STEREO observations of large amplitude whistlers in Earth's radiation belts: Implications for relativistic electron acceleration and loss

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Discovery of very large amplitude whistler-mode waves in Earth's radiation belts

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I. Brief introduction to studies of whistlers in radiation belts

II. Overview of Dec. 12, 2006 STEREO radiation belt passage

III. S/WAVES TDS data

IV. Test particle studies of effect of waves on electrons

V. Comparison of STEREO-A and STEREO-B passes-’new’ belt

VI. SAMPEX data - MeV electron loss from radiation belt

VII. Conclusions

1) Whistler waves with amplitudes >200 mV/m observed in outer belt
2) Non-dispersive, obliquely propagating with large longitudinal component
3) Waves have dramatic effects on electrons in tenths of a second
4) ST-A/ST-B comparison shows short time-scale for MeV flux enhancements, consistent with test particle simulations
5) Rapid loss consistent with SAMPEX microburst observations

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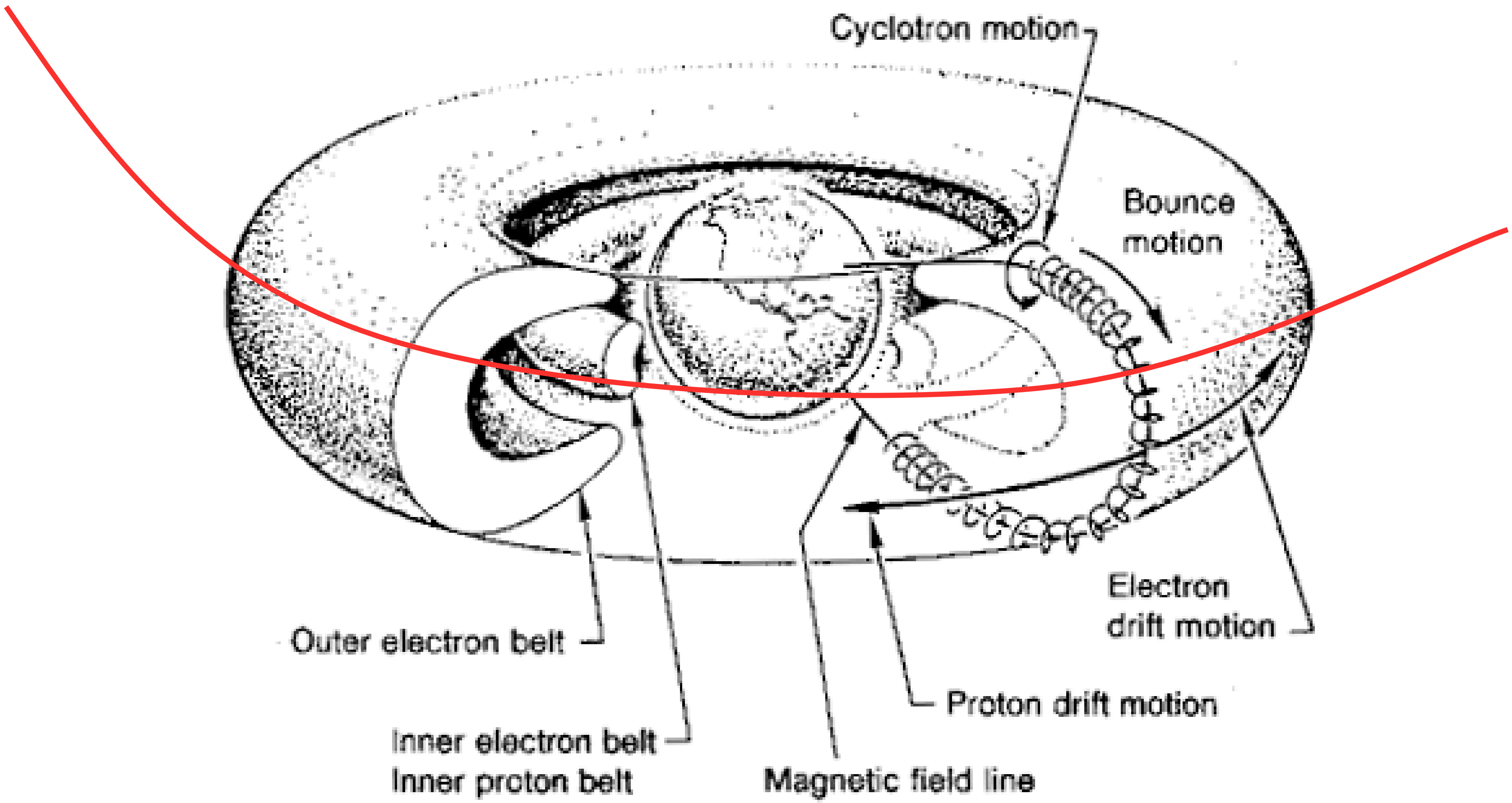
Usual QL approach (timescales of many hours to days) may be inadequate for radiation belt dynamics

On 12/6/2006 STEREO traversed radiation belts entering on afternoon side, exiting on morning side. 1.6 hr delay between A and B.



Three adiabatic invariants. For a 1 MeV electron in the outer belt, timescales are approximately 0.0001s (gyration), 0.5s (bounce) and 3000s (drift).

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Whistlers and radiation belts

- Stably trapped fluxes (Kennel and Petschek, 1966): $\omega - k_{||} v_{||} = m\Omega_e/\gamma$
- Focus on whistlers as scattering (loss) mechanism, primarily parallel waves
- Several studies (Temerin et al.,Alpert, Roth et al.) examined acceleration via whistlers and effect of waves with **k** oblique to **B**
- Explosion of studies of scattering and energization, primarily taking quasi-linear approach.
- Some research using coherent acceleration (most small amplitude, ~.1-1 mV/m). Several new studies motivated by Cluster 30 mV/m observation (still parallel) found nonlinear acceleration/trapping
- Whistler observational studies have primarily used frequency domain data and low time resolution, so large amplitudes could be missed

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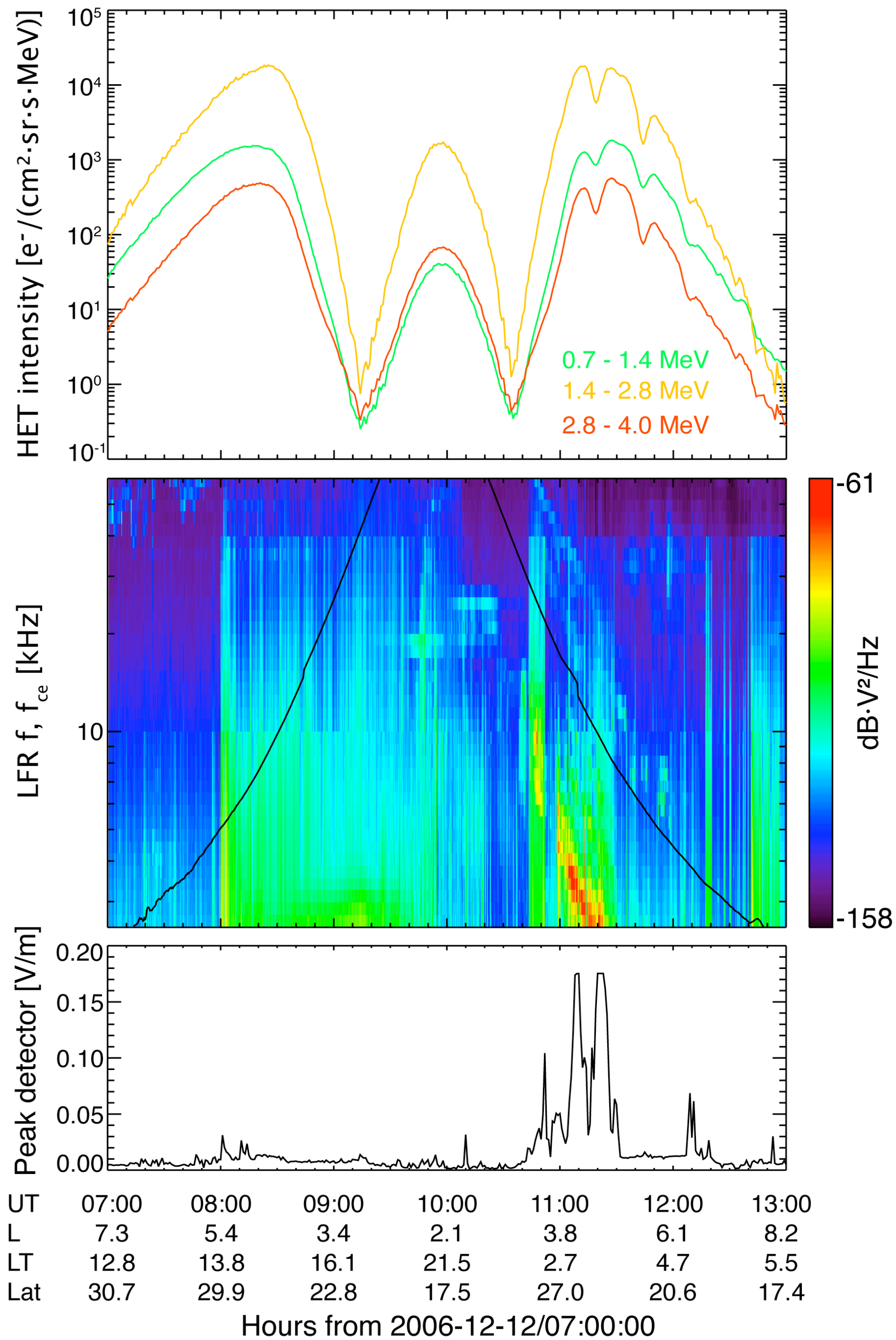
STEREO-B Dec. 12, 2006



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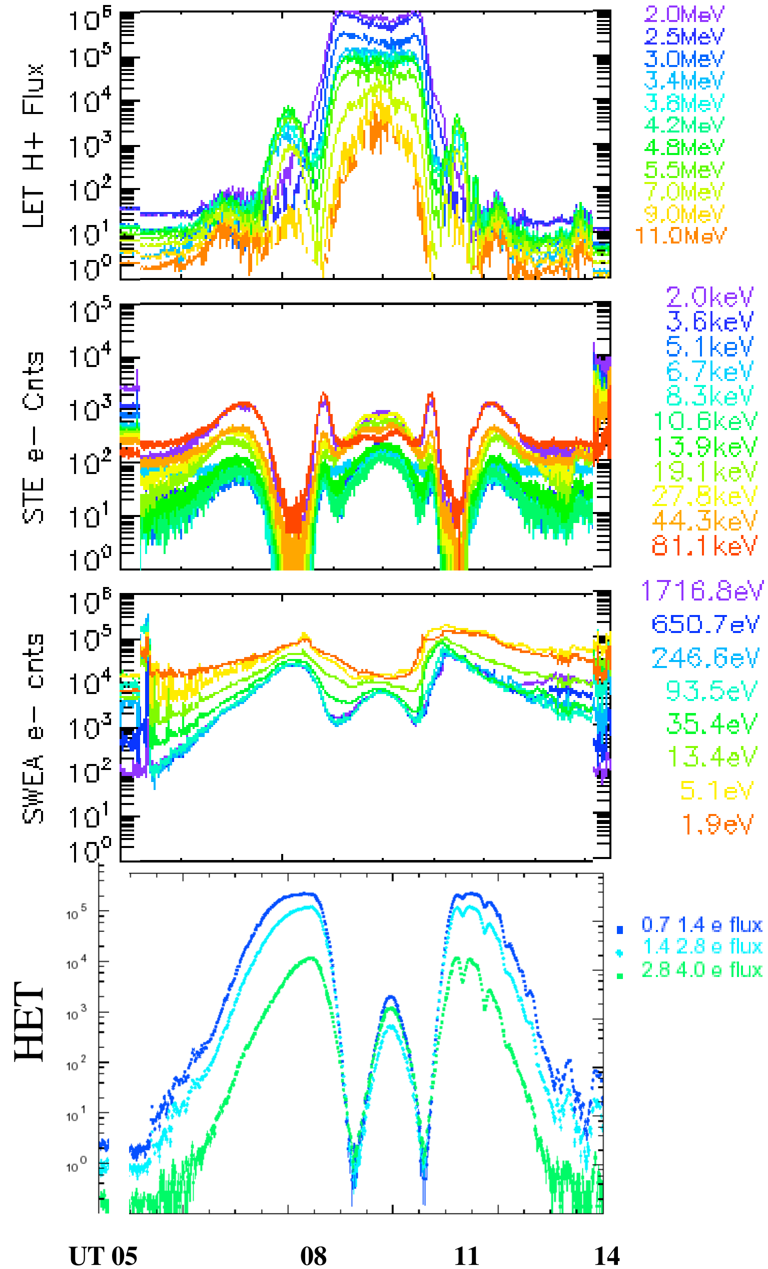

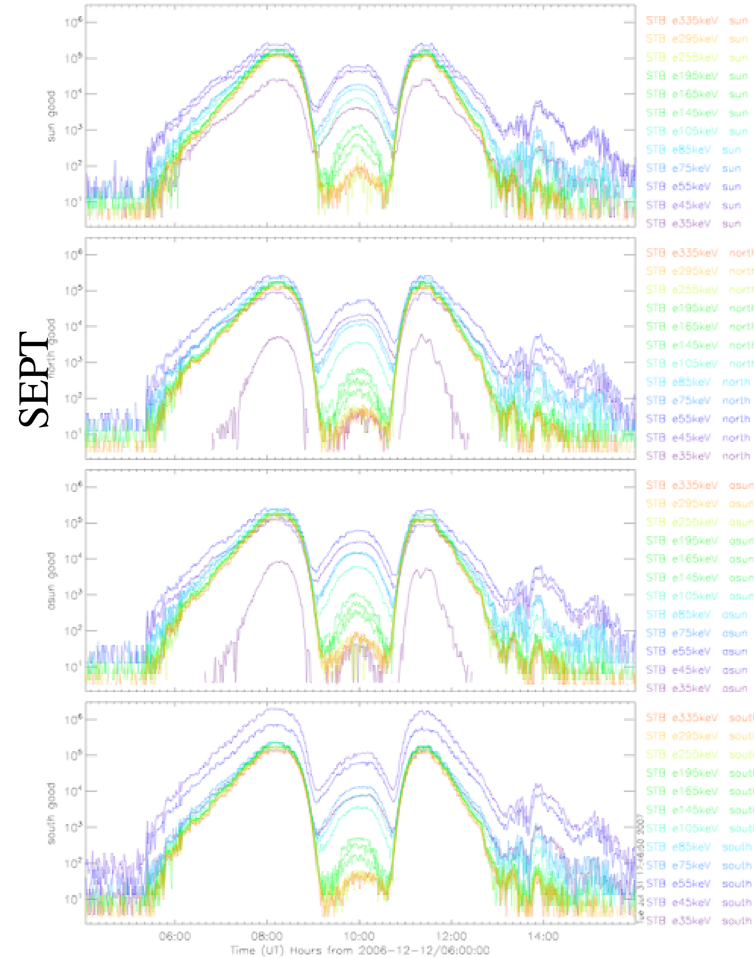

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DECEMBER 12, 2006 STEREO B

Several of IMPACT particle detectors had doors closed; seeing penetrating energetic electrons.

Parameters:

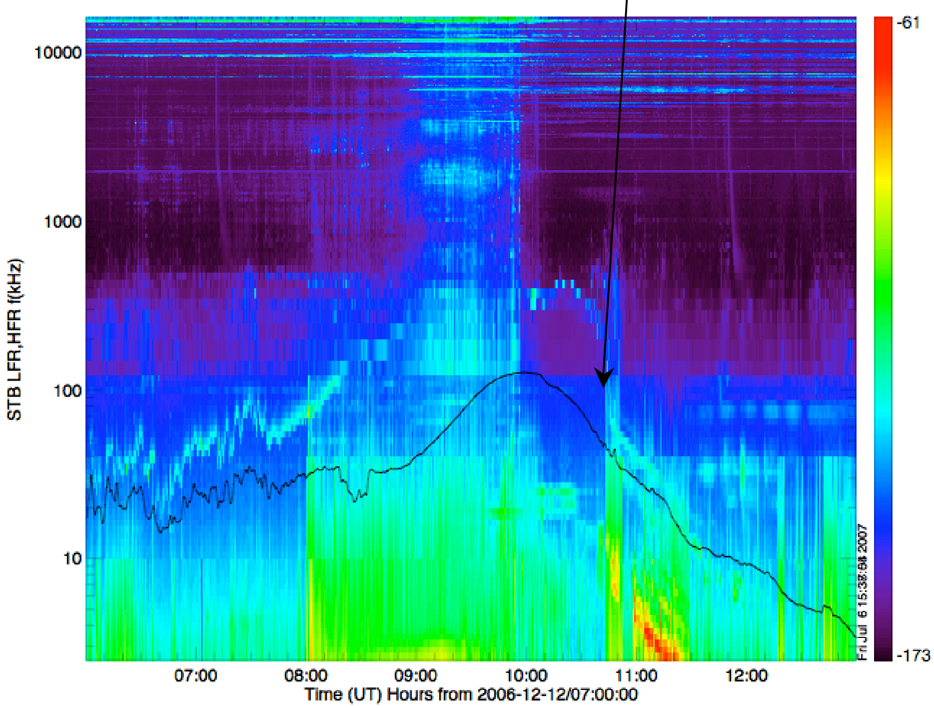
$n \sim 1\text{-}5/cm^3$

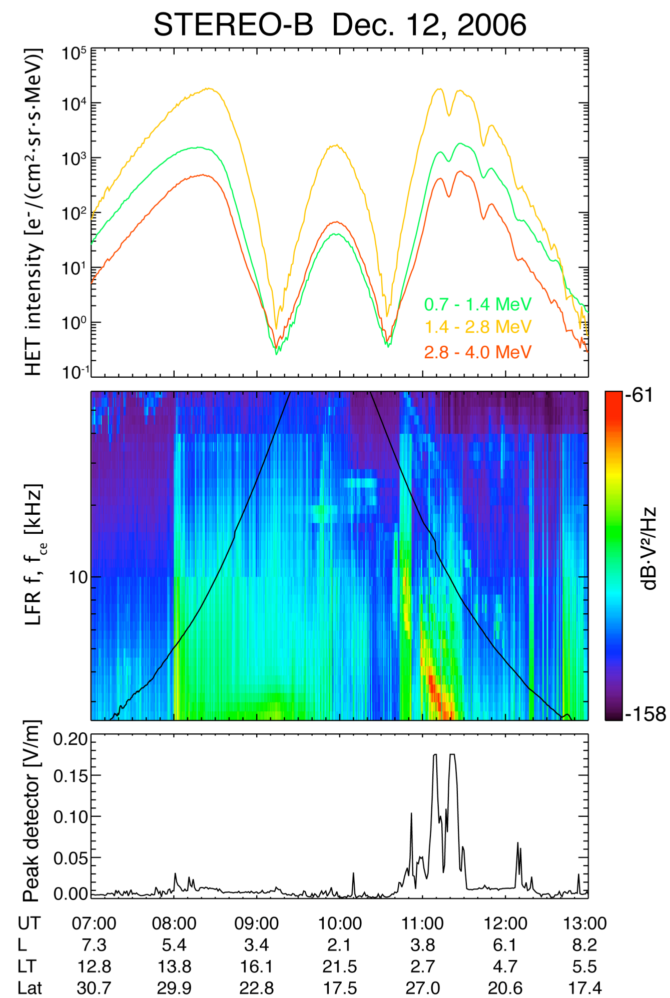
[from upper hybrid line, plasmapause at ~10:43]

B~300-350 nT

f_{pe} ~9-20 kHz

f_{ce} ~8.6-9.8 kHz



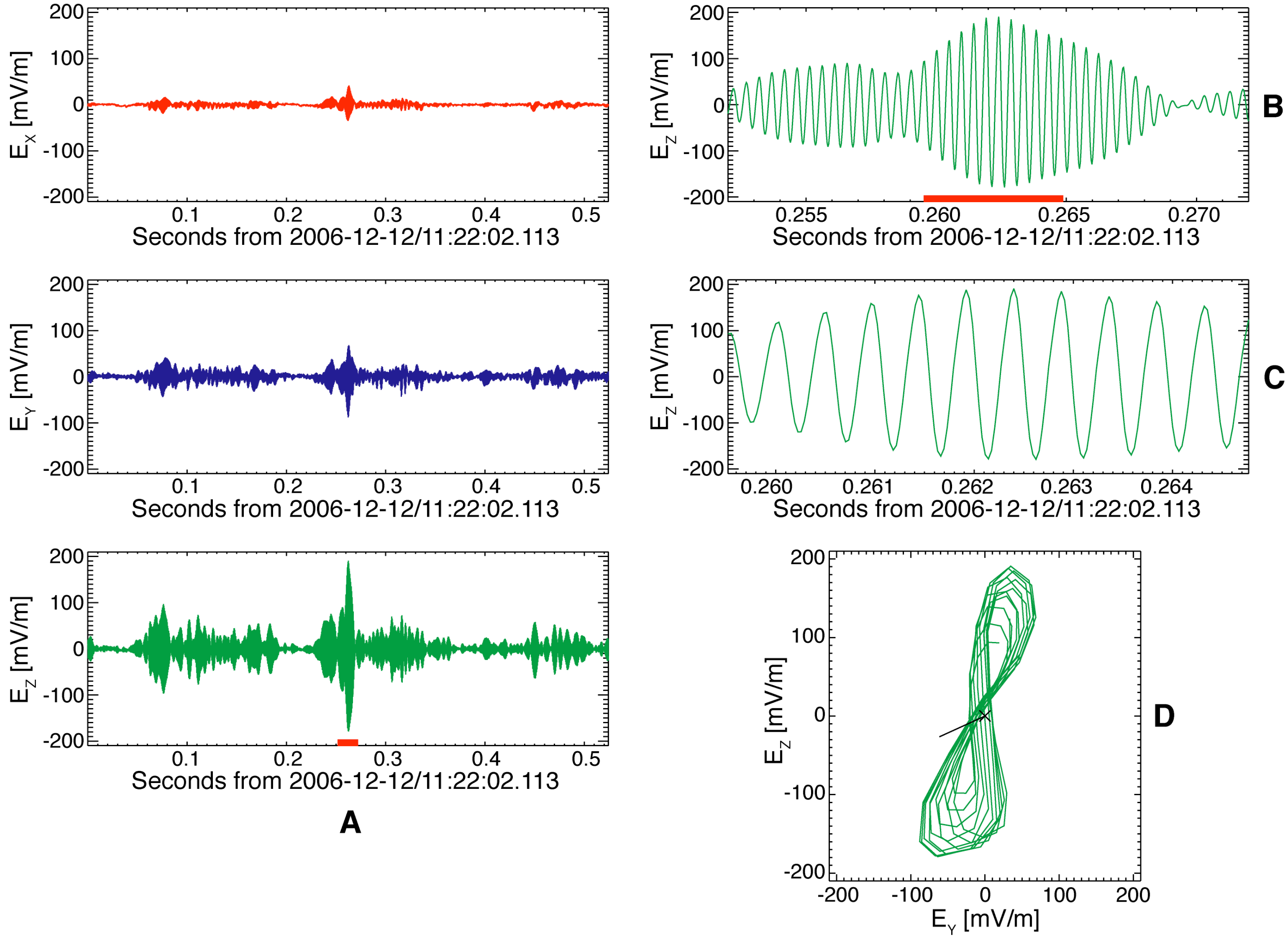


24 TDS samples obtained over ~ 4 minute interval (11:20:21-11:24:26)

87% had amplitudes >100 mV/m

f ~2 kHz to 2.2 kHz, ~0.22 f_{ce},

STEREO-B Dec. 12, 2006 S/WAVES TDS, Min. Var. Coordinates



duration= 0.52s ; 32 ksamples/s

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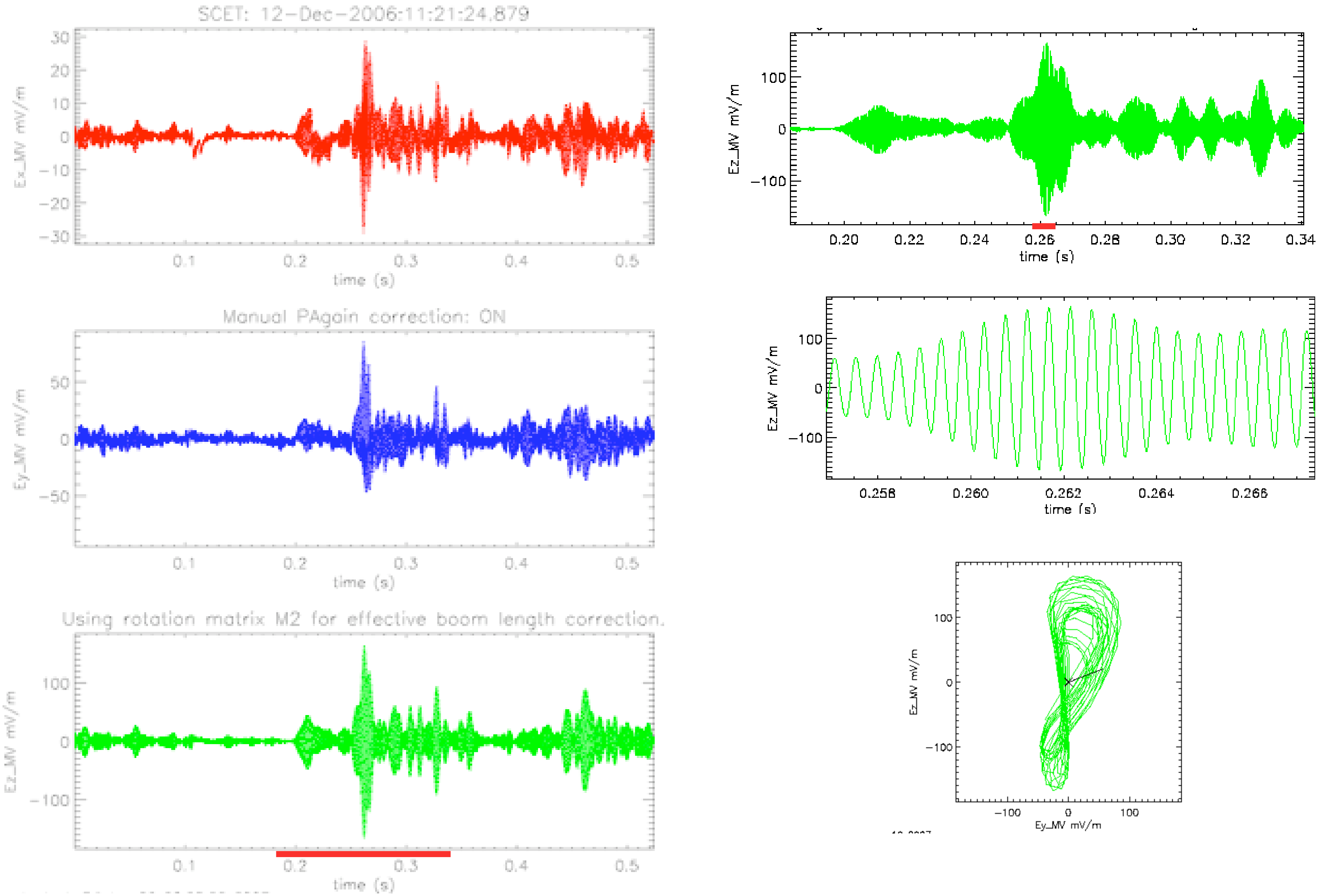

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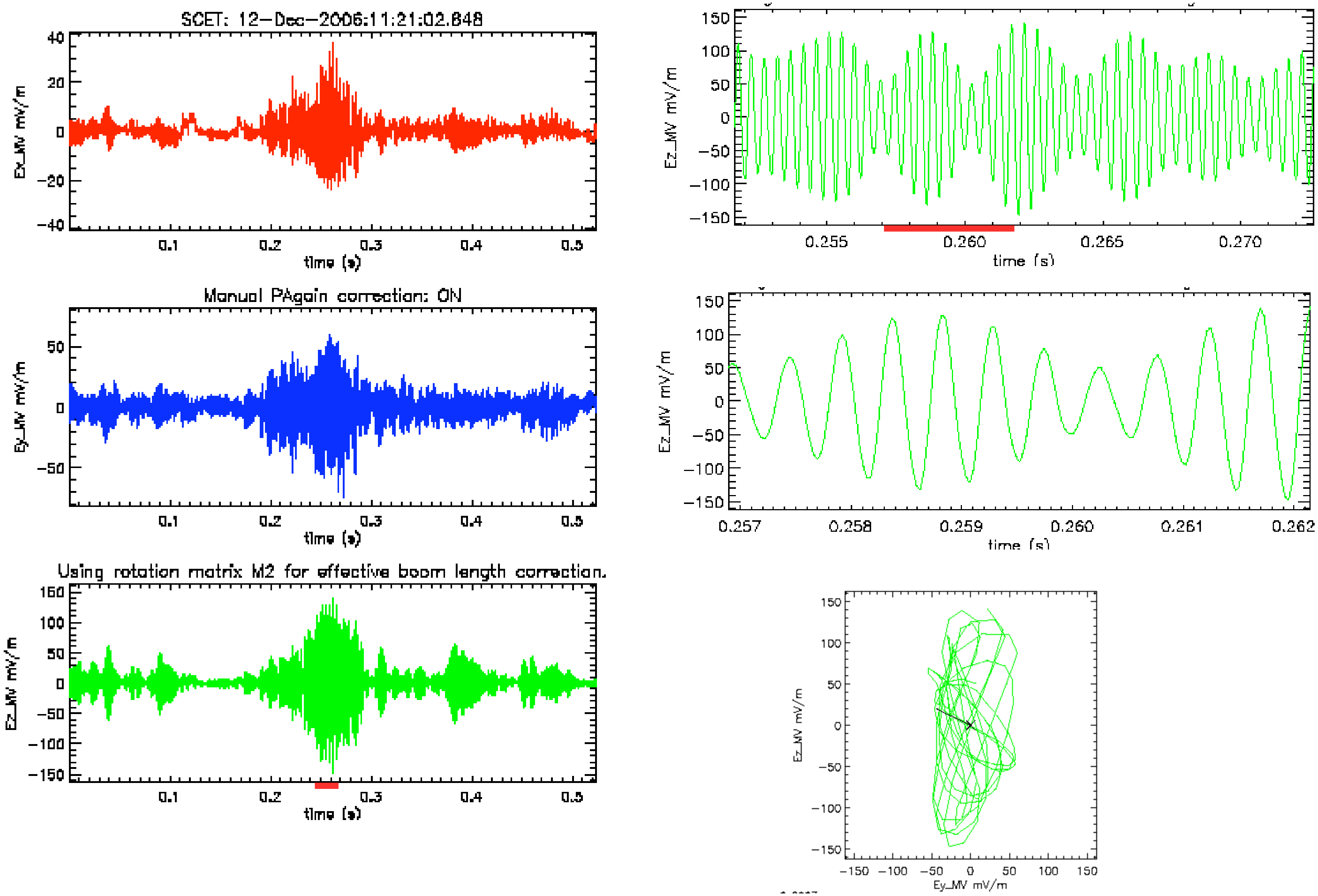
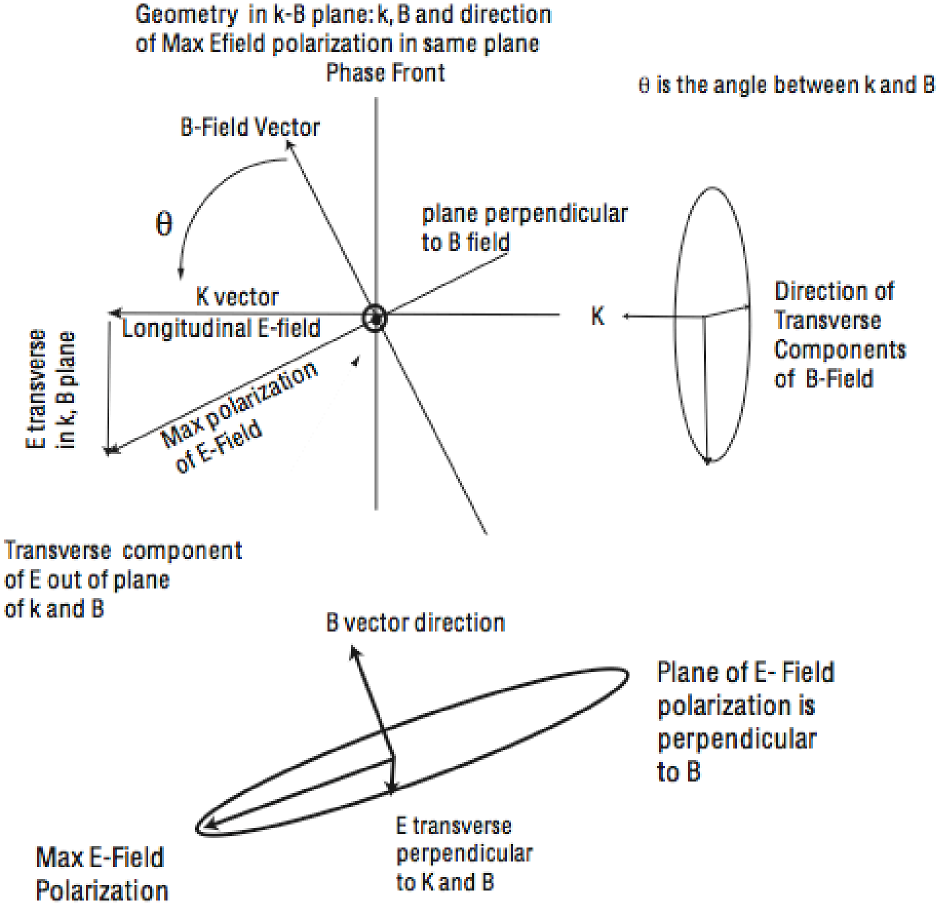
TDS waveform sample, min. var. coordinates



TDS waveform sample, min. var. coordinates



Wave **E** in the max. var. direction is vector sum of longitudinal comp. (along **k**) and the transverse comp. in **k - B**$_0$ plane and ⊥ to **k**. Another transverse component, ⊥ to **k - B**$_0$ plane, is in intermed. var. direction. Wave $\mathbf{B_w}$ determined from $\mathbf{E_w}=v_{ph}\,(\mathbf{k}/k)\times\mathbf{B_w}$ (v_{ph} is the phase velocity). Linear dispersion relations can be used with the measured parameters to determine v_{ph} , magnitude of **k** and $\mathbf{B_w}$

For n of 2-5/cm^3 , B$_0$ of 300-350 nT and measured wave parameters: Waves are very oblique with the propagation angle w/r to **B**$_0$ ranging from ~45°-60°. v_{ph} is ~35,000-70,000 km/s and δB~0.5-2 nT

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Comparisons to previous whistler-mode studies

- Amplitude: Largest previously reported was up to 30 mV/m, observed by Cluster (Santolik et al., 2003). Statistical studies conclude ~.1-1 mV/m .*STEREO->240 mV/m*
- Propagation direction: Previous studies parallel to **B** (within ~10°-12°). *STEREO- oblique (~40-60°), near resonance cone*
- Frequency structure: Near-equatorial chorus lower band (below 0.5 f_{ce}) highly dispersive waves, usually with rising tones. *STEREO- not dispersive. Frequency at peak power is ~.2 f_{ce} throughout 4 minute interval.*
- Electric field direction: Previous studies E is purely transverse. *STEREO- large longitudinal component and small (~10%) parallel electric field*

⇒ *Although the differences suggest that these very large amplitude whistlers may represent a new instability mechanism or free energy source, some differences may be due to propagation effects since whistlers propagating in an inhomogeneous medium can refract towards the resonance cone where the mode becomes quasi-electrostatic.*

Oblique waves may be more important

- For parallel-propagating whistlers, only the lowest order resonant interaction is effective. For obliquely propagating waves, higher order resonant interactions can occur. Since $R_{ge} \geq k_{\perp}$, many harmonics can contribute.

- Resonant energy is $m^2(\Omega_e/\omega)(B^2 \cos\theta/8\pi n)$, where m is the resonance number, n is the plasma density and θ is the propagation angle

- For a single monochromatic obliquely propagating wave, there exist many cyclotron resonances. There is a finite trapping width proportional to the square root of the wave amplitude associated with each resonance. As wave amplitude increases, the trapping width of the neighboring resonances will overlap, transitioning from regular to stochastic motion of particles. The maximum energy gain is determined by parallel phase velocity of the wave. The presence of several large amplitude waves can reduce threshold for resonance overlap (Karimabadi et al., 1990; 1994).

New test particle simulations using STEREO wave parameters

> Used particle tracing simulation based on Roth et al. (1999)

>Traces electrons in straightened 'dipole' field starting at equator with a fixed wave electric field obeying whistler cold dispersion relation

>A range of electric field amplitudes and propagation angles were used

(1-300 mV/m; $\theta=5^{o}$ to 60^{o})

>A range of initial energies and pitch angles were used

(200 keV to 2 MeV, $\theta=30^{o}$ to 80^{o})

> Single constant wave

Electron gain ~0.1 to 4 MeV in tens of ms. Scattering by angles of ~2° to 40° .
1 to 3 (or more) orders of magnitude larger than those for the ~1 mV/m (or smaller) amplitudes typically assumed. NOT quasi-linear process

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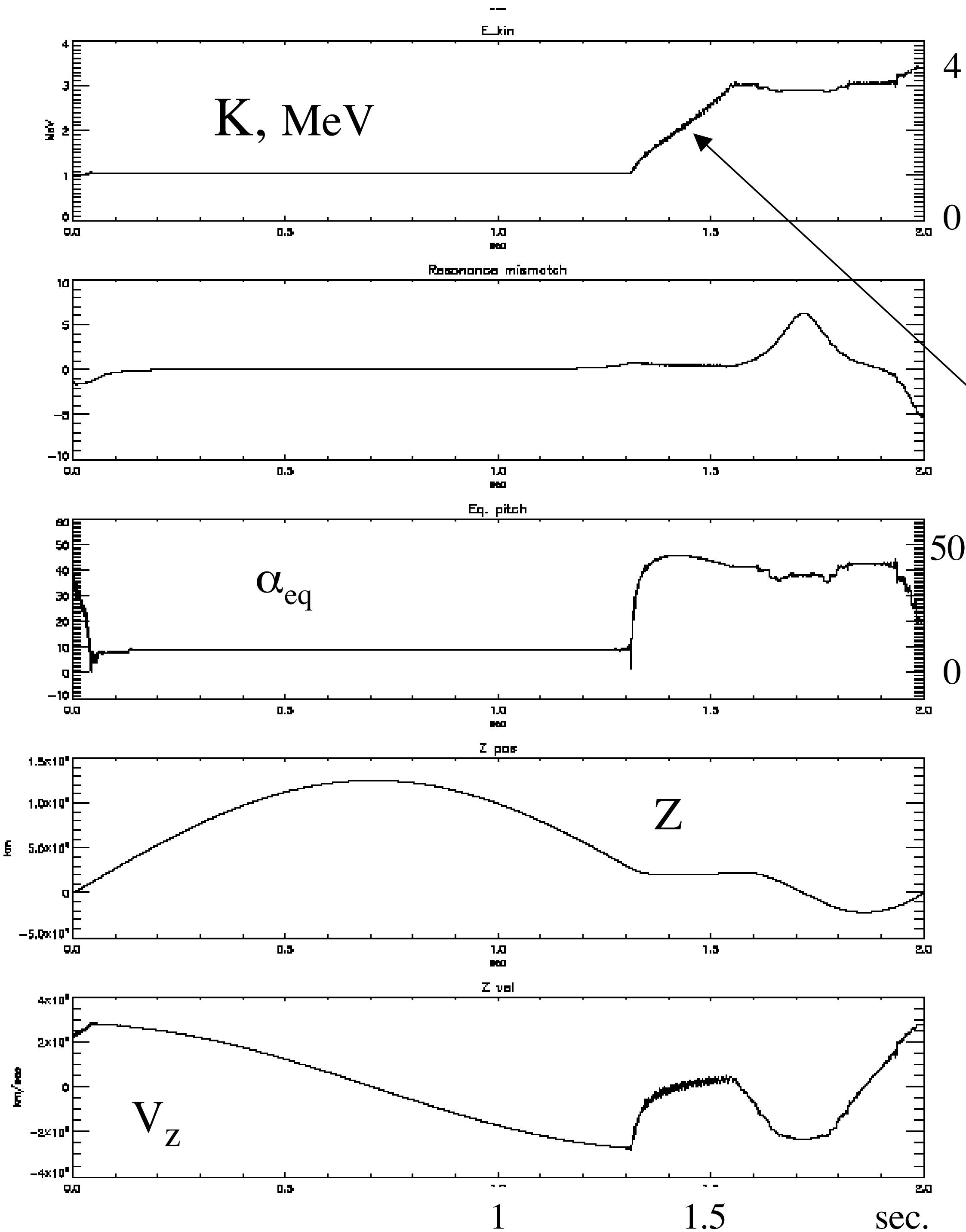
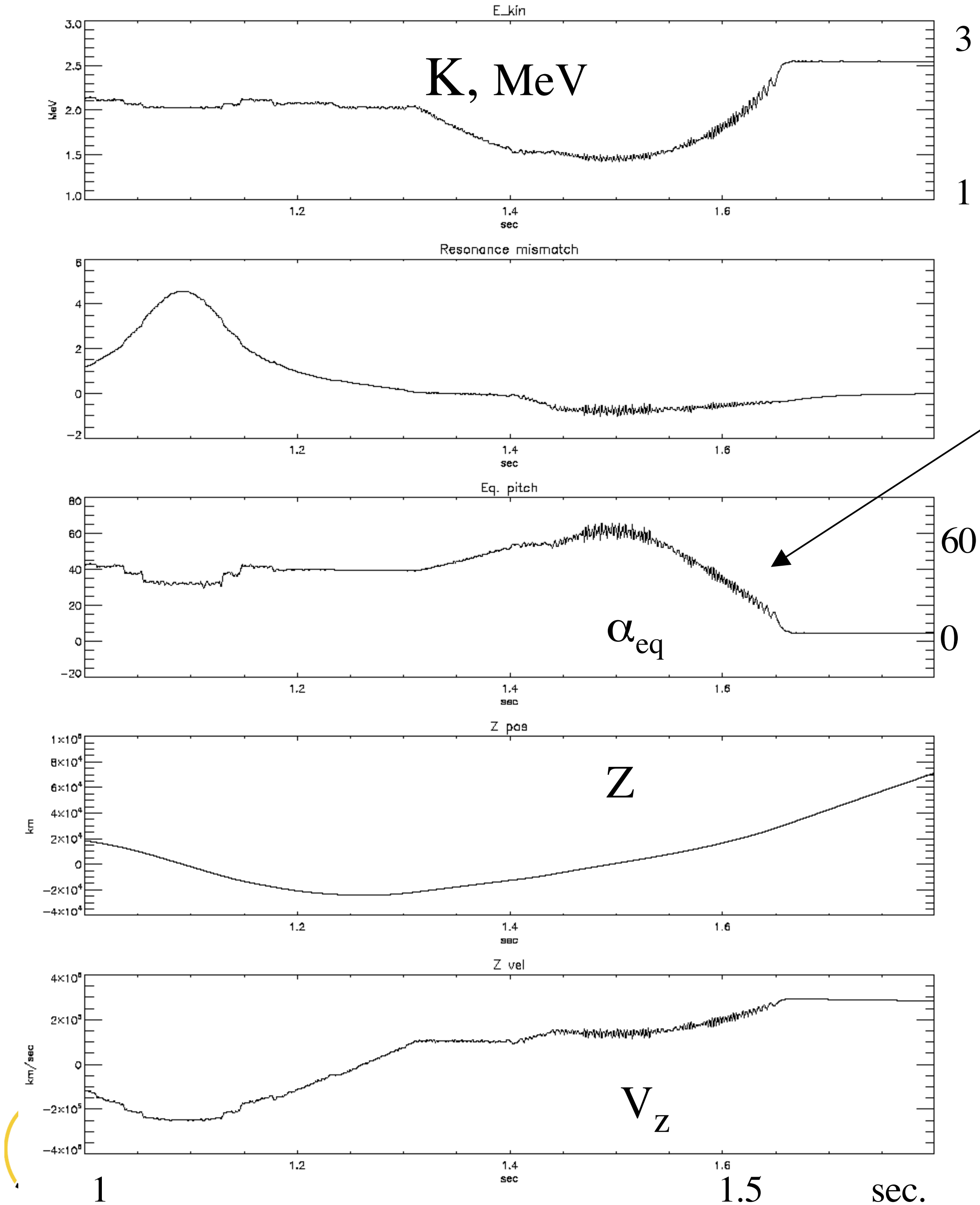


K_0=1MeV α=30°, θ=40°

E=300 mV/m

Energization by 2 MeV in ~.2s



K_0=2MeV α=45°,θ=60°

E=300 mV/m

Scattering into loss cone by 60° ~.1s

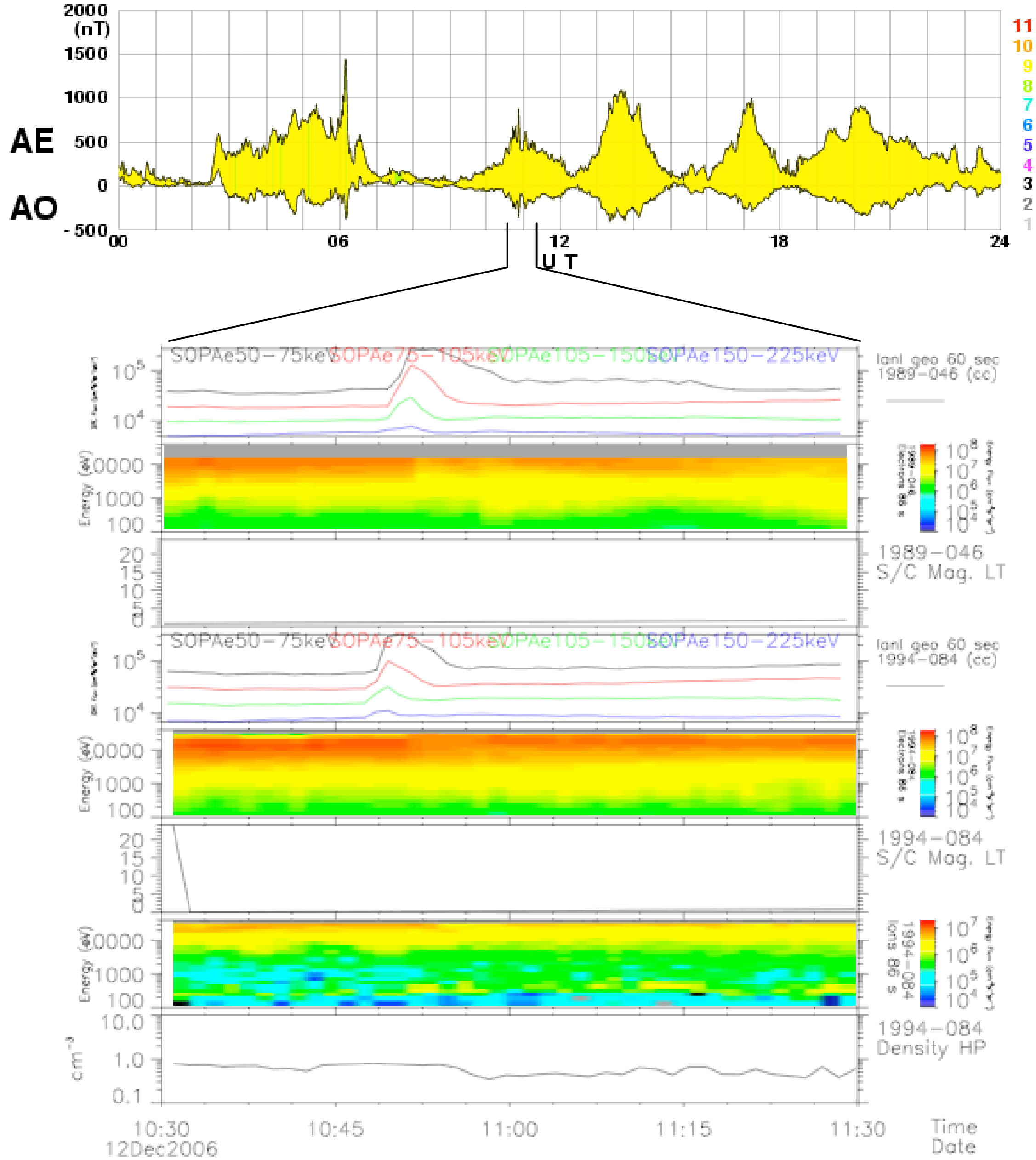
Maximum energy gain (Omura et al., 2007)

$$(\Delta K)_{max} = \frac{5.6 \times 10^4}{L^2\sqrt{1+\xi_0^2}} \frac{B_w}{B_0} \quad (\text{MeV}) \quad ,$$

where $\xi_0^2 = \omega(\Omega_{EQ} - \omega)/\omega_{pe}^2$.

Nonlinear acceleration mechanism associated with particle trapping that resulted in energy gains of ~0.5 MeV in ~1s for waves with amplitudes of tens of mV/m. Amplitudes required for the trapping are 1 to 2 orders of magnitude lower than seen in the STEREO data, while the energy gain in a single interaction scales as the wave amplitude. Consistent with our simulation results.

High speed stream: V_{sw}~650-700 km/s n~2/cm^3



50-225 keV electrons from LANL

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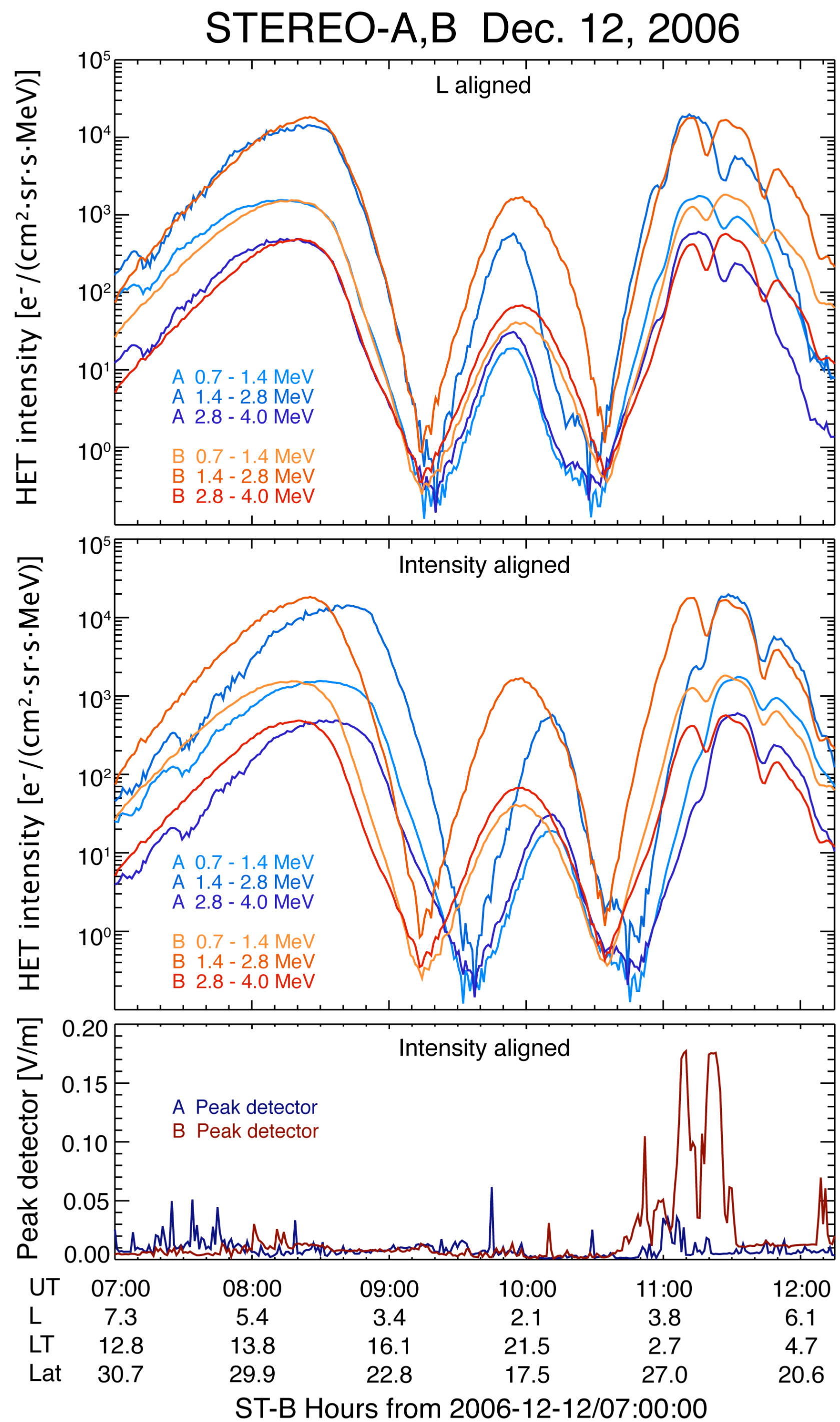
Stereo-A Stereo-B Comparison

Substorm occurs between passage of ST-A and ST-B through outer am-side belt.

Magnetic field is ~10° more dipolar, consistent with given flux tube moving to lower radial distance.

May justify ‘flux’-lag of L~0.6.



Effect of large whistlers on electron loss: Microbursts

- For ~ 10 years, observations of ‘microbursts’ - short bursts of relativistic electrons seen by balloon detectors or low altitude satellites imaging the loss cone [Blake et al., 1996; Millan and Thorne, 2007 for review]

- Not good explanation. EMIC waves often suggested.

- Can STEREO provide more information?

- What does SAMPEX see?

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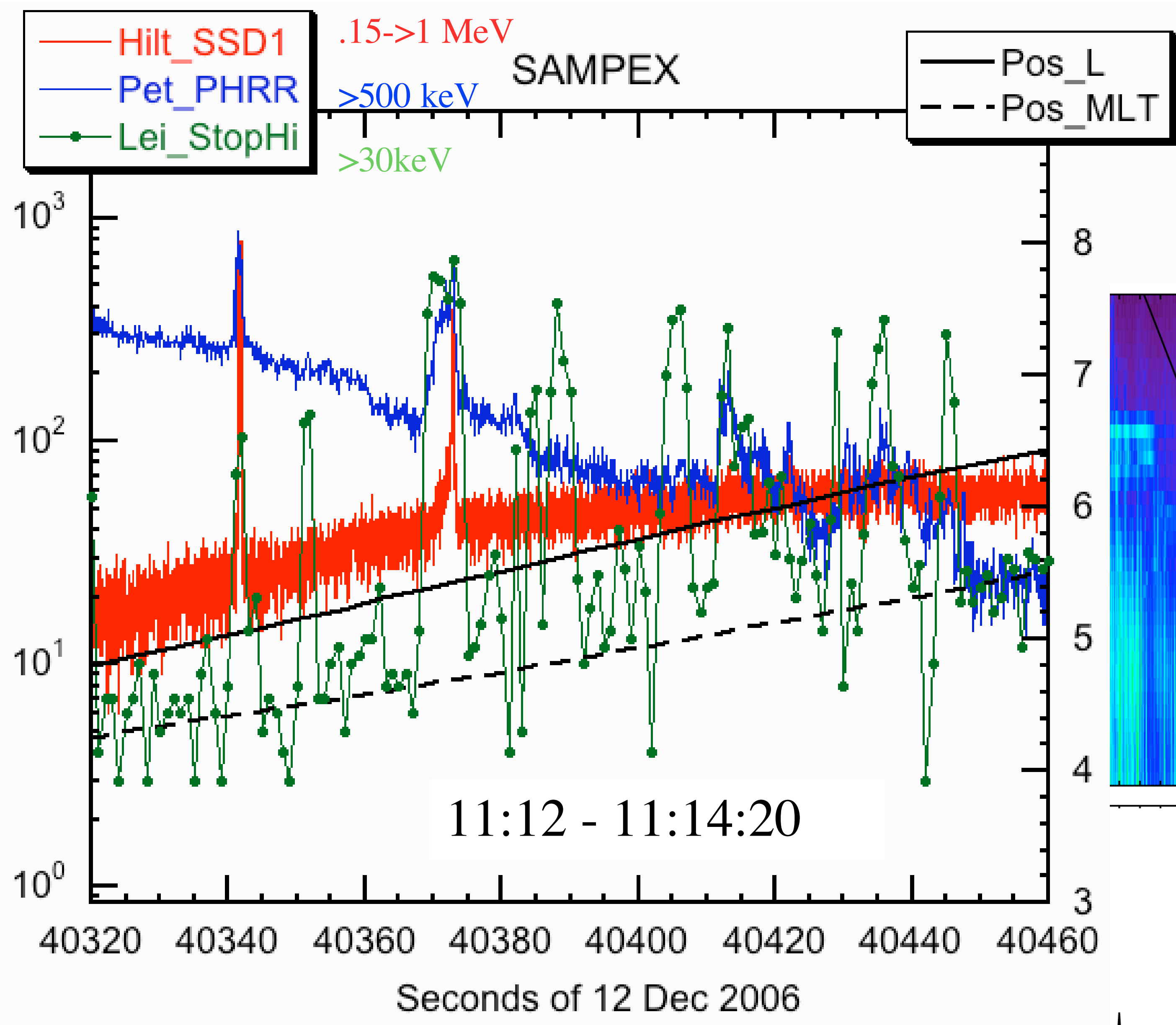
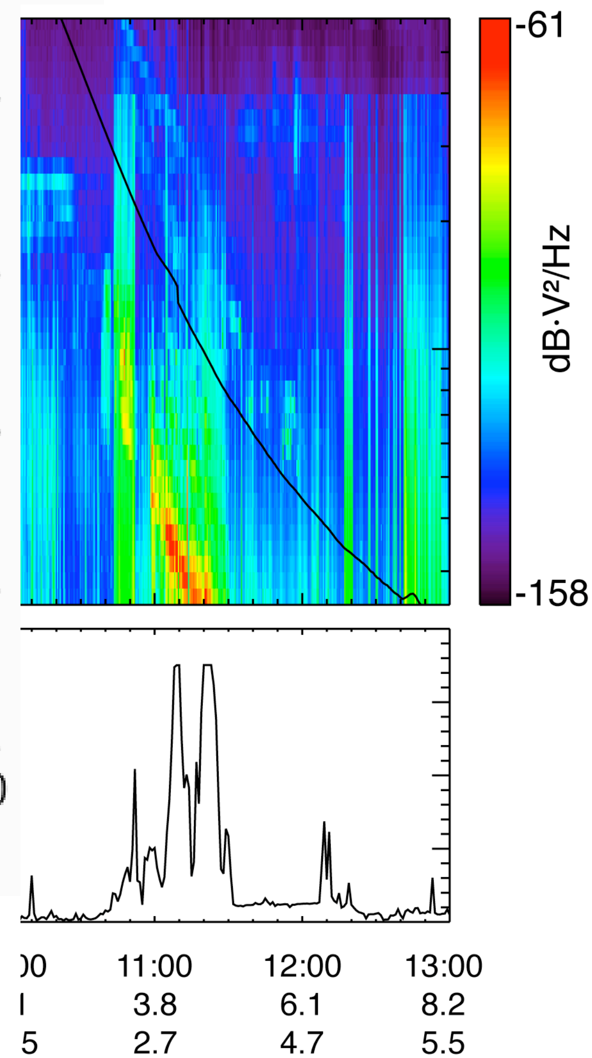
SAMPEX data provided by J.B. Blake





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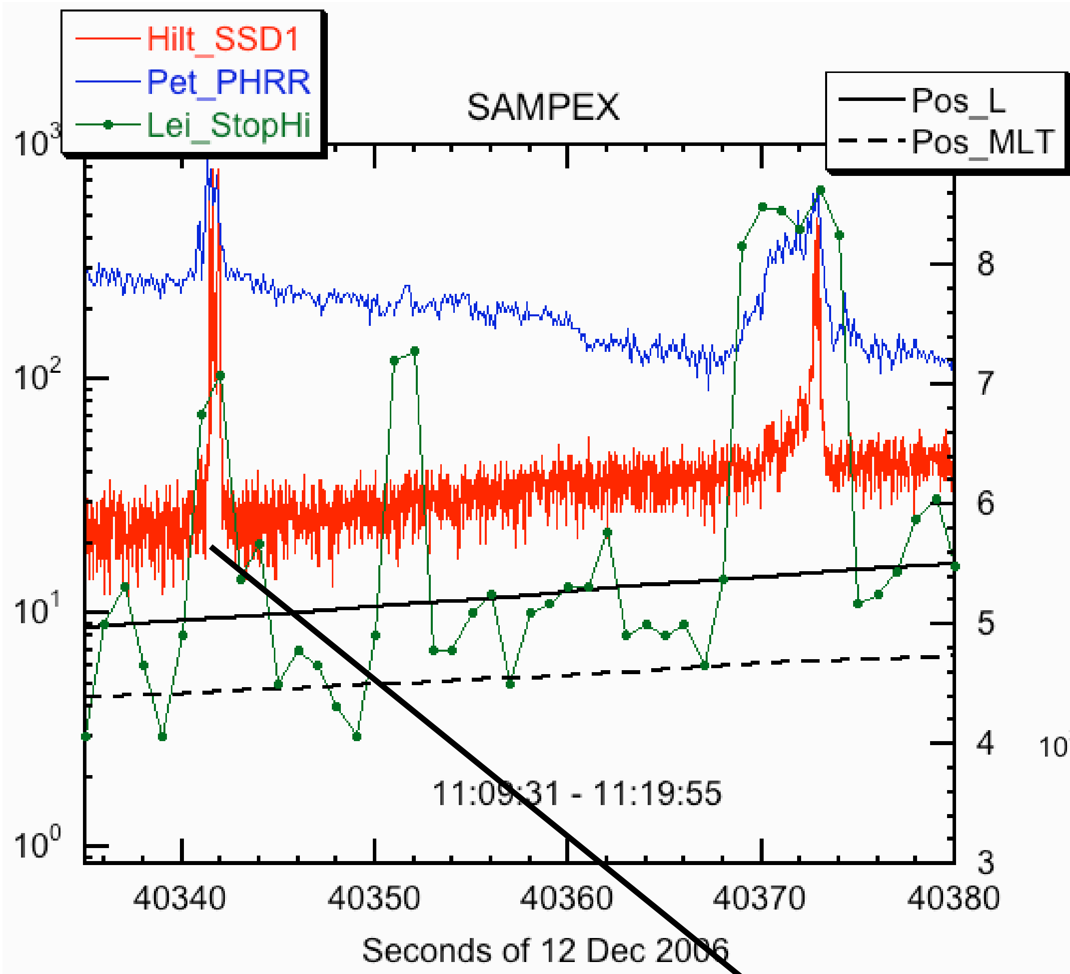
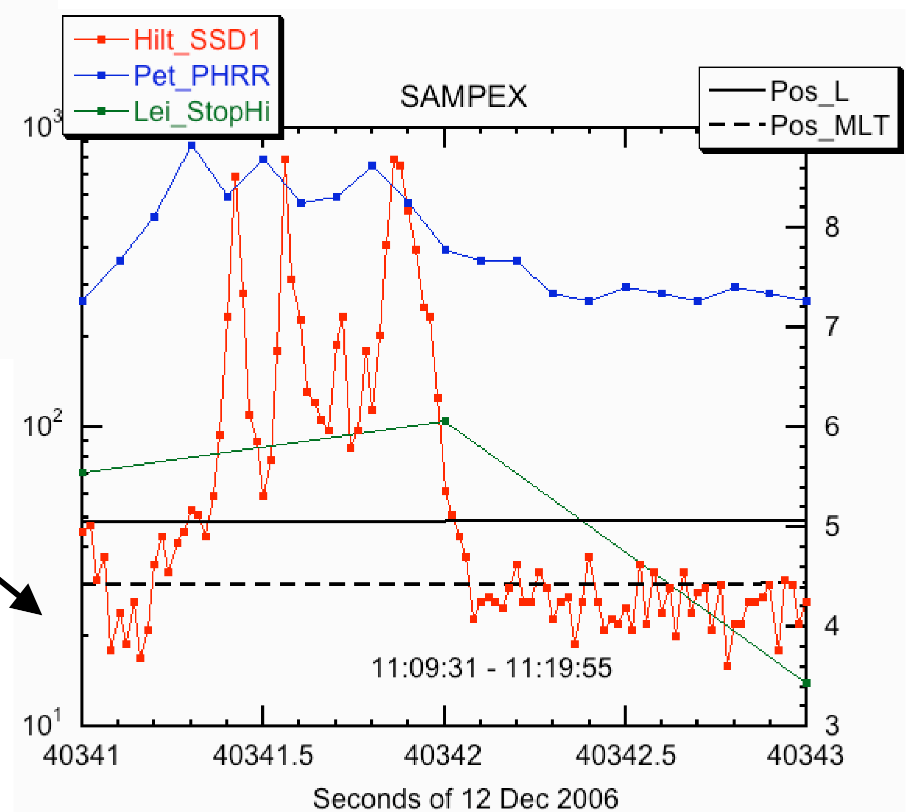


Energies

0.15->1 MeV

>500 keV

>30keV



Impulsive loss of MeV electrons

Consistent with particle tracing results

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Conclusions

- STEREO has measured whistler-mode waves with amplitudes 2-3 orders of magnitude larger than usually observed and 1 order of magnitude larger than largest reported to date. These large amplitudes occur for ~20 min.
- STEREO observations provide evidence that large amplitude whistlers (~200 mV/m) are associated with rapid enhancement (timescale of ~10 minutes) in fluxes of relativistic electrons in outer radiation belt
- Wave properties distinctly different from usual lower band chorus: large amplitude, oblique, non-dispersive, large longitudinal E and significant $E_{||}$
- Waves can result in energization to order of MeV during single wave packet encounter due to coherent, nonlinear processes including trapping
- Waves can scatter electrons by large angles, consistent with simultaneous SAMPEX microbursts
- Observations during high speed stream, after substorm injection, but not associated with storm. Waves may be larger during major storms or after stronger injections.

- Suggests that usual theoretical models of electron energization and scattering via small-amplitude waves, with timescales of hours to days, may be inadequate for understanding radiation belt dynamics

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