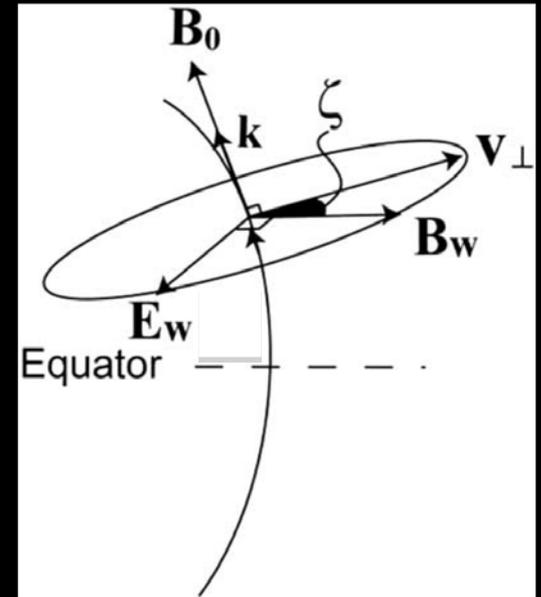
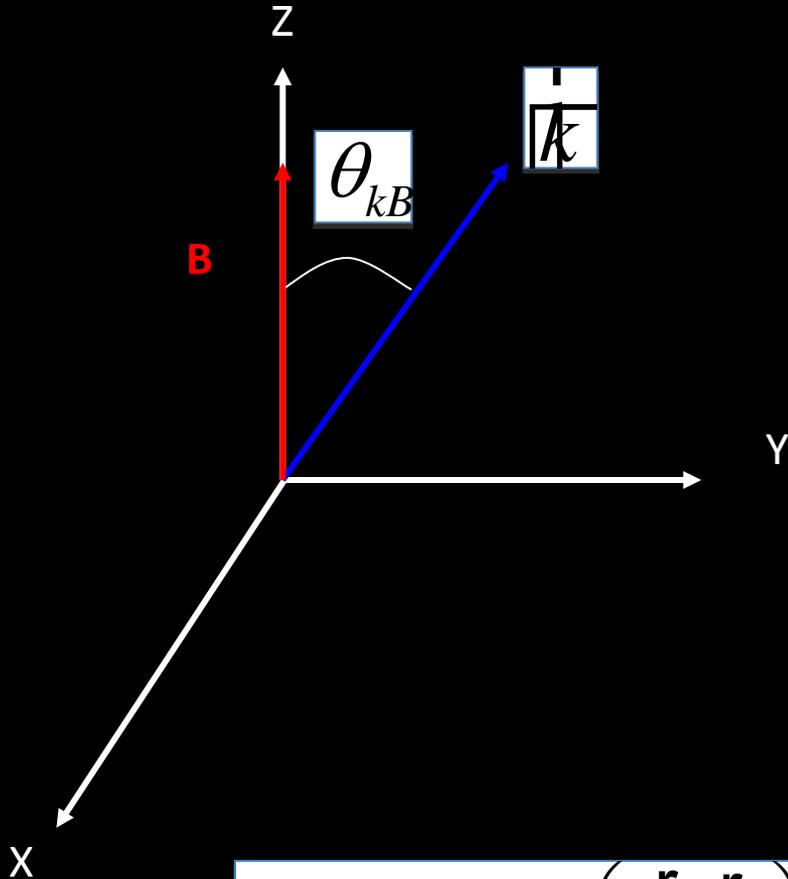
- The waves propagate much more obliquely than predicted by theory (up to  $\sim 50^\circ$ )
- No relationship between  $I_{GSM}$  and  $q_{kB}$ , thus waves do not appear to become more oblique as they propagate
- The majority (162/247) of the waves are observed with  $AE > 200$  nT, but many are observed between  $21 \text{ hrs} \leq \text{MLT} \leq 24 \text{ hrs}$ , thus **cannot be driven by standard substorm injection models**

# Conclusions

- In addition to our results, recent Wind [*Kellogg et al., 2011*], STEREO [*Cattell et al., 2008; Breneman et al., 2011; Kersten et al., 2011*], and THEMIS [*Cully et al., 2008*] observations, we argue that **large amplitude whistler mode waves may not be a rare phenomena in the radiation belts**
- Large Poynting flux estimates combined with test particle simulations by *Cattell et al., [2008]* and *Kersten et al., [2011]* suggest these large amplitude whistler mode waves may play an important role in global radiation belt dynamics

# Extras

# Coordinate Systems Definitions



$$\theta_{kB} = \text{Cos}^{-1} \left( \frac{\mathbf{k} \cdot \mathbf{B}}{|\mathbf{k}| |\mathbf{B}|} \right)$$

# Previous Observations of Whistler Mode Waves

- *Cattell et al., [2008]* discovered whistler mode waves in the radiation belts with  $dE > 200$  mV/m using the STEREO spacecraft

# Previous Observations of Whistler Mode Waves

- Later studies using THEMIS [*Cully et al., 2008*] and Wind [*Kellogg et al., 2011*] supported the observations of *Cattell et al., [2008]*

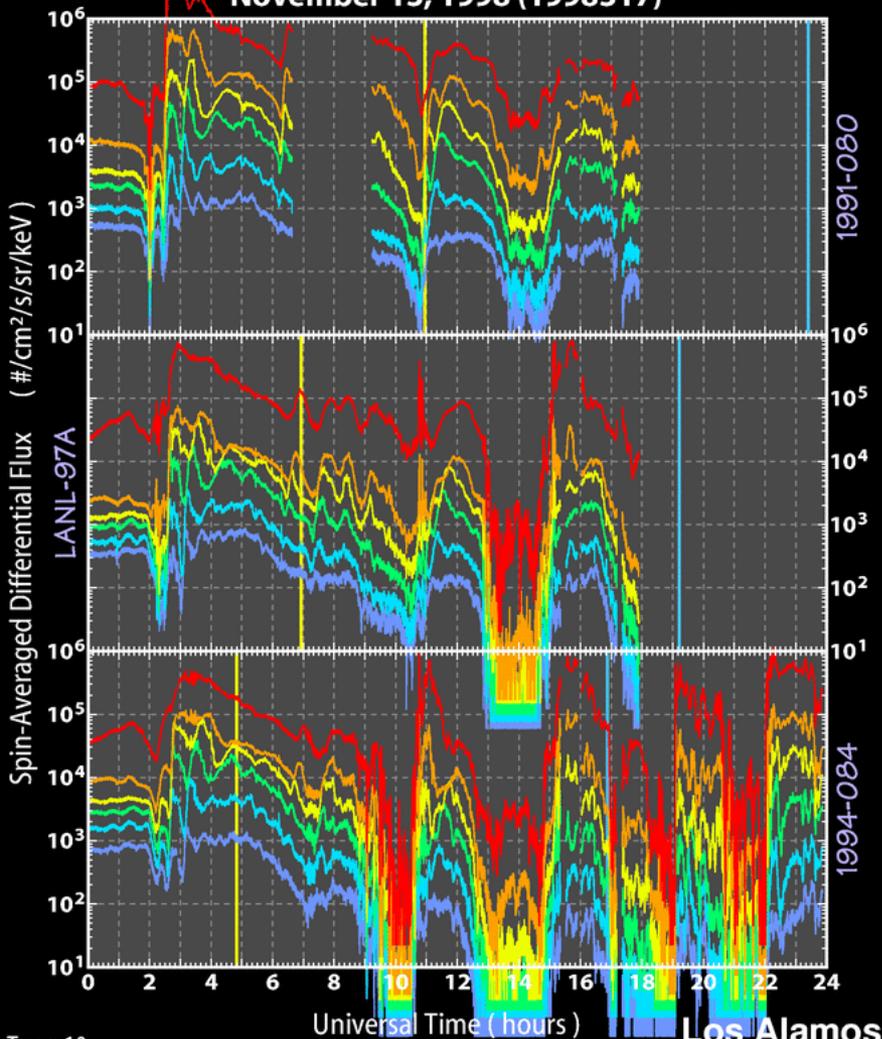
# Relationship to Geomagnetic Activity

*Wilson III et al., [2011]*

*Cattell et al., [2008]*

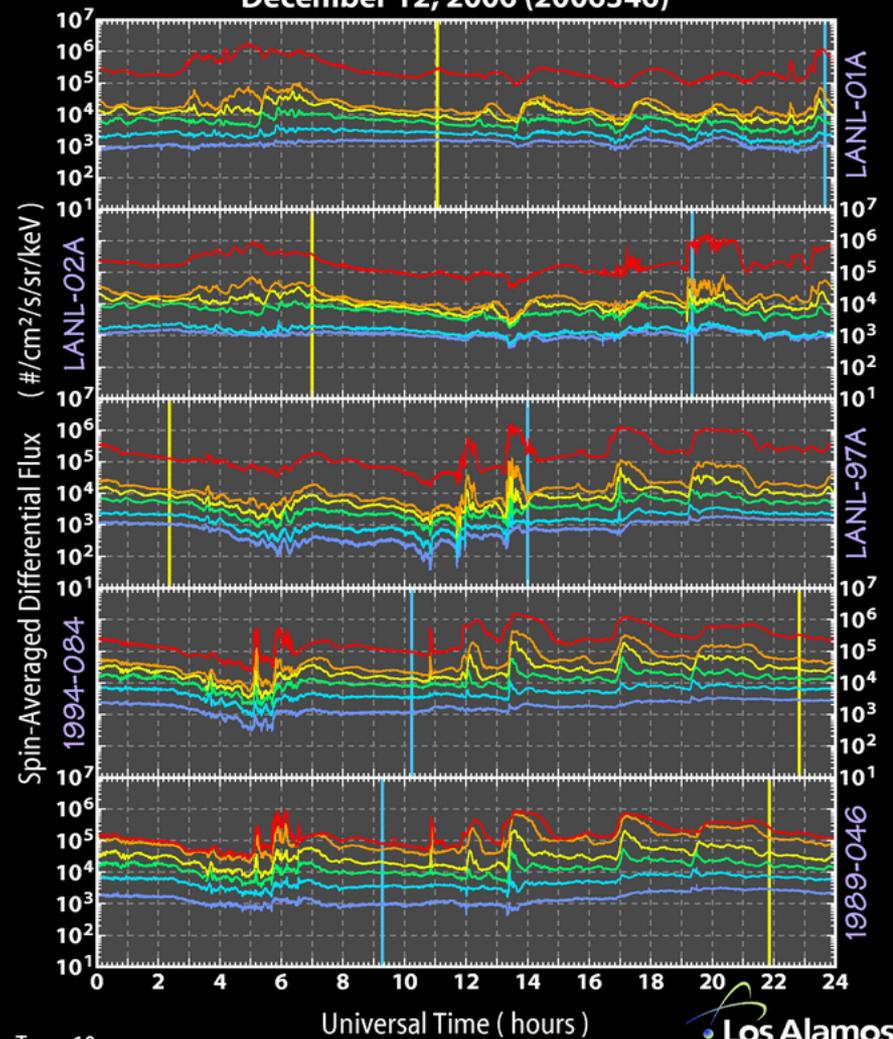
**LANL Geosynchronous Electron Data (LoE)**

November 13, 1998 (1998317)



**LANL Geosynchronous Electron Data (LoE)**

December 12, 2006 (2006346)



# Whistler Mode Waves: Generation

- Early theories showed that an over abundance of perpendicular electron kinetic energy (i.e.  $T_{\text{perp}}/T_{\text{para}} > 1$ ) due to substorm injection is a source of free energy for whistler mode wave growth [*Kennel and Petschek, 1966*]
- More recently [*Tokar et al., 1984; Zhang et al., 1993; Sauer and Sydora, 2010*], theorists have suggested that electron beams propagating parallel to the magnetic field can drive oblique (i.e.  $q_{\text{kB}} \neq 0^\circ$ ) whistler mode waves unstable (i.e. they grow)
- There are numerous other free energy sources in different space plasma regimes...

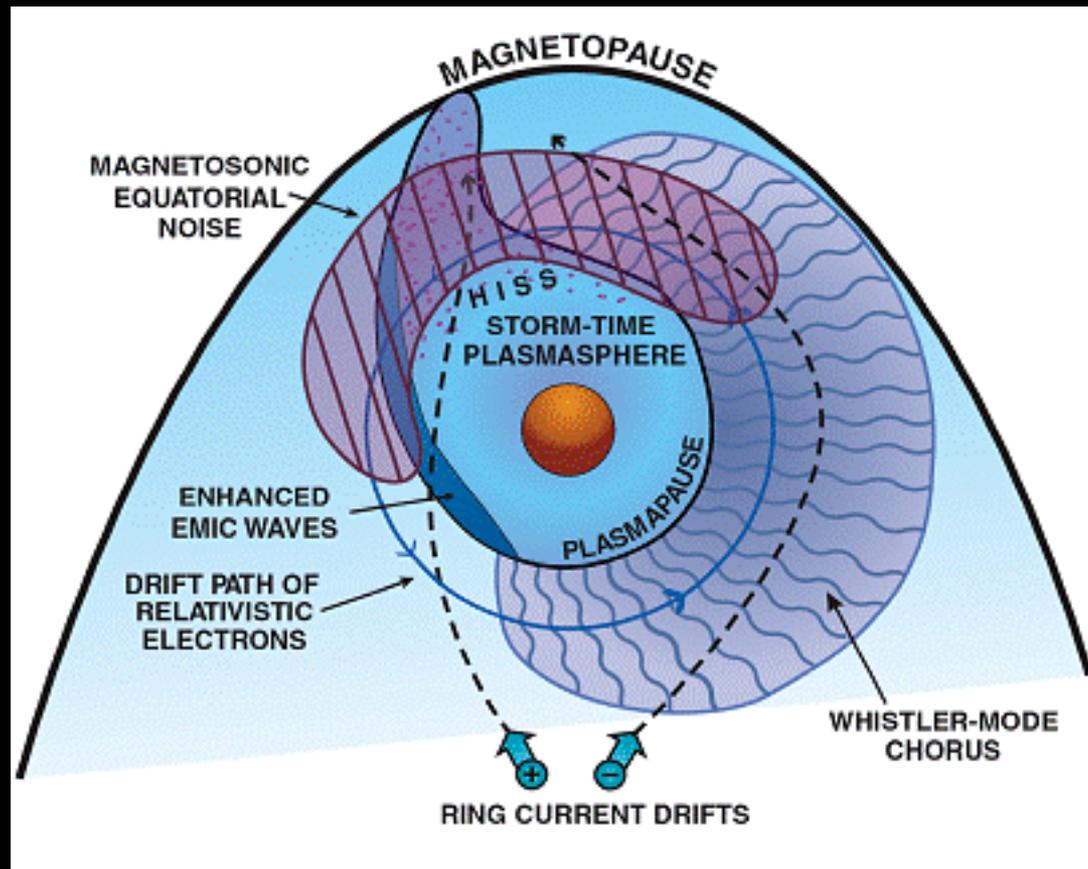
# Definitions

- **Wave Vector,  $\mathbf{k}$** : defines the direction of propagation and wavelength of phase fronts of a wave
- **Electromagnetic (EM)**: wave with finite electric (dE) and magnetic (dB) field fluctuations at oblique angles to the background ambient magnetic field ( $B_0$ )
- **Electrostatic (ES)**: wave with finite dE parallel to  $\mathbf{k}$
- **Dispersive**: frequency depends upon the wave number,  $\mathbf{k}$  or vice versa
- **Wave Normal Angles**: propagation direction angles with respect to the magnetic field,  $\theta_{\mathbf{k}B}$
- **Landau Interactions**: phase fronts of wave accelerate(decelerate) particles with velocities lower(higher) than the phase speed of the waves, which causes wave damping(growth)
- **Cyclotron Interactions**: rotating dE in phase with gyration of particles causes an acceleration(deceleration) perpendicular to  $B_0$  which leads to wave damping(growth)

# Conclusions

- Poynting flux estimates ( $\geq 300 \text{ mW/m}^2$ )  $\sim 4$  orders of magnitude above previous estimates [e.g. [Santolik et al., 2010](#)] are consistent with rapid electron energization
- The waves propagate much more obliquely than predicted by theory
- $\geq 8 \text{ nT}$  peak-to-peak wave amplitudes are the largest search coil whistler mode wave observations in the radiation belts
- No relationship between  $l_{\text{GSM}}$  and  $q_{\text{KB}}$ , thus waves do not appear to become more oblique as they propagate
- The majority (162/247) of the waves are observed with  $AE > 200 \text{ nT}$ , but many are observed between  $21 \text{ hrs} \leq \text{MLT} \leq 24 \text{ hrs}$ , thus cannot be driven by standard substorm injection models

# The Standard Model for Wave Growth



# Previous Observations of Whistler Mode Waves

- Previous studies primarily focused on **time-averaged spectral intensity** data, with typical wave zero-to-peak amplitudes of  $dE \sim 0.5$  mV/m [e.g. *Meredith et al., 2001*], and  $dB \sim 0.01$ - $0.1$  nT [e.g. *Horne et al., 2003; 2005*]
- *Tsurutani et al., [2009]* showed that time-averaged spectral intensity data can severely underestimate the instantaneous wave amplitudes, shown by example in *Cully et al., [2008]*
- *Cattell et al., [2008]* discovered whistler mode waves in the radiation belts with  $dE > 200$  mV/m using the STEREO spacecraft
- Later studies using THEMIS [*Cully et al., 2008*] and Wind [*Kellogg et al., 2011*] supported these observations
- *Cattell et al., [2008]*, *Kersten et al., [2011]*, and *Breneman et al., [2011]*, using test particle simulations, found the waves capable of producing MeV electrons in fractions of a second

# Whistler Mode Waves in the Radiation Belts: Early Work

- Low energy electron acceleration by low amplitude whistler mode waves (specific type: **chorus**) has been accepted as an important process in global radiation belt dynamics [e.g. *Roth et al., 1999; Horne et al., 2005; Albert and Young, 2005*]
- Early work [e.g. *Lyons et al., 1972*] suggested gap between the inner and outer radiation belts (called the slot region) was caused by pitch-angle diffusion by whistler mode waves (specific type: **plasmaspheric hiss**), which has been supported by more recent studies [e.g. *Meredith et al., 2004; Horne et al., 2005; Meredith et al., 2006*]
- Small amplitude [ $\leq 0.1$  nT by e.g. *Horne et al., 2003*;  $> 0.5$  mV/m by e.g. *Meredith et al., 2001*] assumptions result from the use of **time-averaged spectral intensity** data, which is useful for statistical studies but does not characterize the instantaneous wave amplitudes
- Simulation/Theoretical studies use these small amplitudes and predict high energy ( $> 100$  keV) electron loss with time scales of  $\sim$ day(s) [e.g. *Thorne et al., 2005; Bortnik and Thorne, 2007; Meredith et al., 2003; 2007; 2009*] and acceleration with similar time scales [e.g. *Horne et al., 2005*]

# Whistler Mode Waves in the Radiation Belts: Predicted Impacts

- Global radiation belt dynamics studies show that bulk radial diffusion underestimates flux enhancements during storm times by up to a factor of 5 [*Brautigam and Albert, 2000*], which suggested another acceleration mechanism [e.g. *Horne et al., 2003*]
- Whistler mode waves were originally thought to produce electron microbursts – bursty energetic particle precipitation into the ionosphere - [e.g. *Oliven and Gurnett, 1968; Oliven et al., 1968*], which has been supported in more recent studies [e.g. *Blake et al., 1996; Lorentzen et al., 2001*]
- Observations of whistler mode wave Poynting flux using Cluster show average values of  $0.05 \text{ mW/m}^2$  [*Santolik et al., 2010*], which resulted in predictions of timescales of days for changes of relativistic electron fluxes in the outer radiation belt

# Whistler Mode Waves in the Radiation Belts: New Motivations

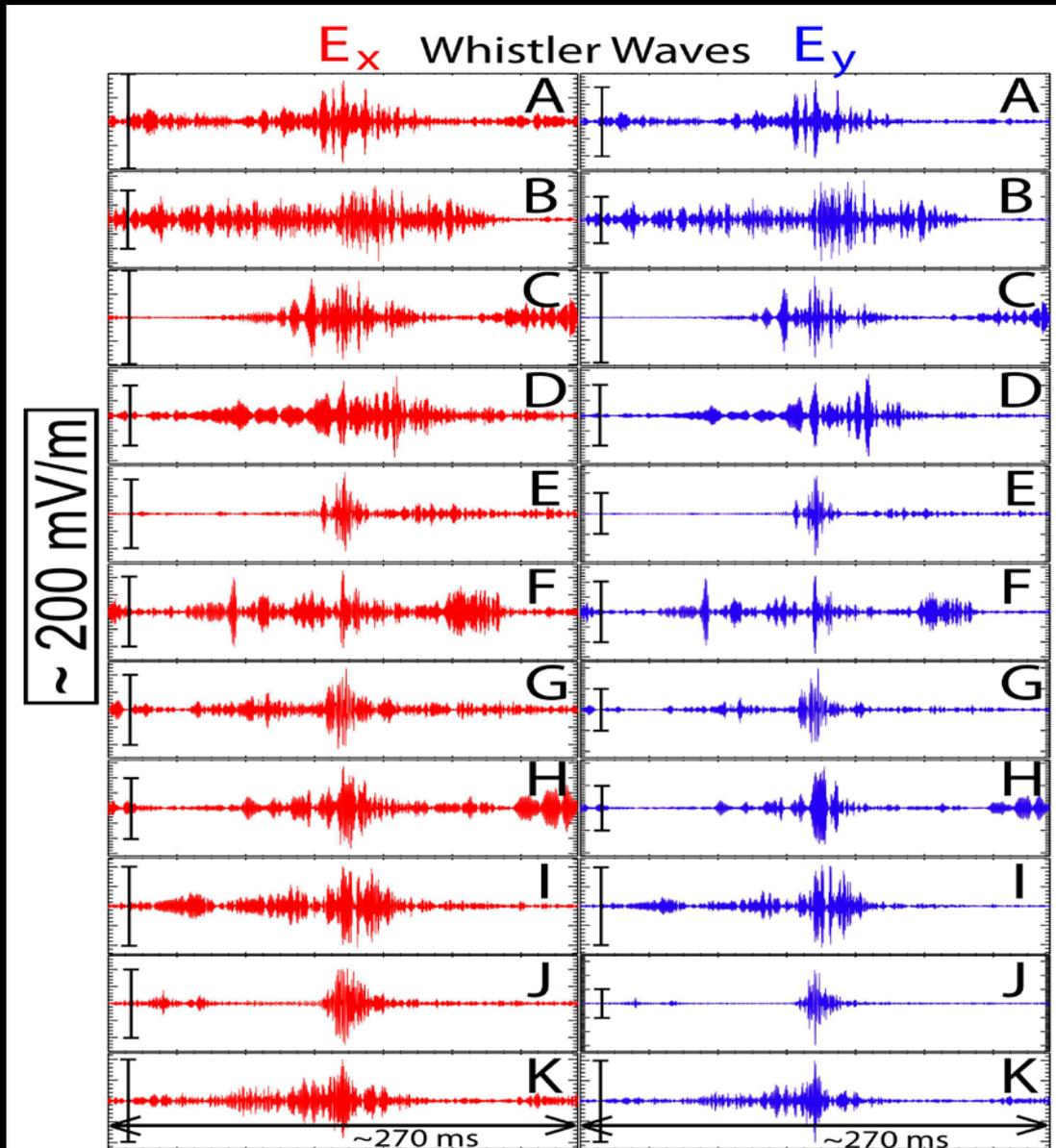
- *Cattell et al., [2008]*, *Kersten et al., [2011]*, and *Breneman et al., [2011]*, using test particle simulations, found that large amplitude whistler mode waves are capable of producing MeV electrons in fractions of a second
- *Breneman et al., [2011]* found lightning- and transmitter-generated whistler mode waves in the inner plasmasphere ( $L < 2$ ) with amplitudes  $\sim 2$ -3 orders of magnitude larger than previous observations in this region
- *Kersten et al., [2011]* using STEREO, SAMPEX, and Wind observations found evidence for electron microburst production by large amplitude whistler mode waves. Their test particle simulations found the waves capable of producing MeV electrons in fractions of a second.
- *Cattell et al., [2008]*, using cold plasma theory, estimated  $\delta B \sim 0.5$ -2.0 nT for the observed whistler mode waves, thus the maximum resulting Poynting flux (using  $\delta E \sim 200$  mV/m) would be  $\sim 40$ -160 mW/m<sup>2</sup>,  $\sim 2$ -3 orders of magnitude larger than estimates of *Santolik et al., [2010]*, which means predictions of timescales for changes of relativistic electron fluxes in the outer radiation belt may be drastically inaccurate
- *Kellogg et al., [2010]* using STEREO and Wind observations showed evidence of wave trapping due to whistler mode waves, causing kV potentials and significant density perturbations

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- *Tsurutani et al., [2009]* showed that time-averaged spectral intensity data can severely underestimate the instantaneous wave amplitudes, shown by example in *Cully et al., [2008]*

# Electric Field Observations (TDSF)

*Wilson III et al., [2011]*



Recall Spectral Intensity Amplitudes =  $\sim 0.03$ - $0.5$  mV/m