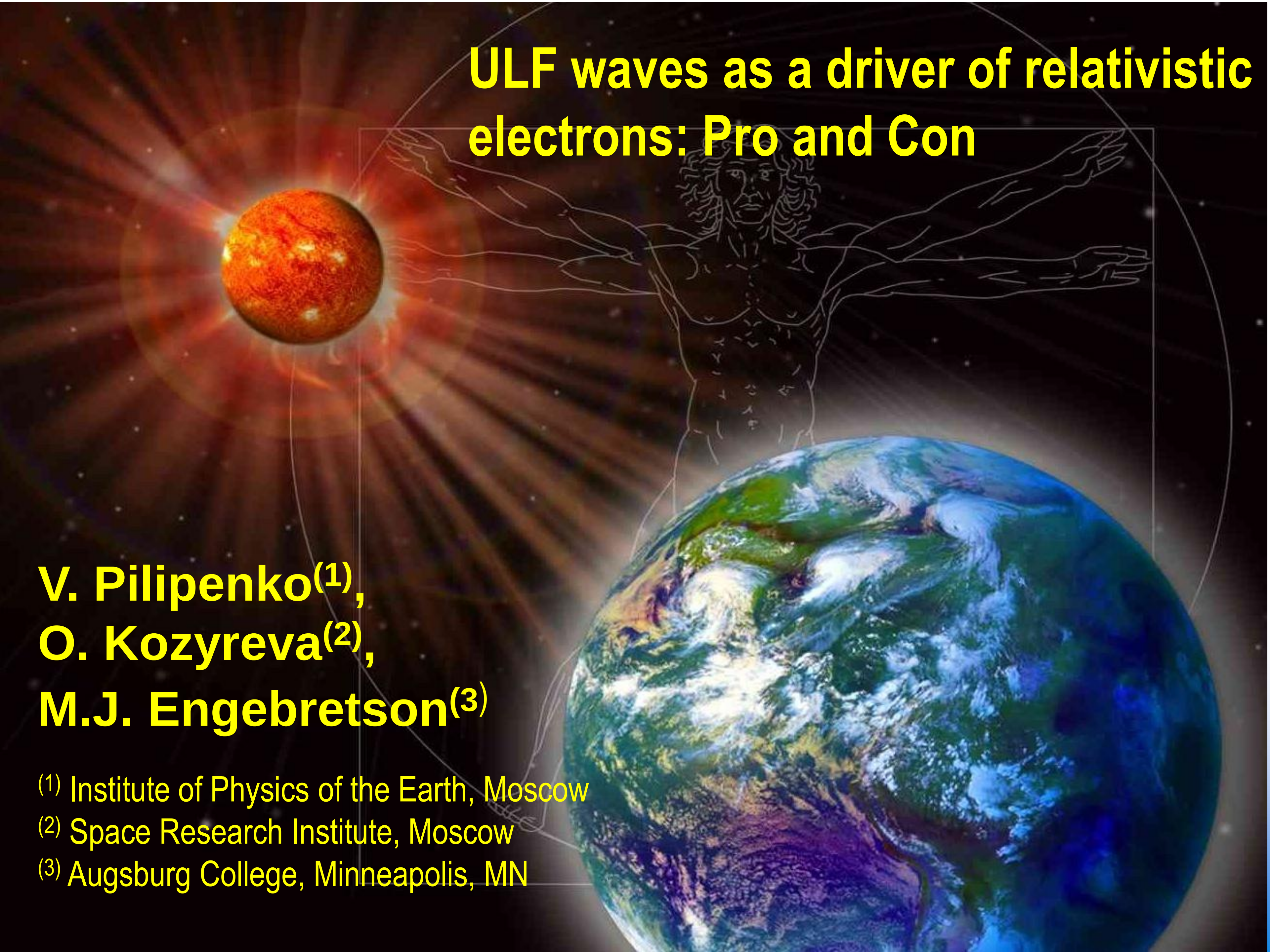

ULF waves as a driver of relativistic electrons: Pro and Con

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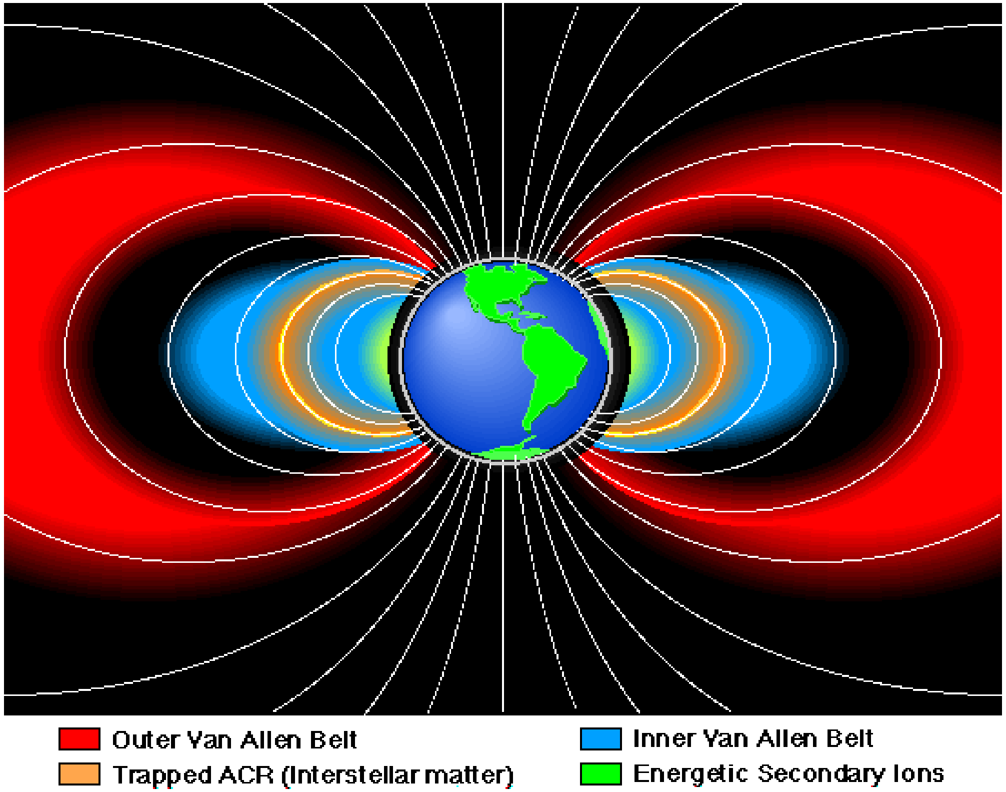
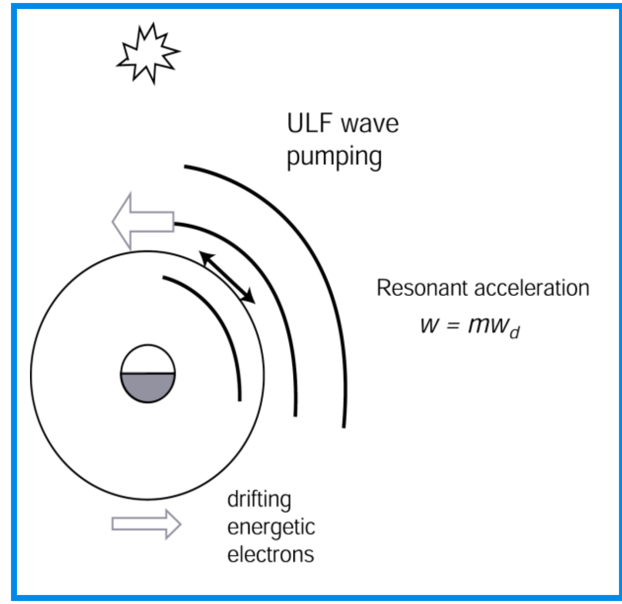
The outer radiation belt is formed due to some internal magnetospheric processes, while electromagnetic fields play a role of intermediary transferring the energy to a small group of high-energy particles.
This energy transfer may happen via a variety of mechanisms of electron acceleration up to relativistic energies, depending on a geophysical situation.



At the storm recovery phase, electron fluxes are adiabatically restored to their pre-storm values. However, in >80% of storms, electron enhancements at some L go well beyond the adiabatic level!
The magnetospheric electron energization during magnetic storms can be categorized as two-step process: combination of fast and slow acceleration processes. The intensification of relativistic electron fluxes occurs:
-first in the heart of the belts and on rapid time scales (about several hours), and
- later and more slowly (days to weeks) at higher altitudes

Geosynchrotron:
ULF waves = intermediary between the solar wind and “killer” electrons?



Appearance at GEO of relativistic electrons following storms resists definitive explanation. While it has been known a general association between the SW velocity and electron enhancements, the wide variability of the response and puzzling time delay (~1-2 days) between storm main phase and the response has frustrated the identification of responsible mechanisms.

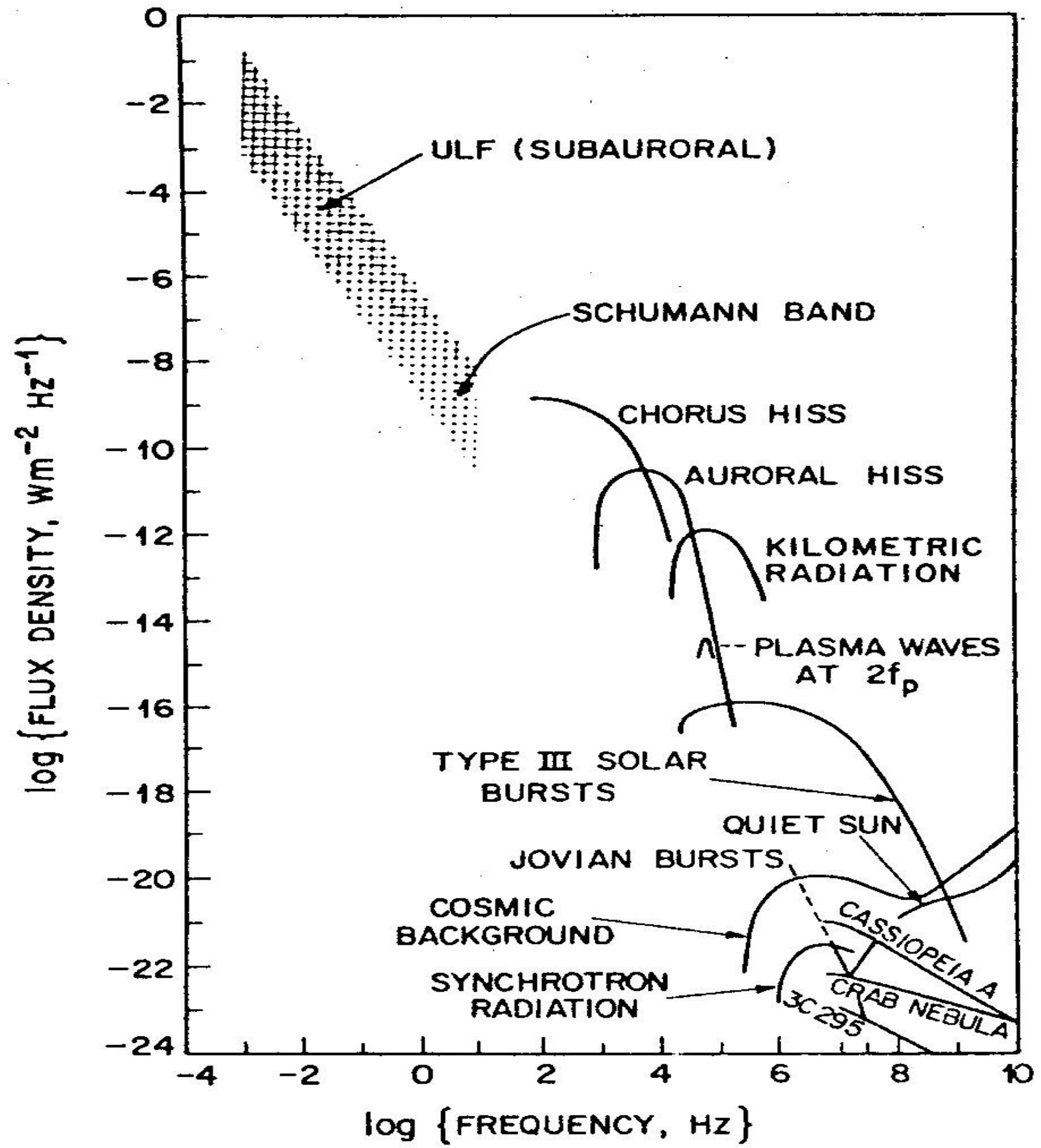
Some intermediary must more directly provide energy to the electrons?

Rather surprisingly, ULF waves in the Pc5 band (~few mHz) have been suggested as a possible energy reservoir: the Pc5 wave power after minimum Dst may be a good indicator of relativistic electron response [*O’Brien et al.*, 2001]. Thus, in a laminar, non-turbulent magnetosphere the “killer” electrons would not appear!?

Acceleration of ~100 keV electrons supplied by substorms may operate as magnetospheric geosynchrotron. Pumping of energy into seed electrons is provided by large-scale MHD waves in a resonant way, when wave period matches multiple of the electron drift period, e.g.

$$\omega = m\omega_d$$

Power spectra of natural e/m emissions in space



ULF waves = most powerful natural e/m waves in near-Earth environment!

During storm recovery phase (no IMF reconnection!) they become a significant channel of the wave energy transfer from the SW into the magnetosphere

Zoo of ULF waves

Toroidal Pc5 pulsations are Alfven azimuthally large-scale (*m*~1) waves: incompressible ($B_{||}$~0) with dominating azimuthal magnetic Bϕ>>Br, and radial electric Er>>Eϕ components.

Poloidal Pc5 storm-time pulsations are Alfven azimuthally small-scale (*m*>>1) waves: dominating components are Br >> Bϕ, and Eϕ >> Er (though they are screened by the ionosphere from ground magnetometers). These waves are commonly coupled with slow compressional mode, so $B_{||}$~Br.

Global Pc5 pulsations are the most intense ULF waves. They are observed during the recovery phase of severe storms and are closely associated with high speed SW streams. They can be interpreted as a **waveguide fast-magnetosonic mode**. Their dominating components are Br and Eϕ.

Drift resonance between drifting electron and azimuthally propagating waves

$$T = T_d / m \quad \text{or} \quad \omega = m\omega_d$$

The energy exchange between electrons and waves

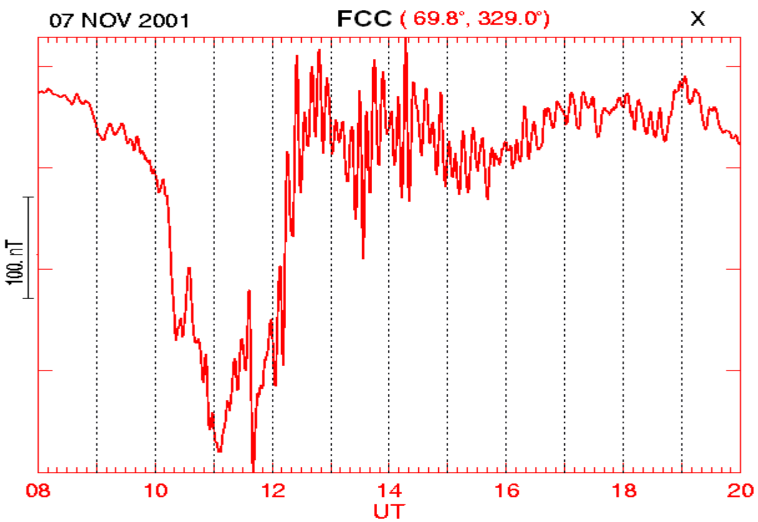
$$\frac{\partial W}{\partial t} = eV_d E_\phi + \mu \frac{\partial B_{||}}{\partial t}$$

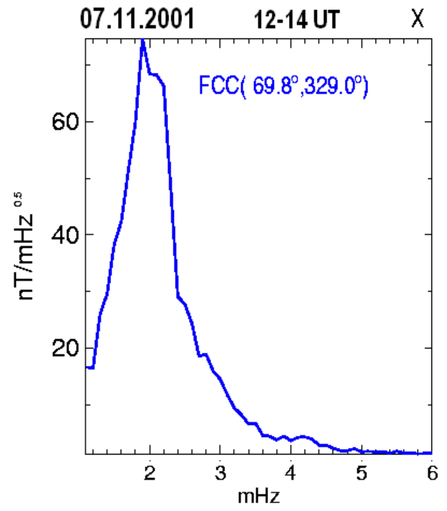
Toroidal Alfven waves & waveguide modes (m~1) can interact resonantly with ~1-MeV electrons.

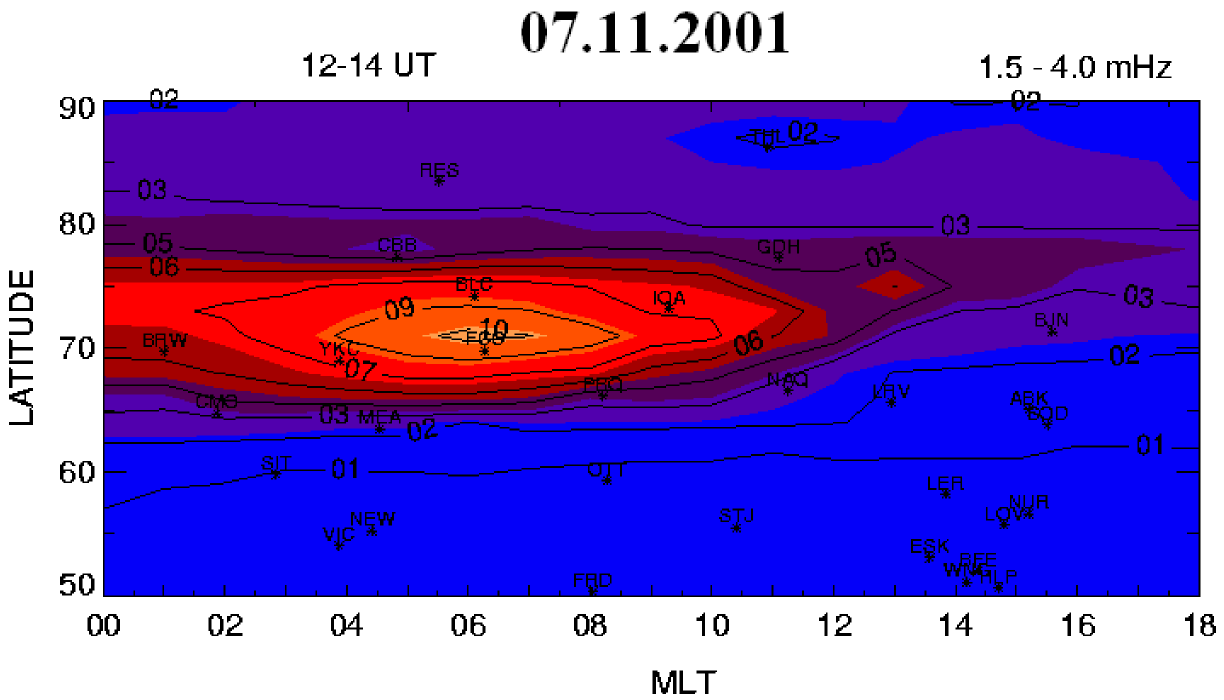
Poloidal Alfven waves (m~20, 3 min) can effectively resonantly interact with 0.1-MeV electrons.

Those Pc5 waves might be a promising candidate to influence the electron dynamics

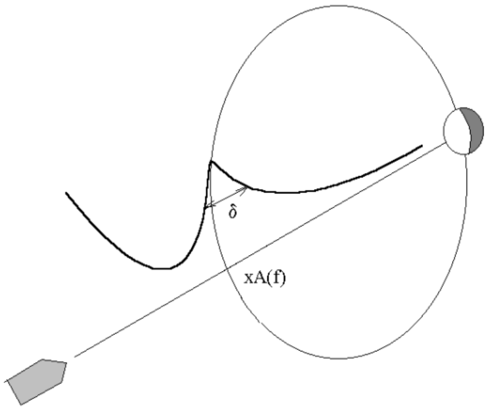
Toriodal Pc5 waves







- *f*~2-3 mHz
- Localized at sub-auroral latitudes ΔΦ~1-2;
- Mostly on the morning flank, anti-sunward propagating;
- Peculiar FLR amplitude-phase structure;
- *mechanism:* FLR driven by magnetopause shear-flow instability

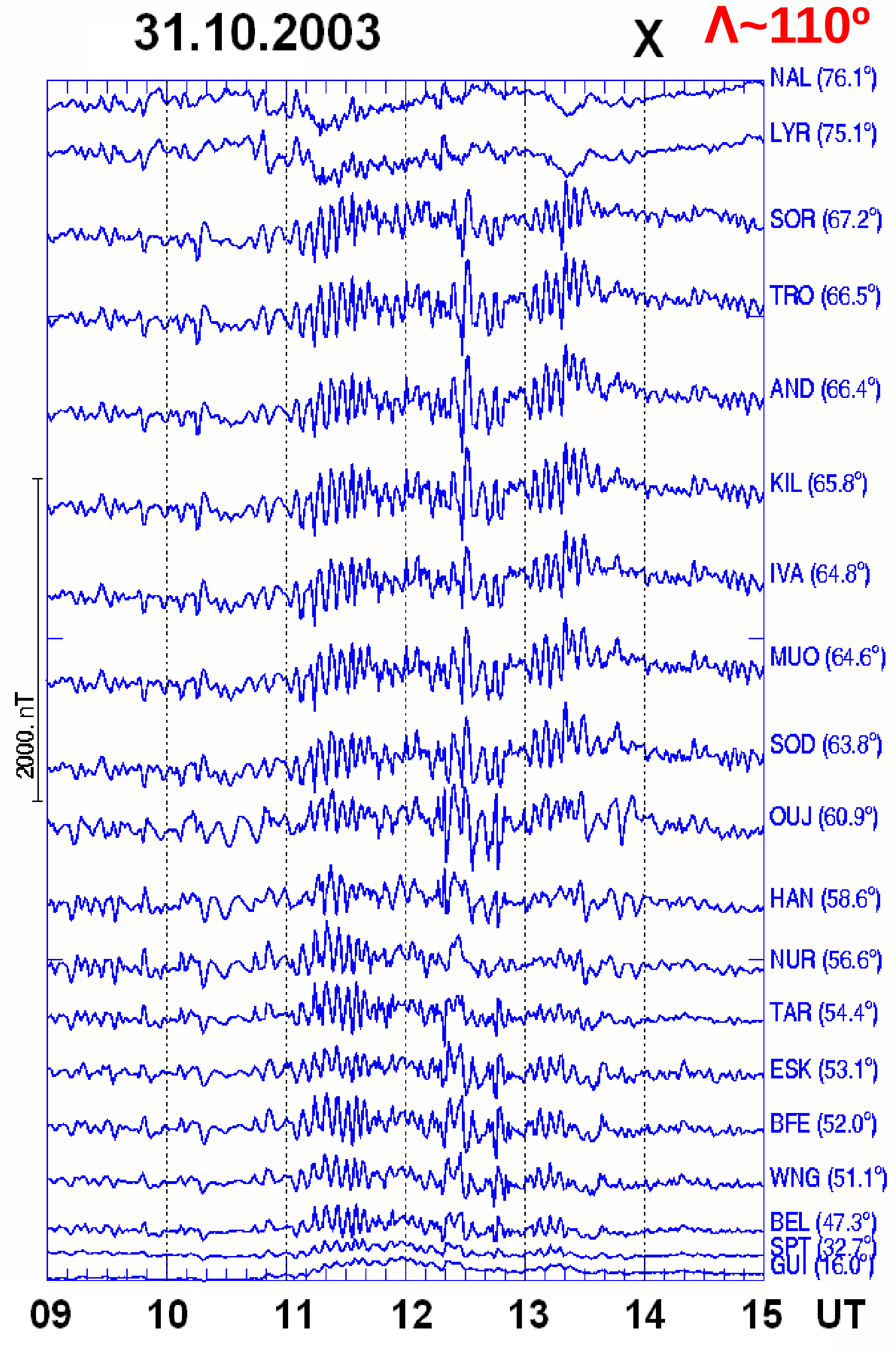


Global Pc5 waves at the recovery phase of a strong magnetic storm

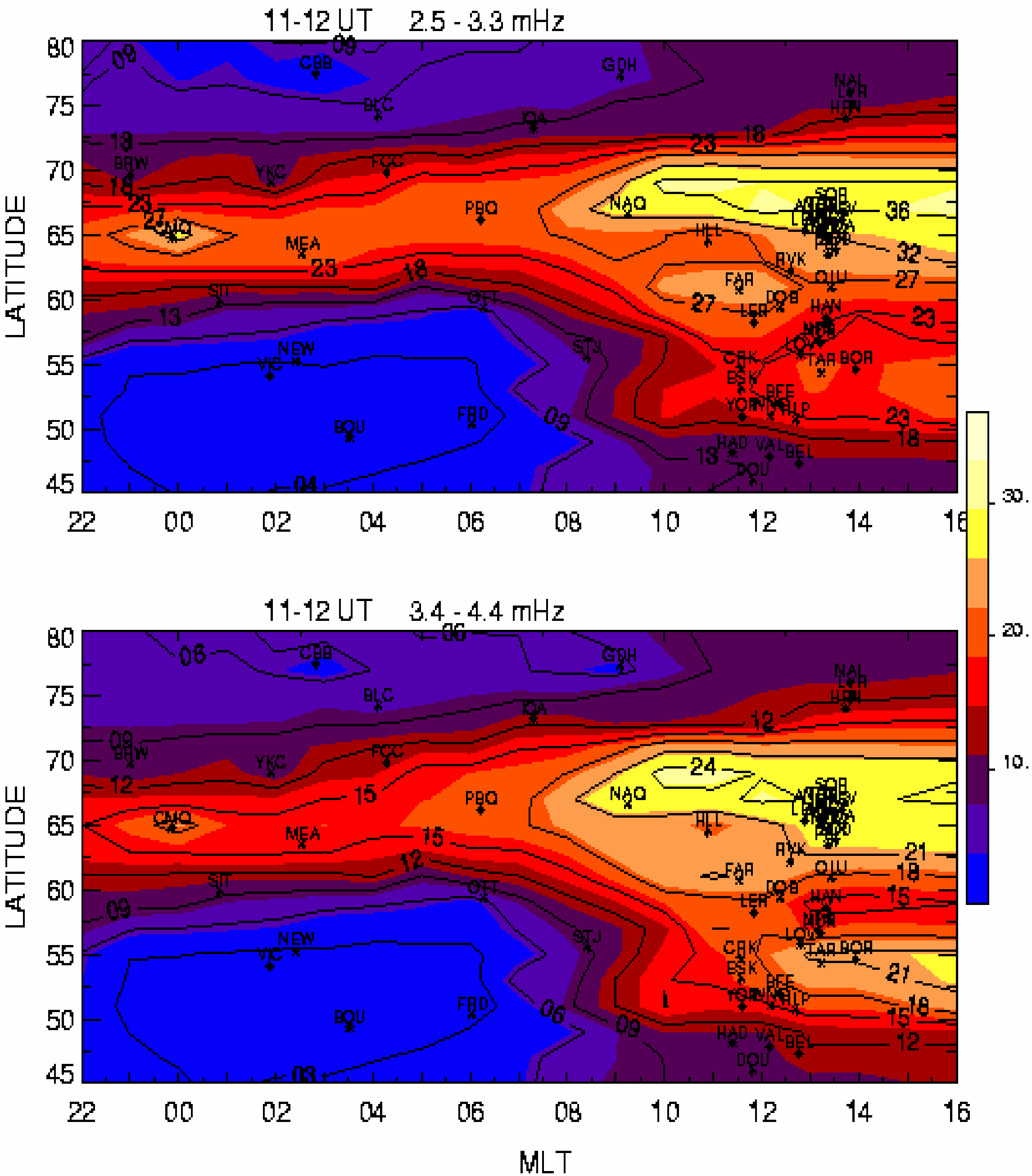
- **Very intense (~400 nT), an order of magnitude higher than common Pc5!**

- **Waveform was coherent with similar amplitudes across very large range of latitudes (from ~55° to ~70°), spectral maxima were latitude independent**

- **It is still unclear whether the mechanism of these pulsations are the same as of common Pc5 (just more intense) or physically different?**



Spatial structure of global Pc5 pulsation



Contrary to common Pc5 pulsations:

- **Penetrate deep into the magnetosphere;**
- **Sometimes more intense in the afternoon sector;**

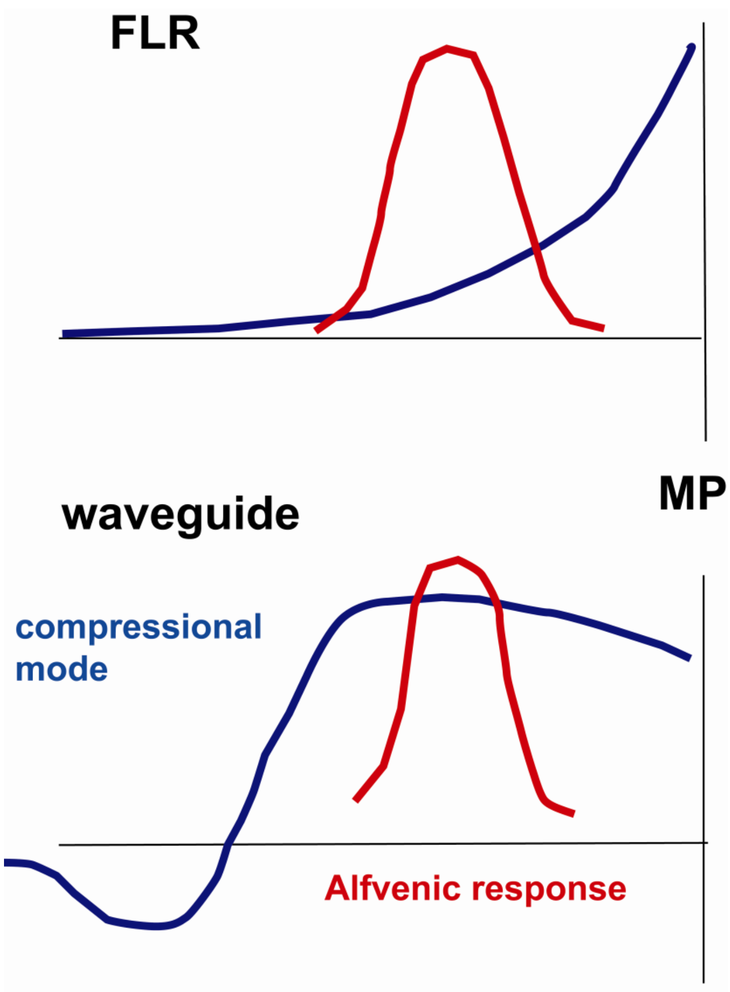
Thanks to their spatial structure they can provide energy to electron energization in a large volume of the magnetosphere!?

Global Pc5 waves: Magnetospheric waveguide?

The difference between common Pc5 waves and Pc5 waves during strong magnetic storms is possibly caused by different regimes of the SW flow around the magnetosphere:

Under moderate V: unstable oscillations are localized at the magnetopause, and decay inside the magnetosphere. Only localized enhancement due to the field-line resonance may occur.
Thermal fluctuations are convected rapidly by SW into magnetotail & do not grow to large amplitudes.

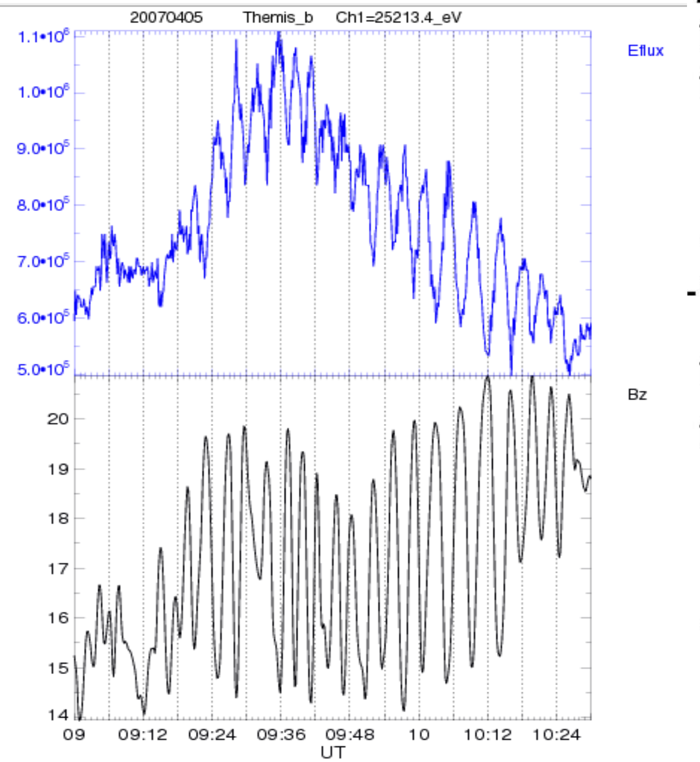
Under high V: the magnetopause becomes over-reflecting, i.e. MHD modes are amplified upon reflection from this moving boundary.
Growing disturbances are global eigenoscillations of the **MHD waveguide**, formed between the MP and inner magnetosphere.

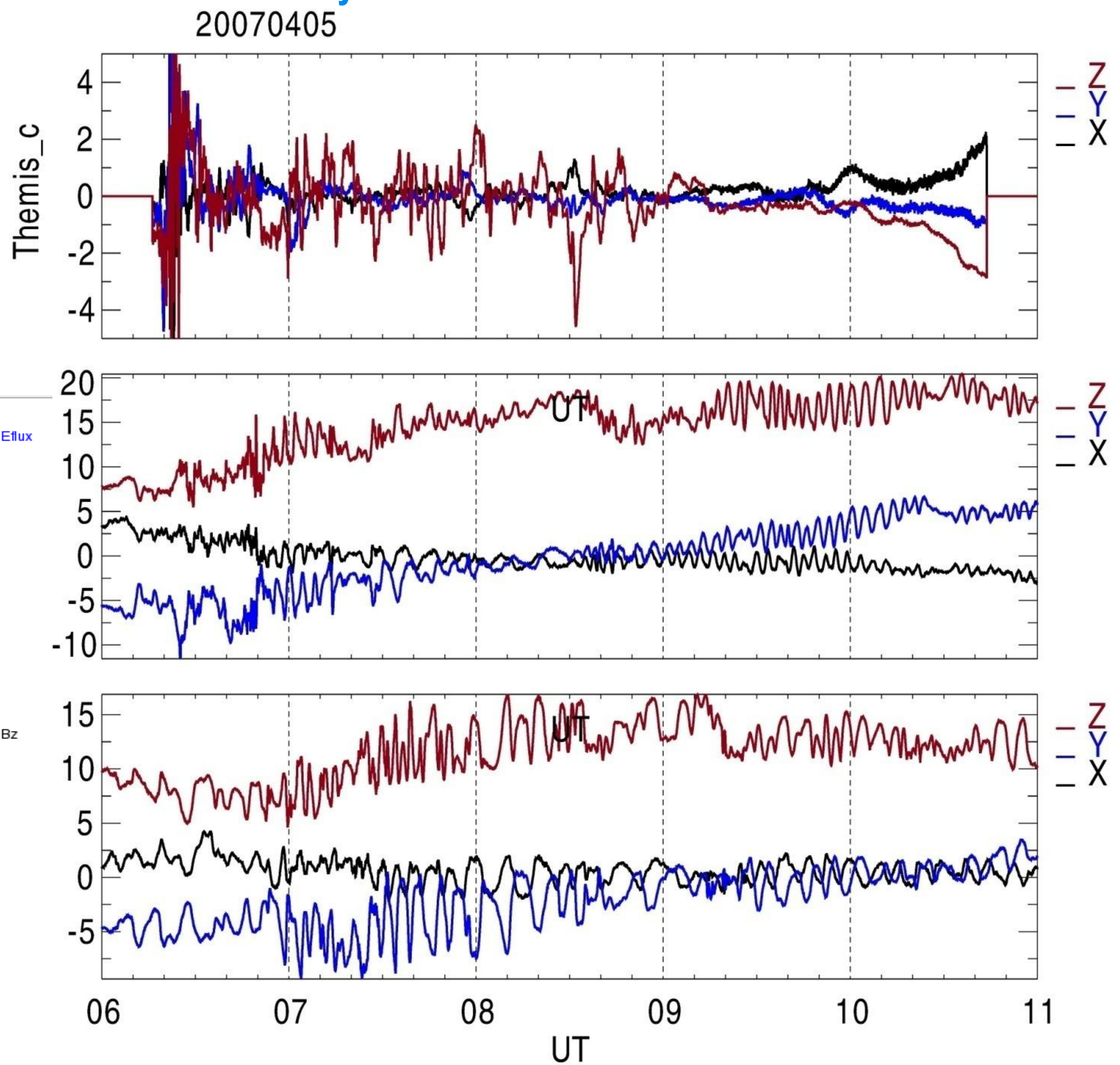


Poloidal storm-time Pc5 waves

Ubiqutious element of the storm recovery phase.
Intense compressional Pc5 waves commonly observed in the dusk sector

Oscillations of magnetic field and plasma are out-of-phase! Modulation depth is nearly the same: ΔB/B~0.3, ΔJ/J~0.4.





Statistical relationships between the ULF activity and GEO relativistic electrons

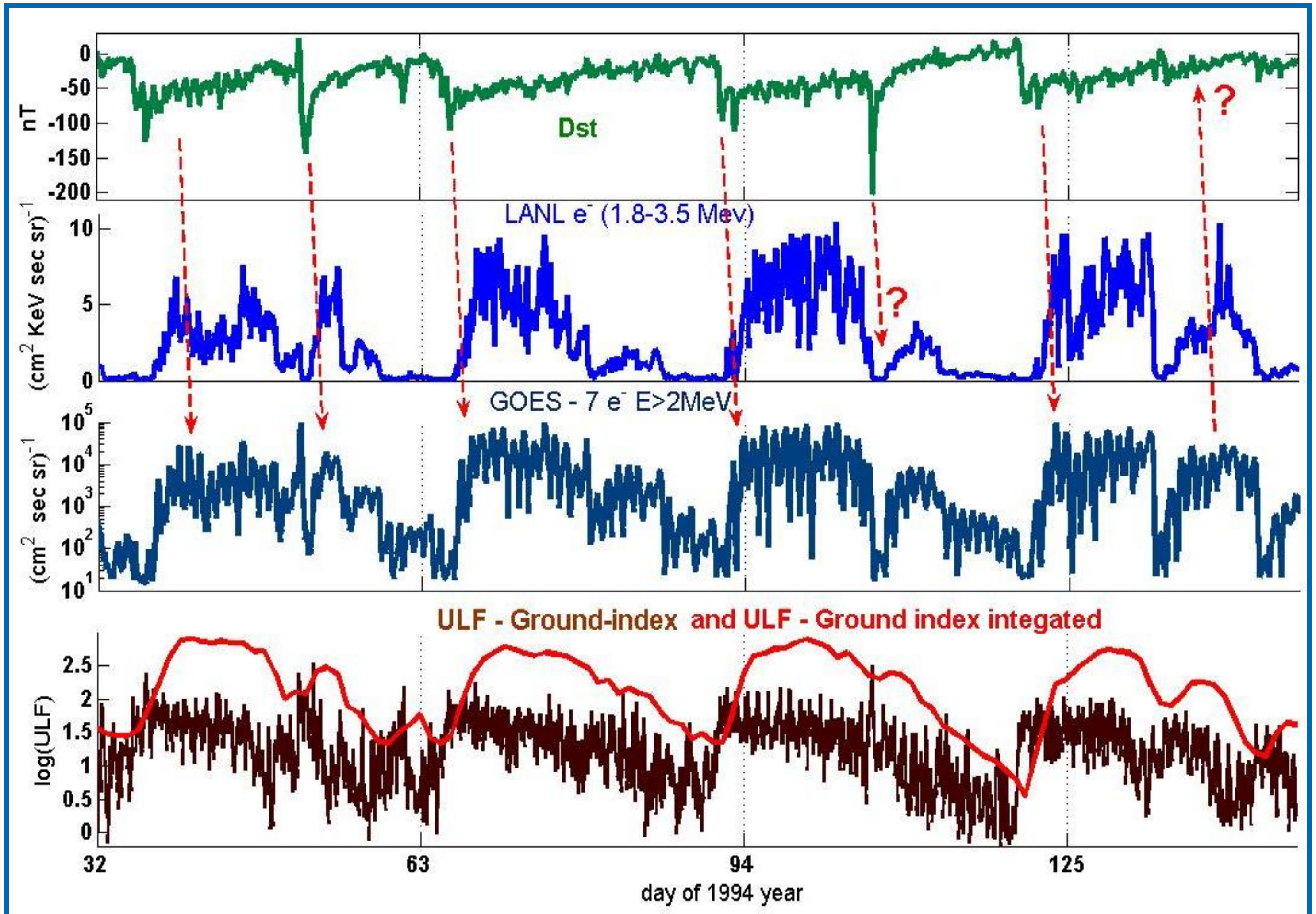
Various geomagnetic indices (Kp, Dst, AE, PC, etc.) quantify the energy supply in certain regions of the coupled SW-magnetosphere-ionosphere system, and characterize the steady-state level of the electrodynamics of the near-Earth environment.

As a measure characterizing the turbulent character of the energy transfer from the SW into the upper atmosphere of near-Earth electromagnetic processes hourly ULF index using the spectral ULF power in frequency band from 2-10 mHz has been used.

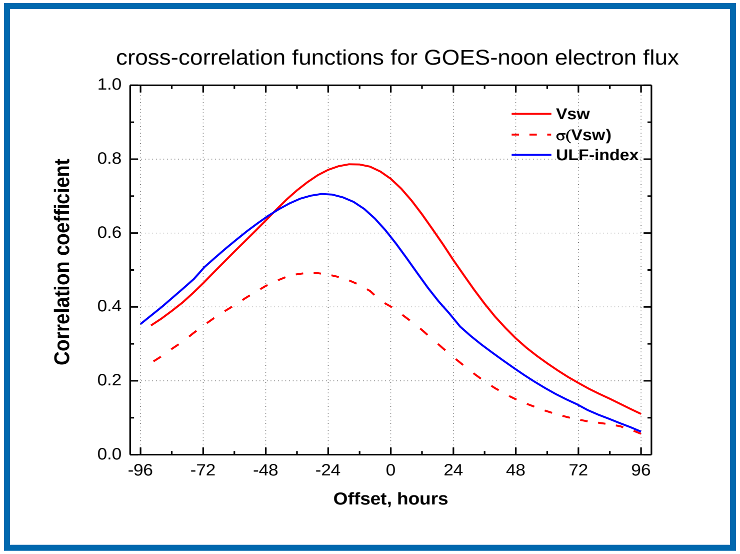
This wave power index characterizes the ground ULF wave activity on a global scale and is calculated from a world-wide magnetometer array.

ULF wave activity and relativistic electron acceleration

Surprisingly, the sustained increase of GEO relativistic electrons (E>2 MeV) fluxes up to ~10^4 is observed after the weak storm (|Dst|<100nT), whereas the increase after the strong storm (|Dst|~200nT) is much shorter and less intense (up to ~10^3 only). The electron behavior matches well the variations of the ULF-index: after the weak storm this index increases much more substantially and for a longer period than after the strong storm!



Cross-correlation between the electron flux variations, ULF-index, and solar wind velocity

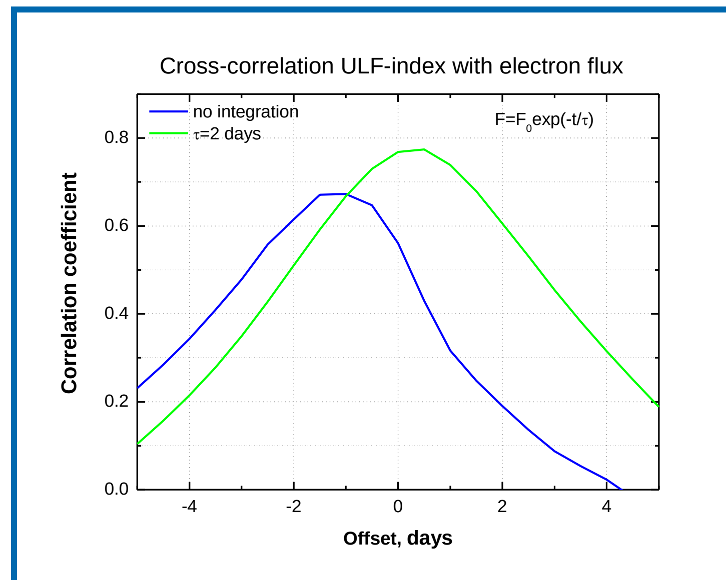


The cross-correlation function shows that the electron flux increases about a day after the enhancements of ULF wave activity and solar wind velocity

Correlation between the ULF-index and electron flux somewhat increases for the time-integrated over pre-history ULF index values:

$$J(t) = \int_{-\infty}^{t} J(t')\exp[-(t-t')/\tau]dt'$$

Increase of correlation probably implies the occurrence of the cumulative effect, that is, the the long-lasting (with characteristic time τ) ULF wave activity is important for the electron flux increase, but not just instant values!



Pro: results of the statistical analysis

- **ULF wave index is as good indicator of the relativistic electron dynamics as Dst index and solar wind velocity (sometimes even better!) and should be taken into account by any adequate space radiation model;**

- **ULF wave index can be used as a “precursor” (alert time is 1-2 days) of the appearance of “killer” electrons at the geostationary orbit;**

- **The acceleration of relativistic electrons is a cumulative effect of the ULF wave turbulence with typical time scale ~1day;**

Latitudinal structure of ULF activity and outer radiation belt

To determine a physical mechanism of the magnetospheric electron acceleration to relativistic energies it is necessary **to identify the region of electron energization** and its possible drivers in the context of structure of the magnetosphere.

During storms both the outer radiation belt and all magnetospheric domains (magnetopause, polar cap, plasmasphere, …) are very dynamic, so any empirical models cannot help much.

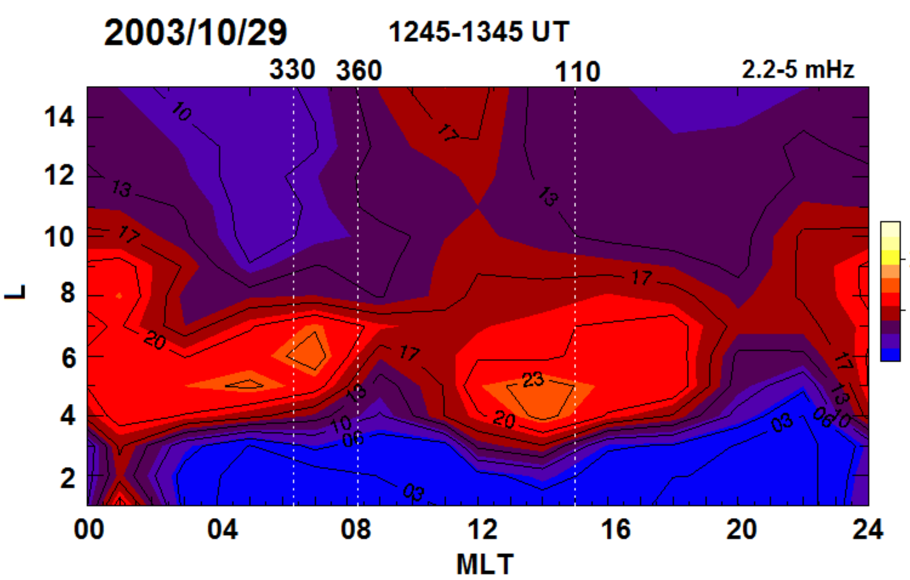
- **Plasmapause?** (plasma density controls the efficiency of VLF emission generation and ULF propagation)

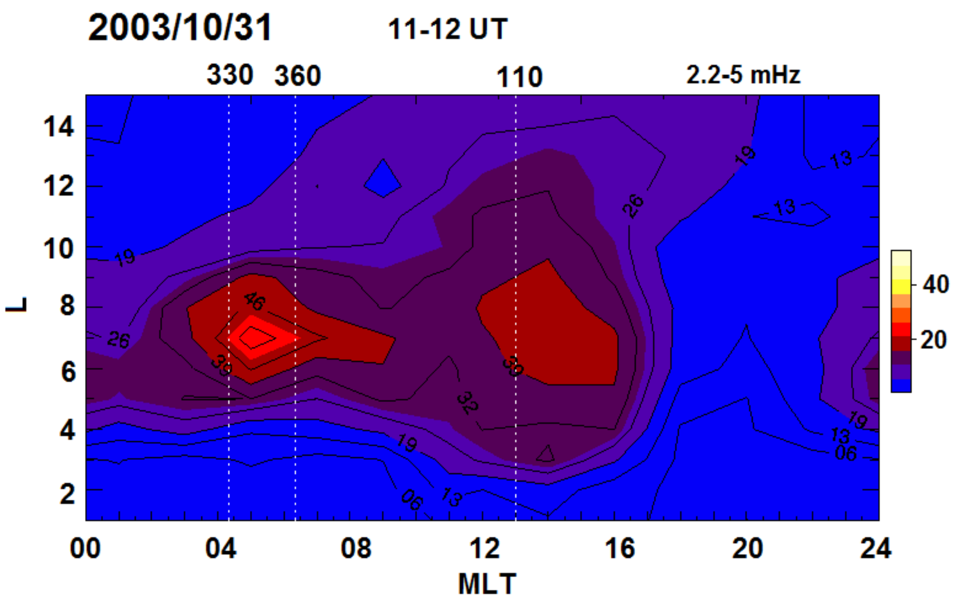
- **Ring current?** Betatron acceleration of electrons injected into a depressed B-field during its recovery can produce necessary energization without ULF/VLF turbulence [Tverskoy, 1968]?

- **Auroral oval?** (intense field-aligned currents, high turbulence, distortions of the magnetic field geometry, intense fluxes of seed auroral electrons, ….)

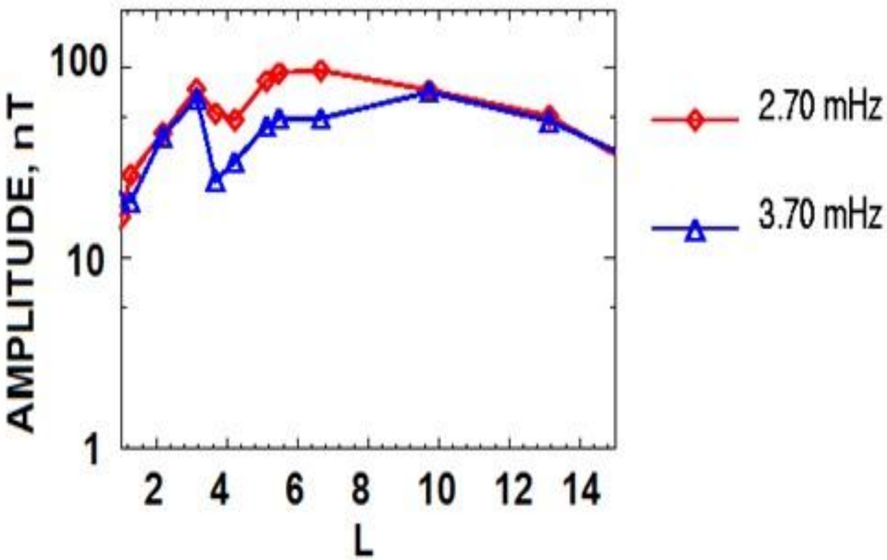
Global Pc5 waves

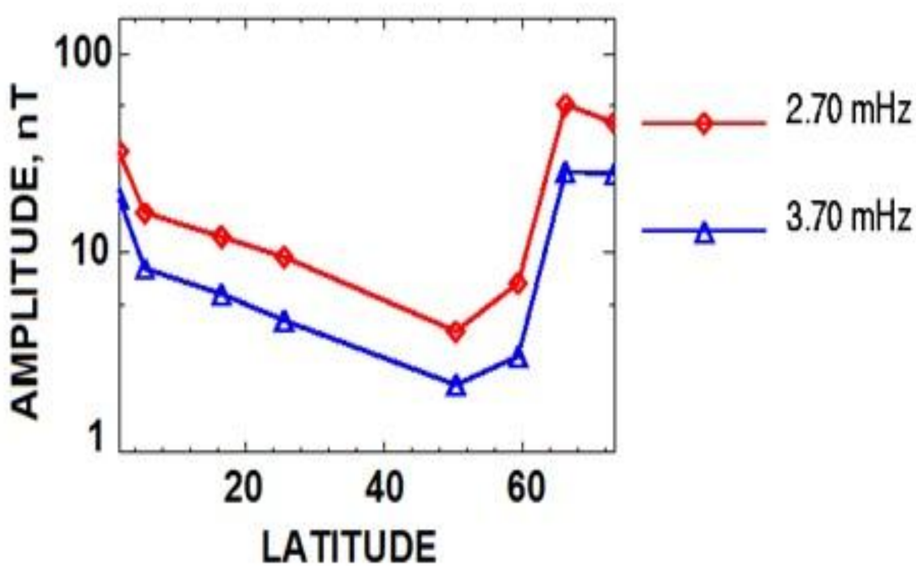
Pc5 activity during recovery phase of strong storms, besides common morning activity centers, has additional "epicenter" in the post-noon hours





Latitudinal structure of global Pc5 waves





Latitudinal distributions of spectral amplitude on the morning & postnoon flanks turn out to be different.

- In the **post-noon sector** (Λ~110°) latitudinal distribution of spectral power has a wide maximum between *L*~4 & ~12.
- At **mid-latitudes** (*L*<4), another amplitude maximum at Φ~56.5°, separated by a local minimum (~59^0) is observed.
- At **low latitudes** wave activity experiences an additional enhancement of the spectral power upon approaching the equatorial region (Φ<50°).

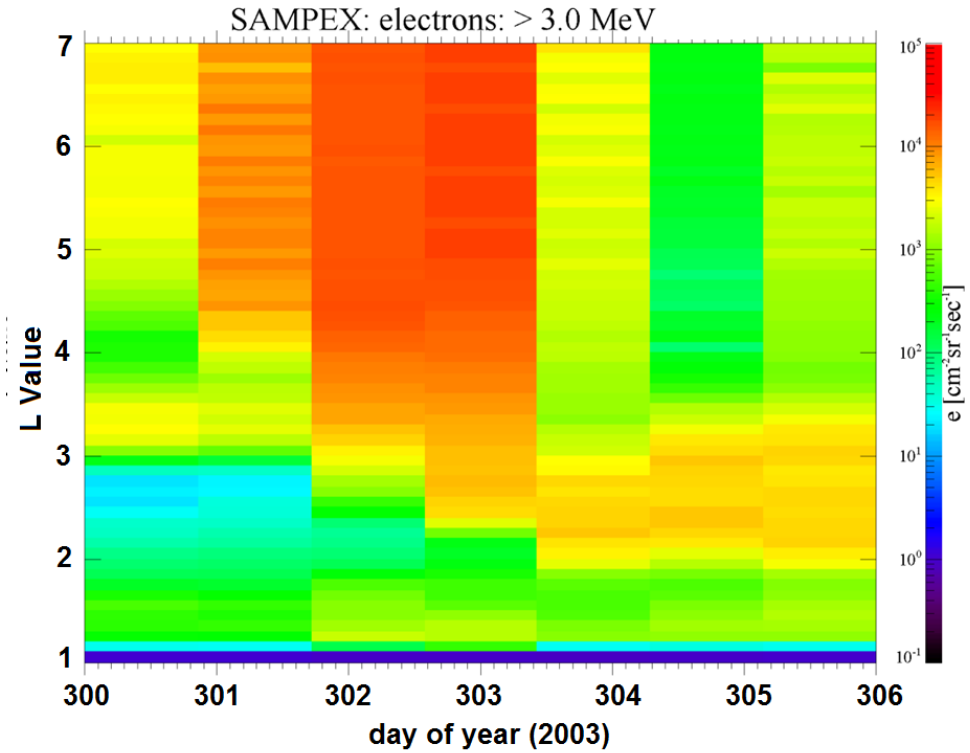
Pro: deep penetration of global Pc5 wave power into magnetosphere

While Pc5 waves at the morning flank are latitudinally narrow, the very intense postnoon waves are observed throughout a wide region from ~50º to ~70º.

The "equatorial enhancement" can be seen from ~50º equatorward, which is possibly caused by energy transmission via compressional waveguide mode.

Therefore, **Pc5 waves during magnetic storm can penetrate deep into the magnetosphere, in the region of relativistic electron energization.**

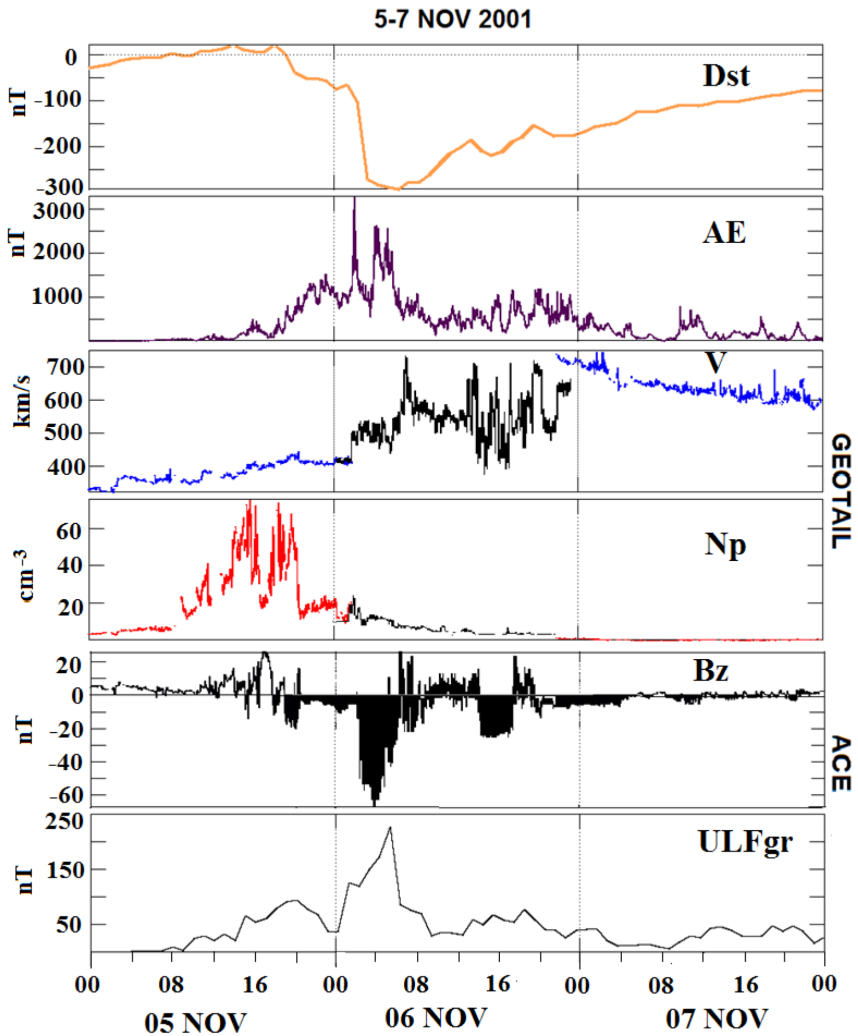
Any adequate model of the outer radiation belt should incorporate a realistic information about the ULF wave characteristics during strong magnetic storms.

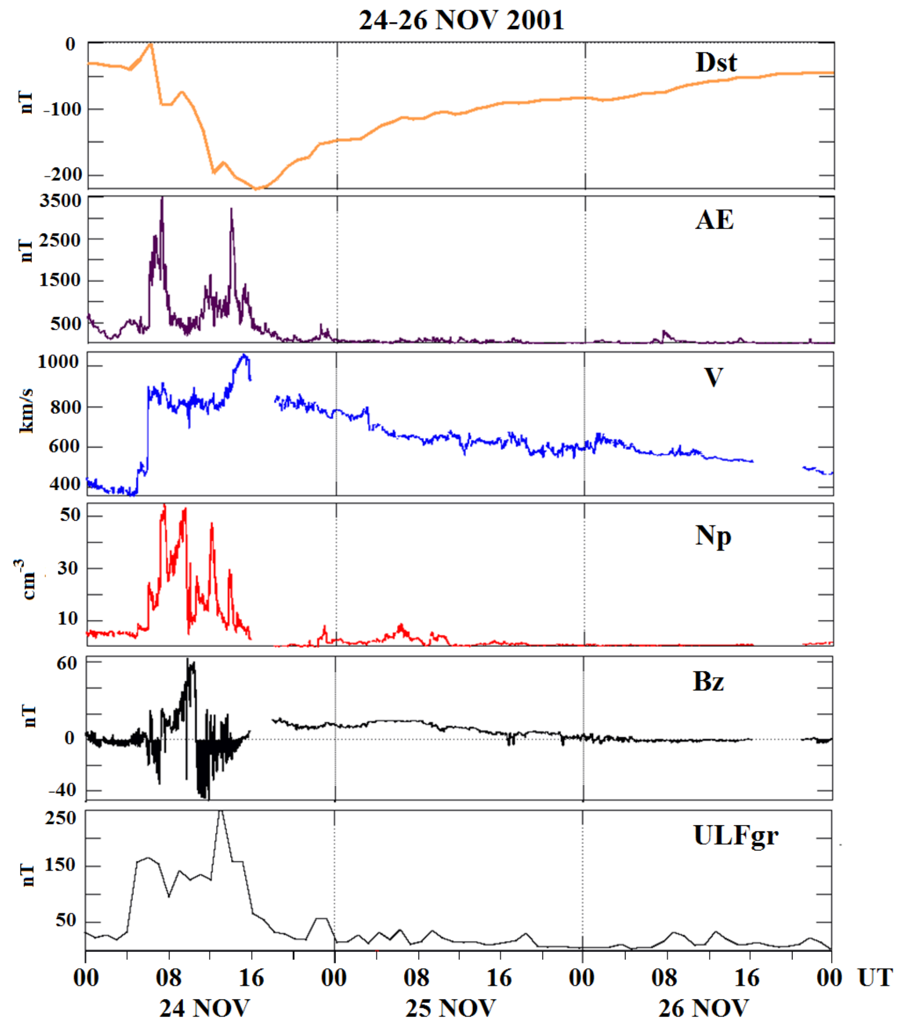


Correspondence between the radiation belt, auroral oval, and Pc5 wave activity

Storms in November 2001 were caused by high solar wind flow with V~900 km/s and N~50cm^{-3} after intense solar flares. During storms different classes of ULF activity in the nominal Pc5 band are observed:

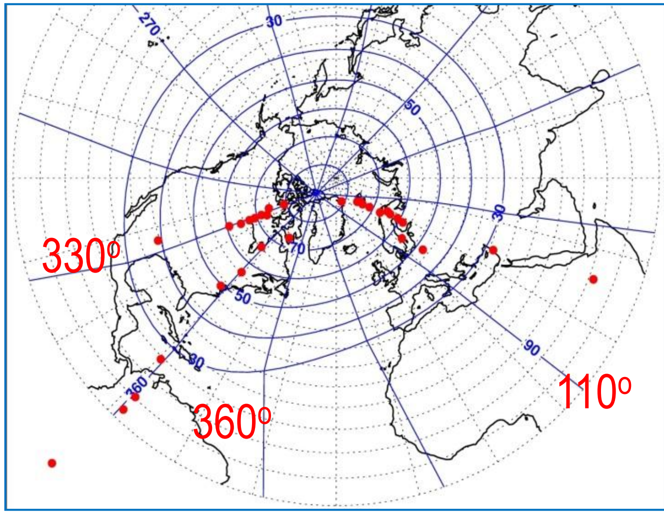
- **Broadband Pc5/Pi3** pulsations
- **Narrowband Pc5** (f~3 mHz) waves





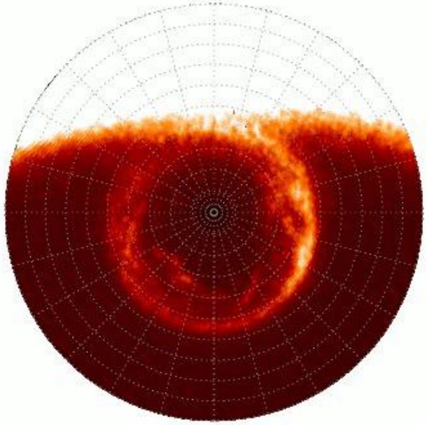
The world-wide magnetometers have been grouped into the latitudinal geomagnetic profiles:

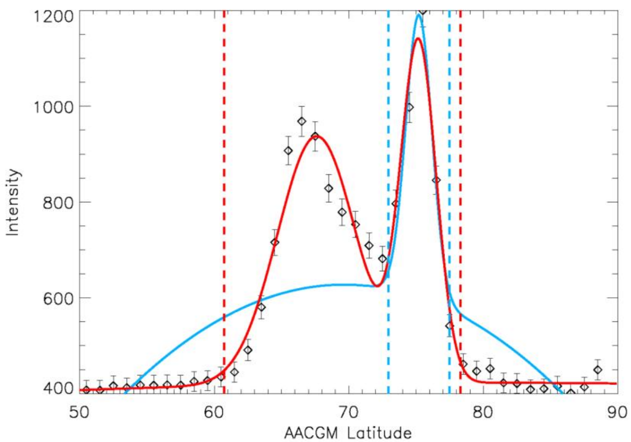
- 330° **Trans-Canadian profile** from CARISMA stations;
- 360° **Pan-American profile (C**ARISMA, INTERMAGNET, MACCS);
- 110° **Scandinavian profile** composed from IMAGE stations



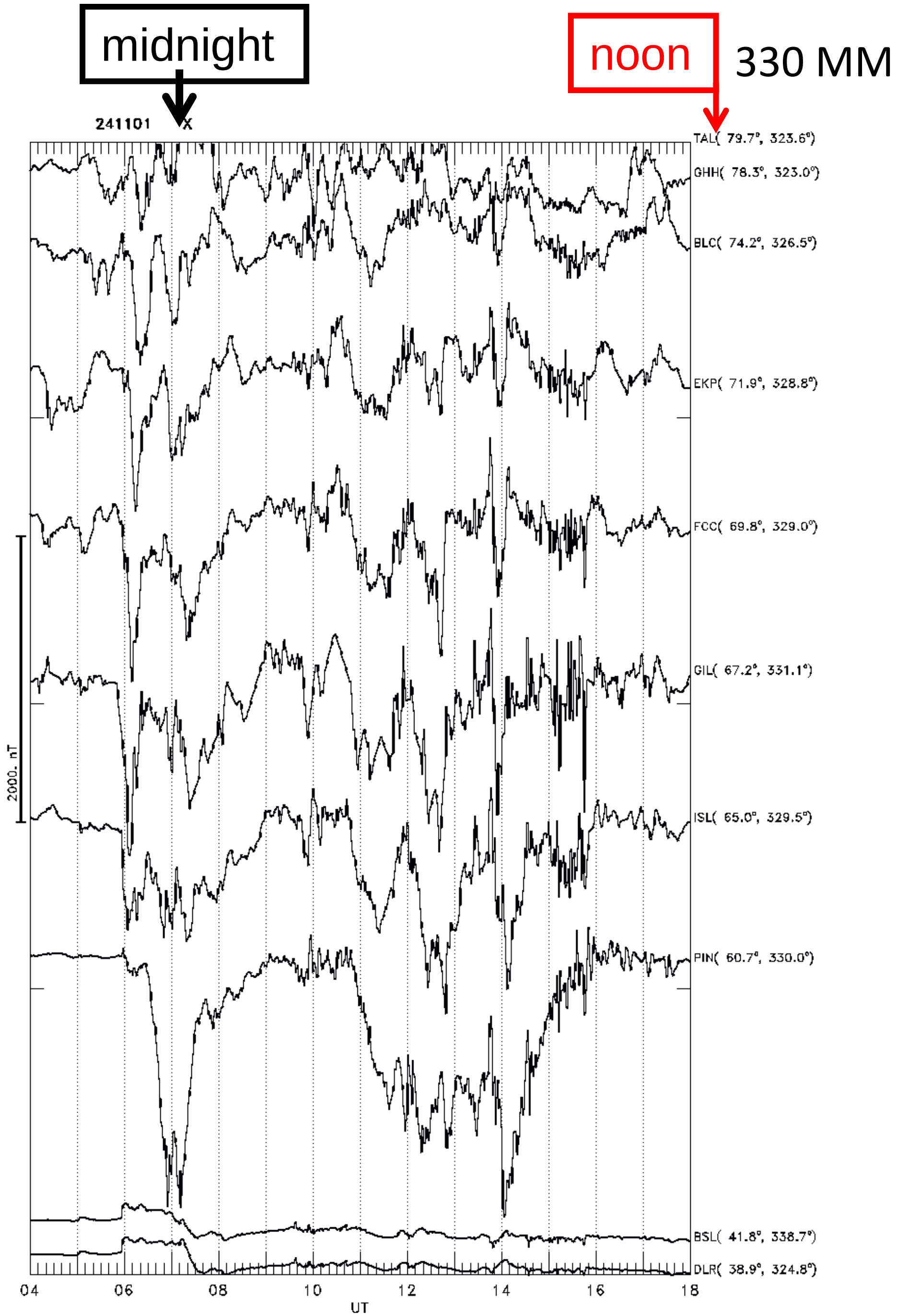
To monitor the **radial distribution of high-energy electrons** we used data from low-orbiting satellite CORONAS-F at circular Sun-synchronized ~500 km orbit with inclination ~82° covering dawn-dusk sector.

To estimate the **poleward and equatorward boundaries of auroral oval**, we used the BAS database The FUV auroral image data from the IMAGE satellite was divided into segments covering 1 h of MLT. For each MLT segment, an intensity profile was constructed, and the auroral boundaries were estimated using the width of the approximation Gaussian function

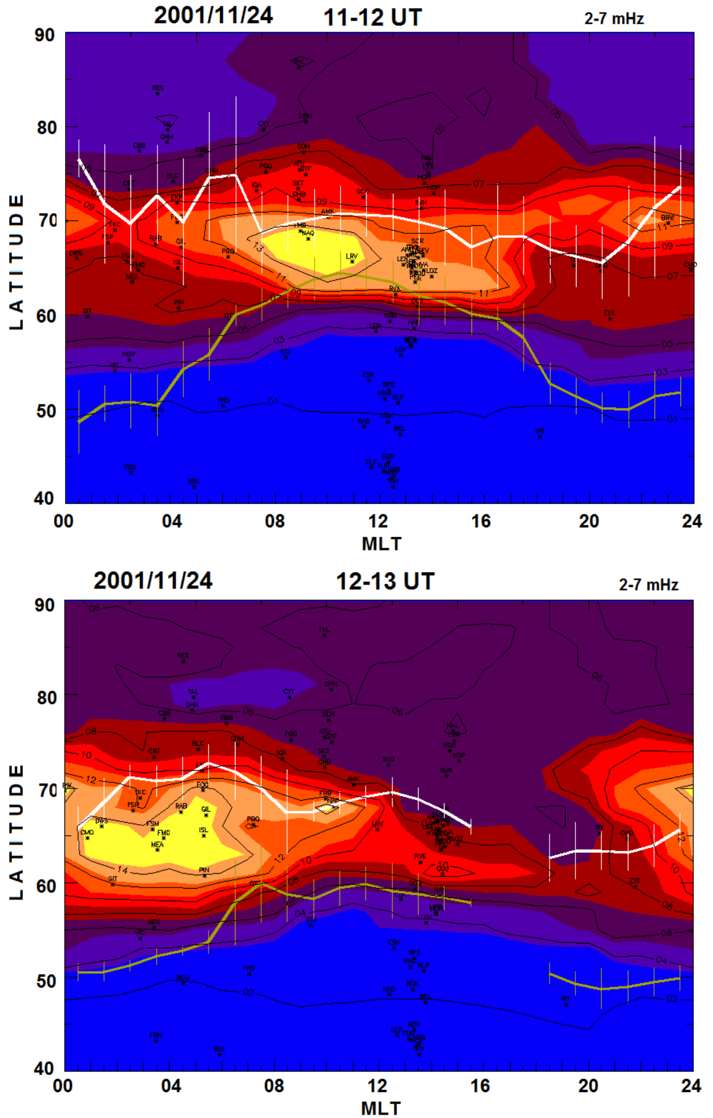




Broadband Pc5/Pi3 pulsations during the storm main phase

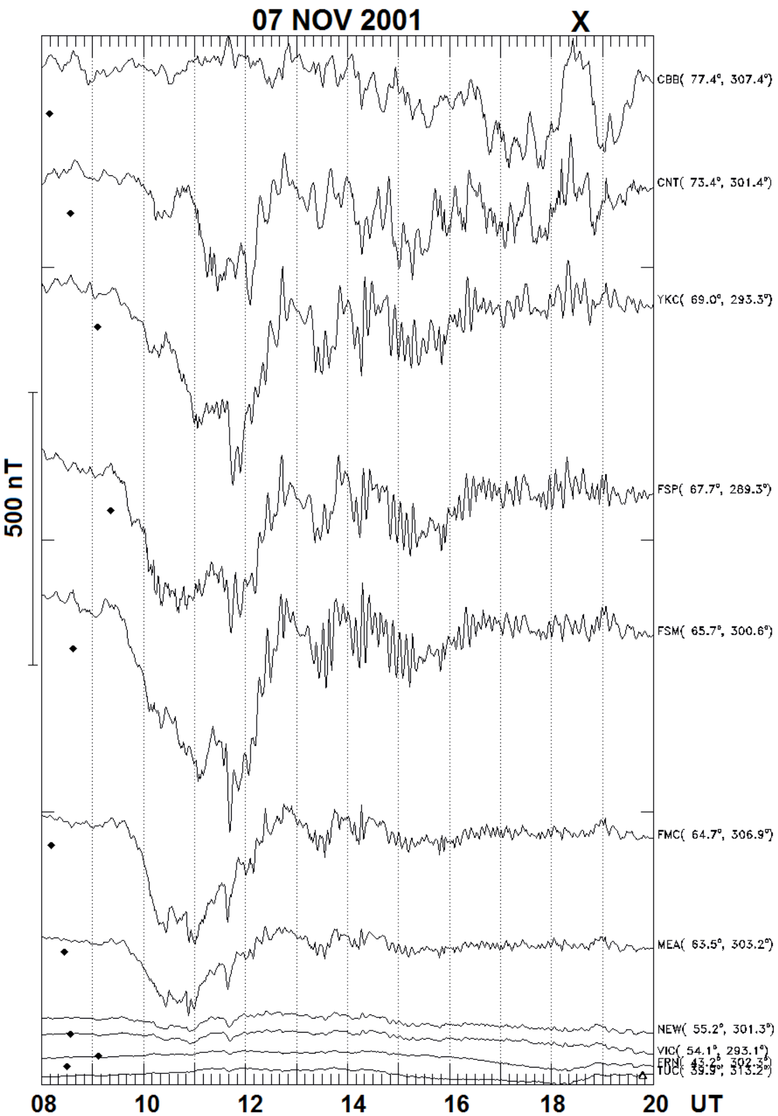


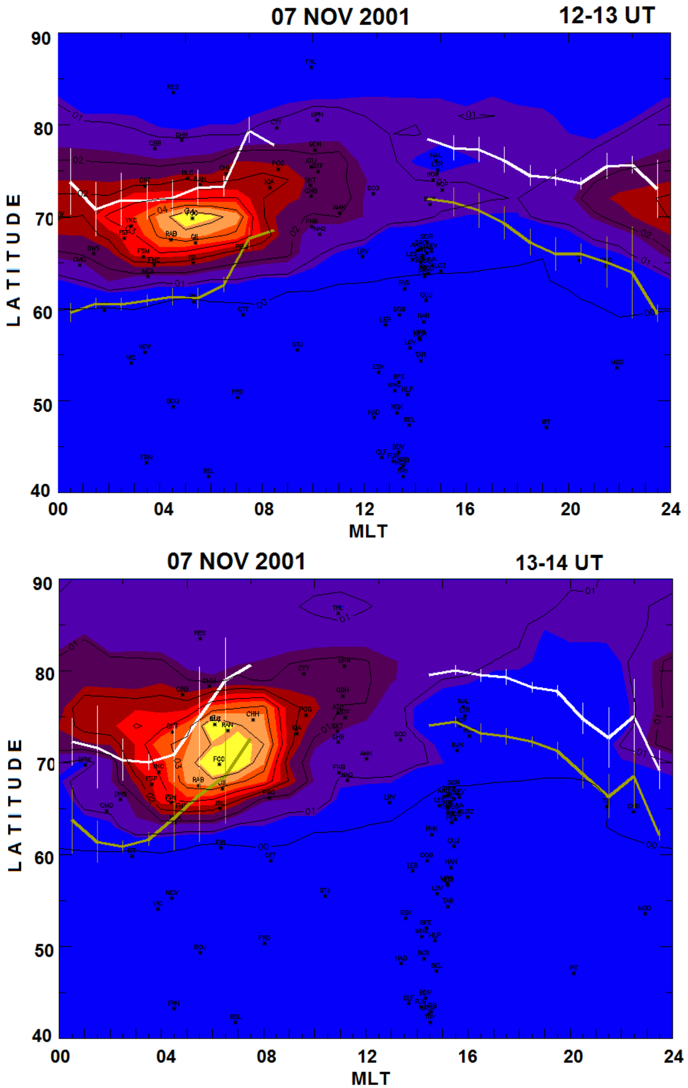
"Epicenters" of Pc5/Pi3 magnetic fluctuations are concentrated inside the auroral oval!



Narrowband Pc5 waves during recovery phase

Quasi-monochromatic “classical” Pc5 waves are observed in the morning sector after substorm.

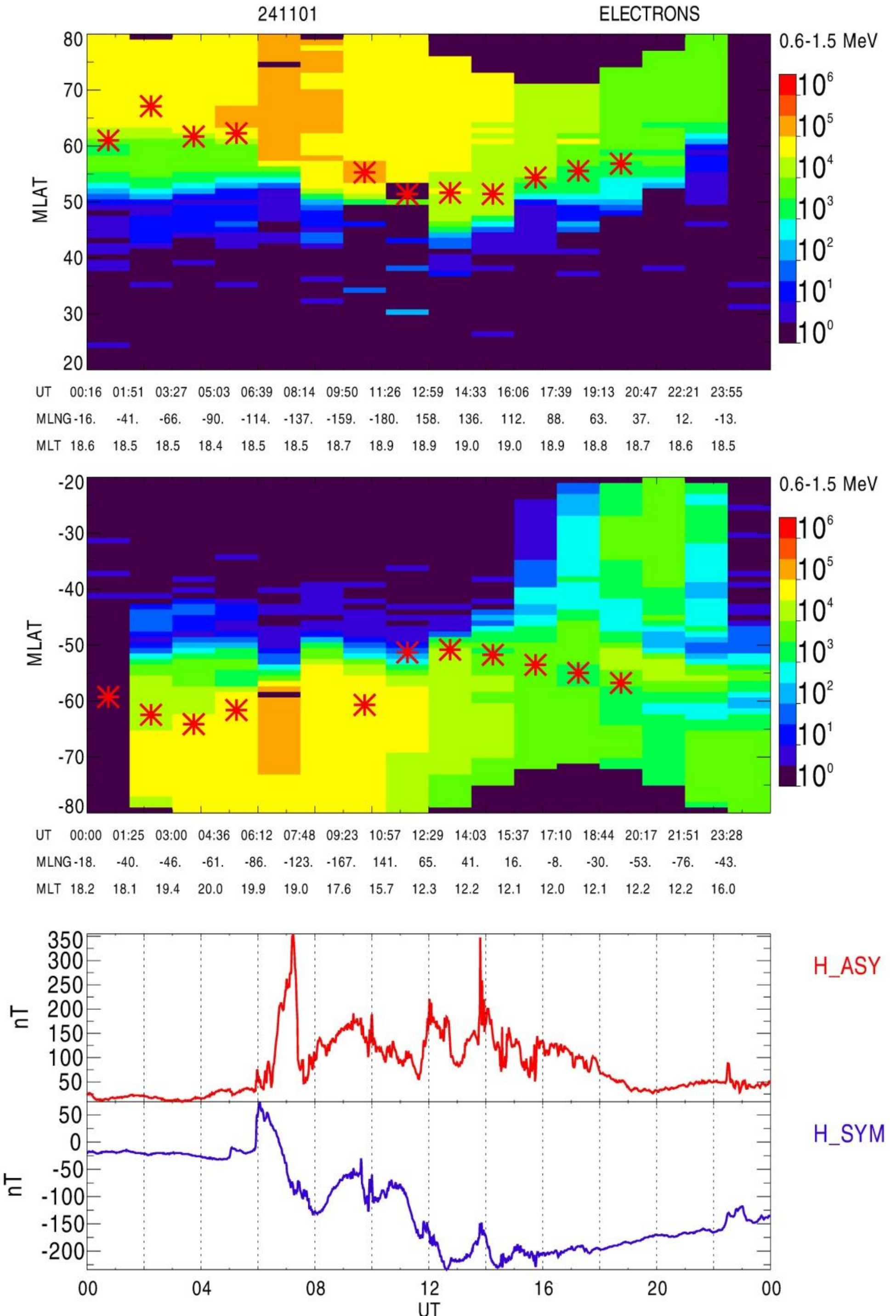




2D distribution of hourly Pc5 wave power shows that **Pc5 waves are closely related to location of the auroral oval** (or its equatorward border).

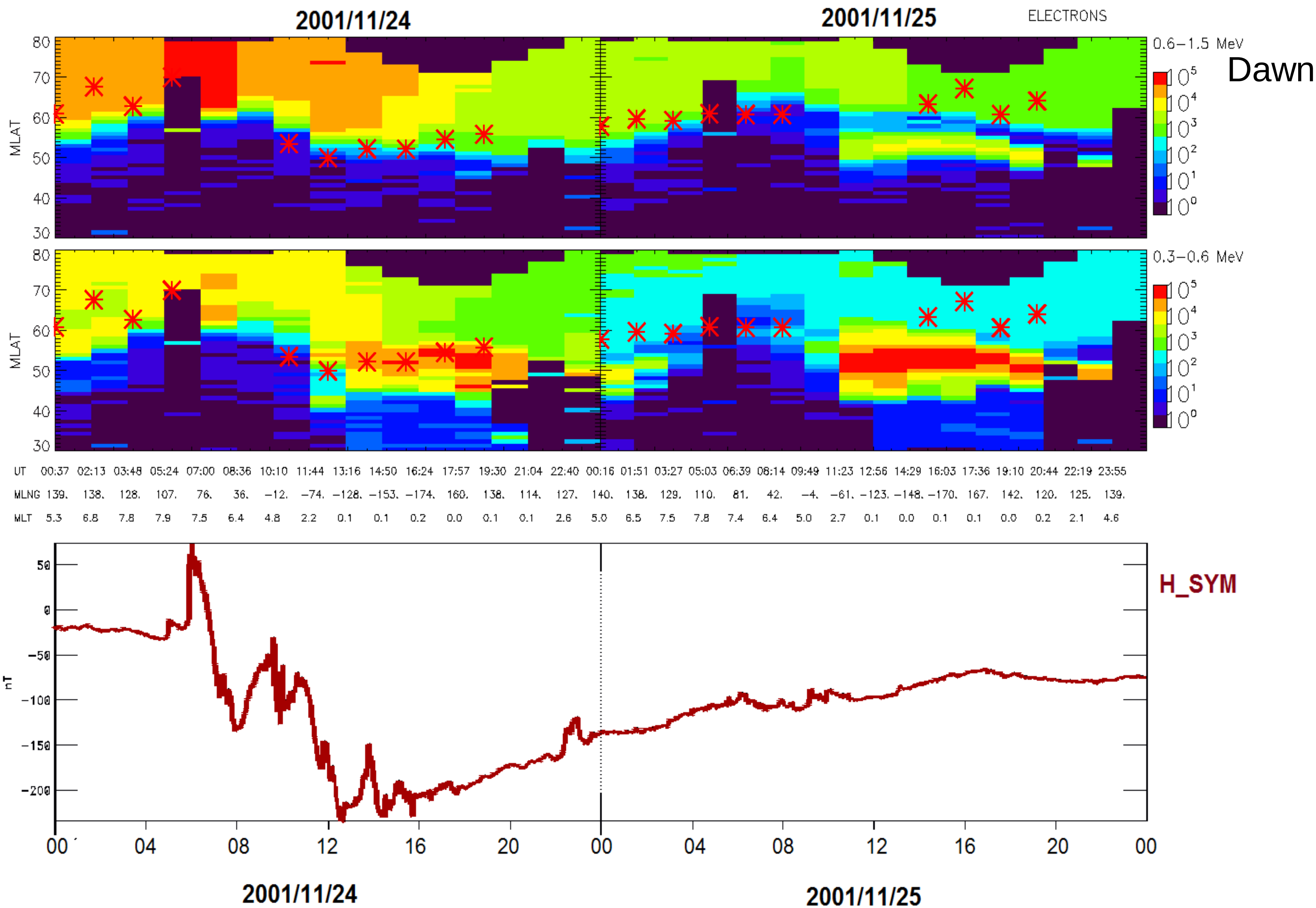
Injection boundary of solar electrons

Solar electrons are injected into high-latitude magnetosphere, illuminate entire polar cap, and penetrate down to the **equatorward boundary of the auroral oval** (asterisks).

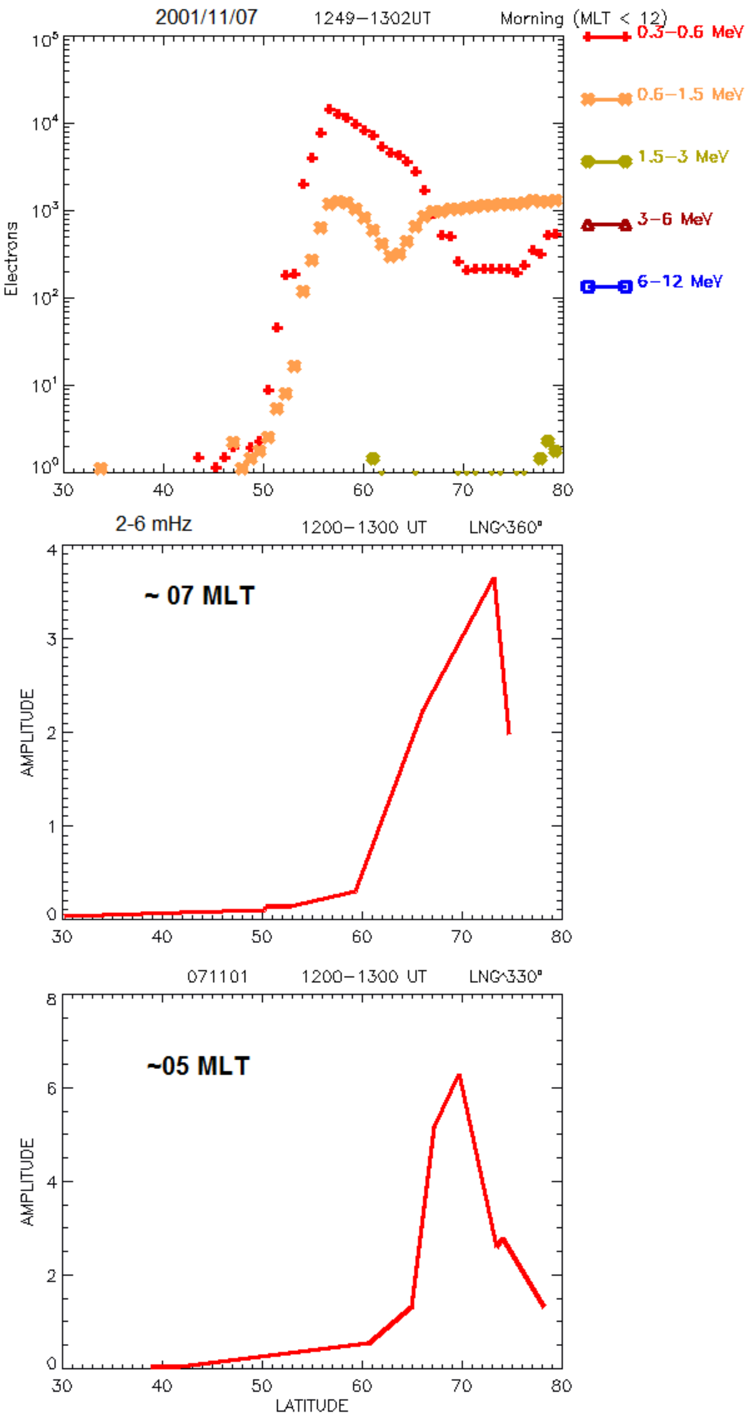


The ring current during the storm main phase is strongly asymmetric

The buildup of the radiation belt as observed by CORONAS



Early buildup (0.3-0.6 MeV electrons) starts near the auroral oval equatorward boundary



How does the location of rebuilt radiation belt at the storm recovery phase correspond to the epicenter of concurrent ULF wave activity?

We compare

- ➢ radial profile J(Φ) of electron fluxes in various energy channels along the orbit
- ➢ with the latitudinal distribution of hourly-integrated wave power in the Pc5 band in the morning sector.

During both storms, the peak of a new radiation belt is around Φ~60°.

At the same time, Pc5 activity along profiles at 7 MLT (middle panel) and 5 MLT (bottom panel) is concentrated in a wide region peaking at Φ~70°.

The inner boundary of Pc5 activation region Φ~60° coincides with the location of rebuilt radiation belt.

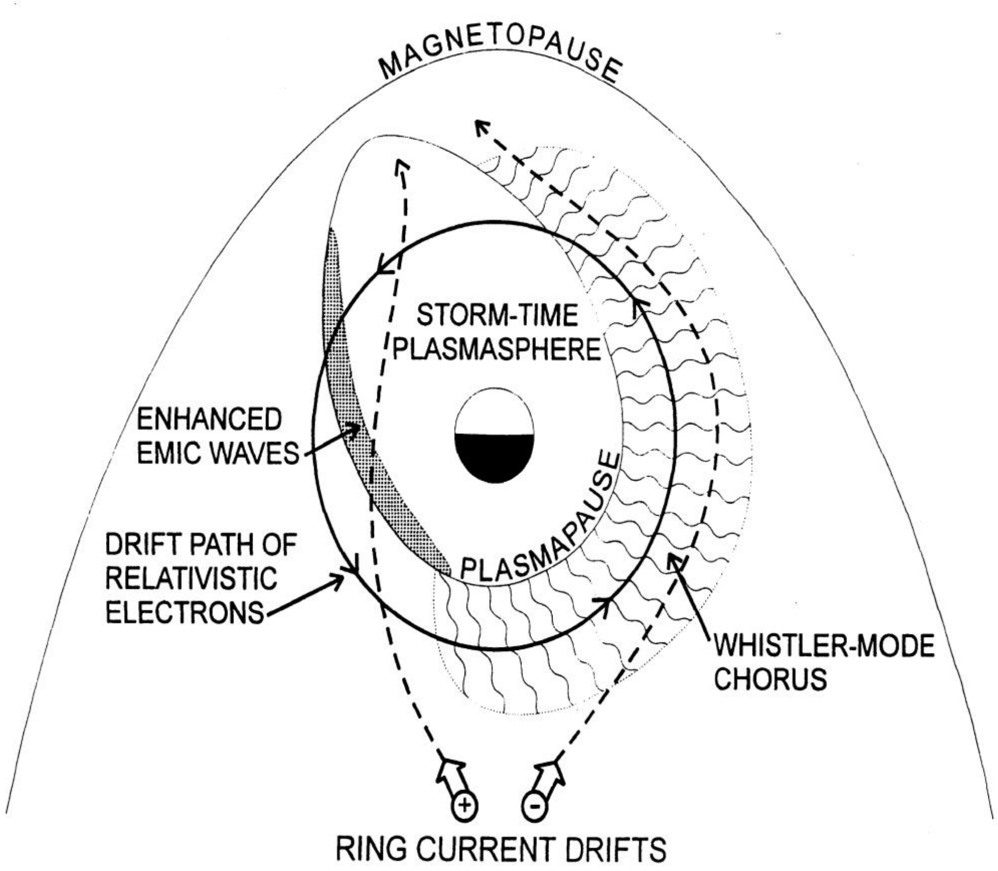
Azimuthal propagation of Pc5 waves and magnetospheric electrons

The resonant condition indicates that **waves must propagate in the same azimuthal direction as electrons**, and with the same phase velocity as electron drift.

Is this condition fulfilled for toroidal, poloidal and waveguide Pc5 pulsations?

$$\frac{\omega}{m} = \omega_d$$

SUMMERS ET AL.: WAVE-PARTICLE RESONANT DIFFUSION

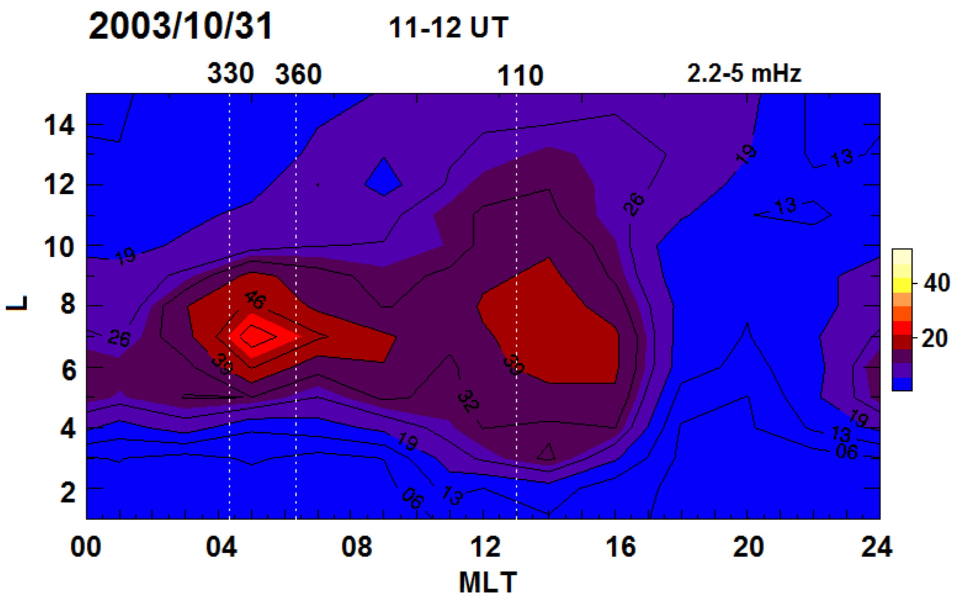


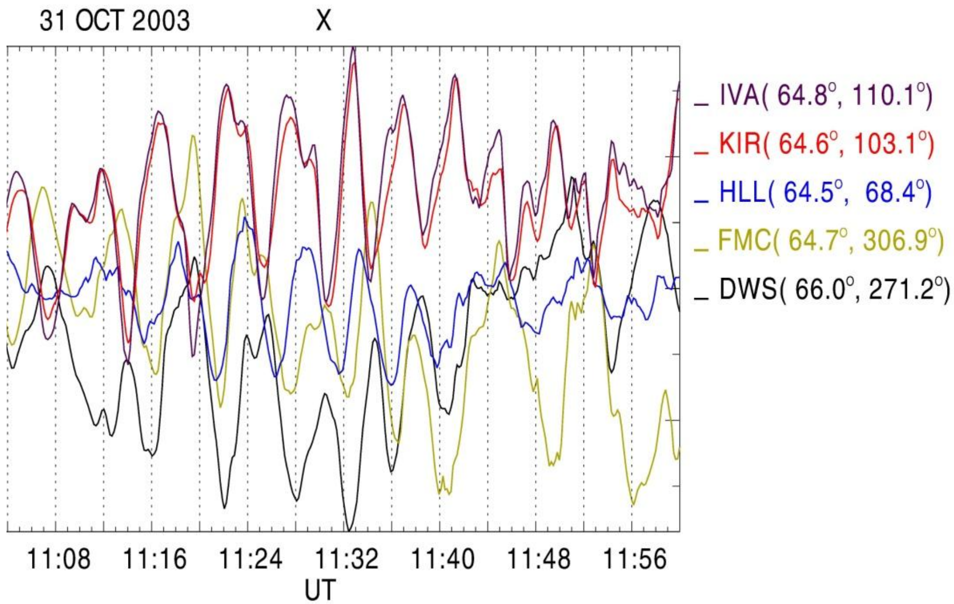
Toroidal and global Pc5 pulsations

Global Pc5 activity (~3 mHz), besides common morning center, has additional epicenter in post-noon hours

Even visual comparison of magnetograms shows **westward** propagation both in morning/afternoon sectors.

Cross-correlation: in the afternoon sector (IMAGE) *m*~1.0-2.1; in the morning sector (CARISMA) *m*~0.3-0.5.





Con: Wave signatures from longitudinally separated magnetometers show that global Pc5 waves propagate westward both during morning and afternoon hours, though with somewhat different phase velocities.

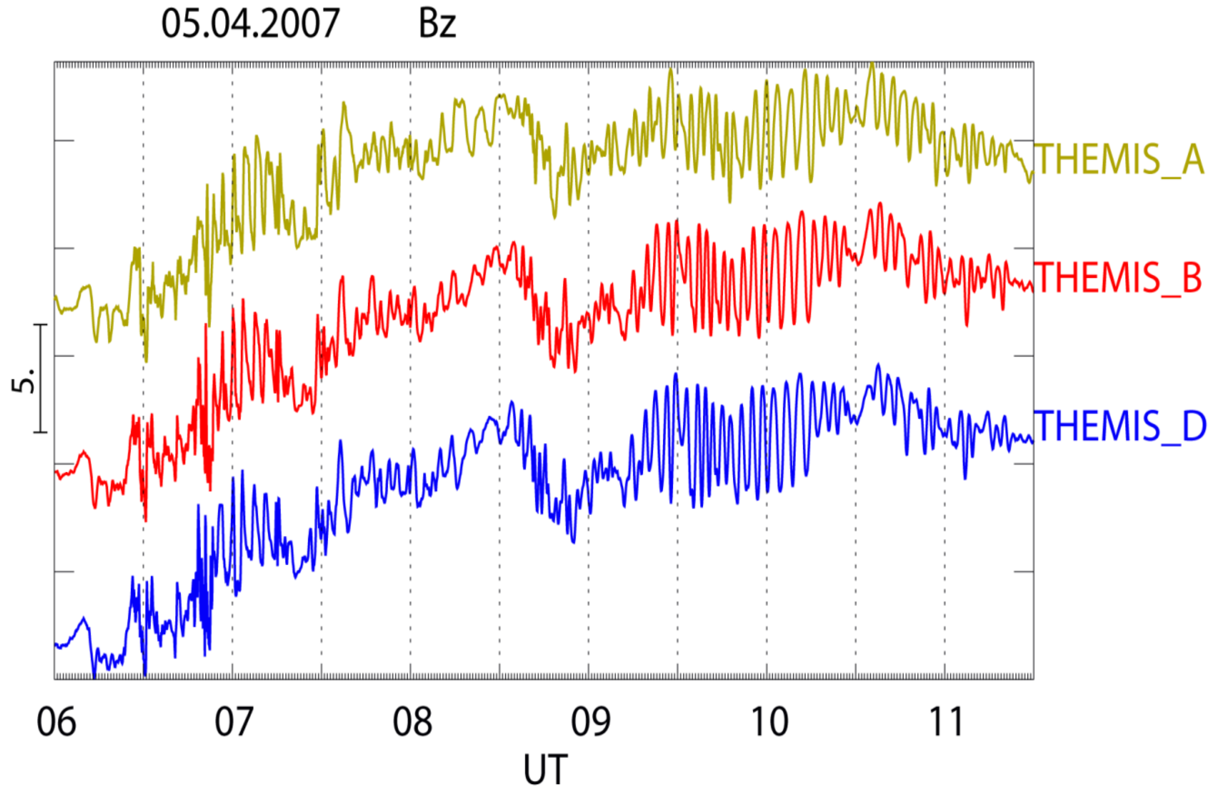
Westward wave propagation makes drift resonance with **eastward drifting electrons** impossible.

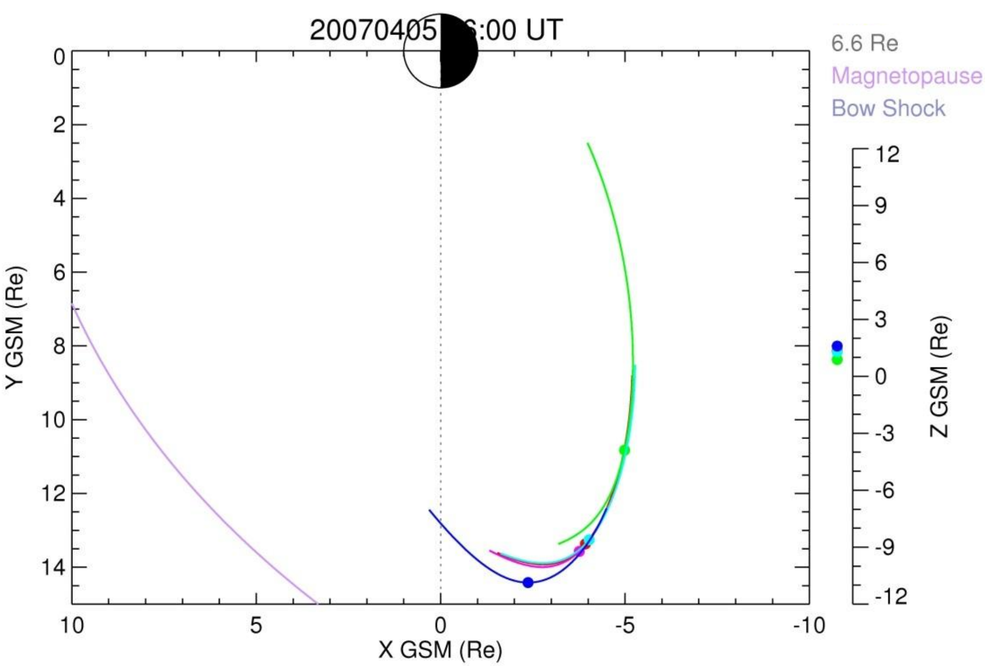
A possibility of electron energization by typical toroidal and global Pc5 waves seems questionable?

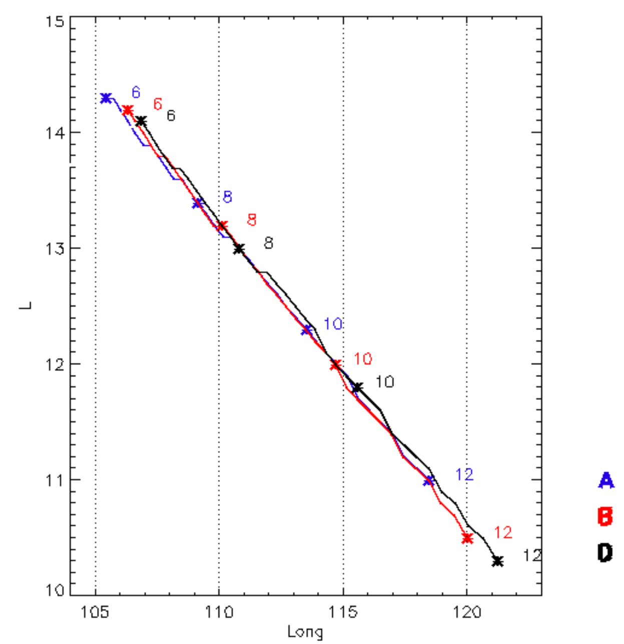
Gradient observations in space by THEMIS probes

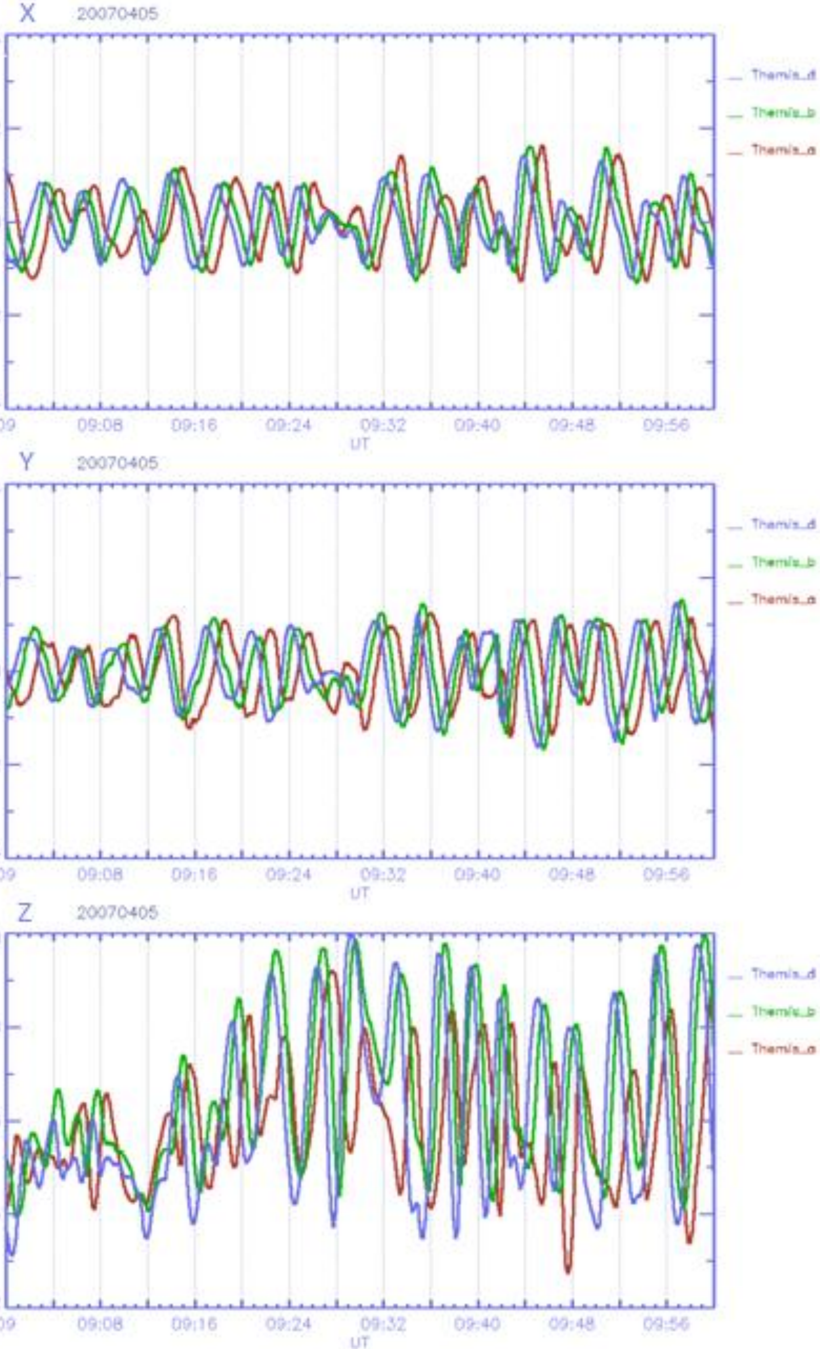
The satellites move along descending trajectory in the equatorial plane in the dusk sector

For spacecraft D-B-A separation $\Delta L \sim 0.2\text{-}0.3$, and in longitude $\Delta\Lambda < 2^{o}$







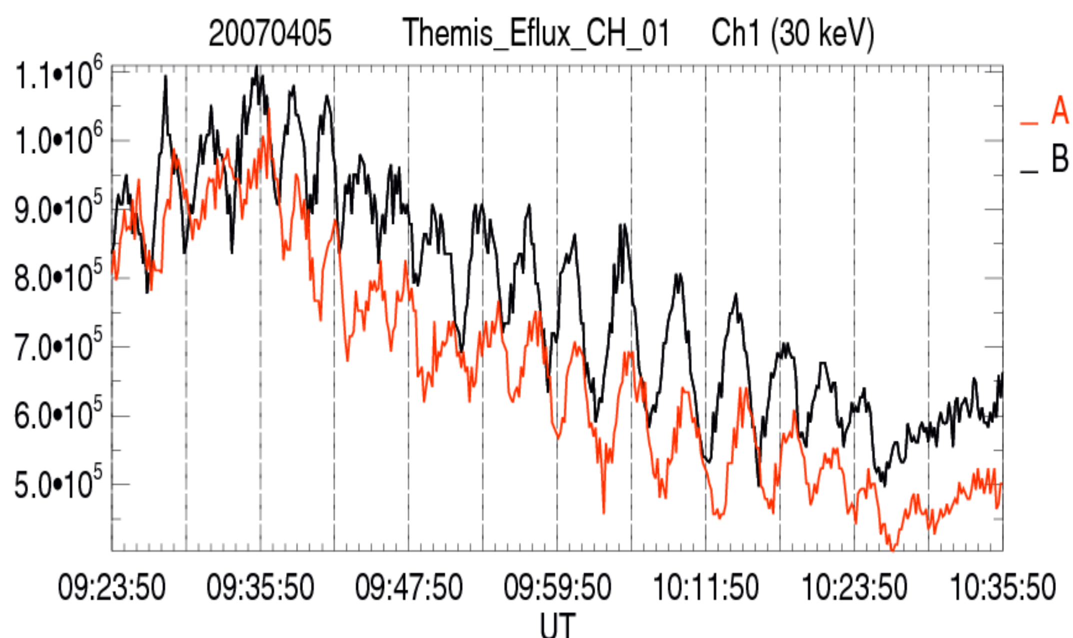


Poloidal wave propagation

Magnetograms from satellites D-B-A reveal a regular time delay between them Δt~1 min.

Apparent propagation velocity is directed **sunward** in the azimuthal direction!

Oscillations of particle flux propagate in the same direction!



Con: Poloidal Pc5 waves: wrong propagation direction?

The delay $\Delta\phi \sim 40°$ for $\Delta\Lambda \sim 2°$ corresponds to $m = \Delta\phi / \Delta\Lambda \sim 20$.

Such high m & consequently small phase velocities are typical for storm-time Pc5 pulsations excited by energetic protons.

Small-scale azimuthally poloidal Pc5 pulsations are most probably generated by energetic protons injected into the magnetosphere, so they propagate in the direction of proton drift, that is opposite to the electron drift.

They hardly can resonantly interact with electrons?!

Arguments pro:

✓ ULF Pc5 waves are one of the largest energy container during the storm recovery phase. ULF wave index was shown to be a good indicator of the relativistic electron dynamics (even better than Dst index and solar wind velocity) and should be taken into account by any adequate space radiation model. The electron acceleration is a cumulative effect of the ULF wave turbulence with typical time scale ~1day. The ULF wave index can be used as a "precursor" (alert time is 1-2 days) of the appearance of "killer" electrons at GEO.

✓ Global Pc5 pulsations during magnetic storm recovery phase can penetrate deep into the magnetosphere, in the region of relativistic electron energization.

✓ The early rebuilding of the radiation belt originates near the equatorward boundary of the auroral oval, near inner edge of Pc5 power latitudinal distribution.

✓ Pc5 wave power is closely related to the location of the auroral oval. This feature is not taken seriously into account by modern theories of ULF waves.

Arguments con:

❖ Mismatch between electron drift direction and Pc5 (both toroidal & poloidal) phase velocities.

❖ Latitudinal difference during the storm recovery phase between the location of radiation belt and epicenter of ULF activity