Solar/Interplanetary Effects and Possible Consequences for Atmospheric Vorticity*

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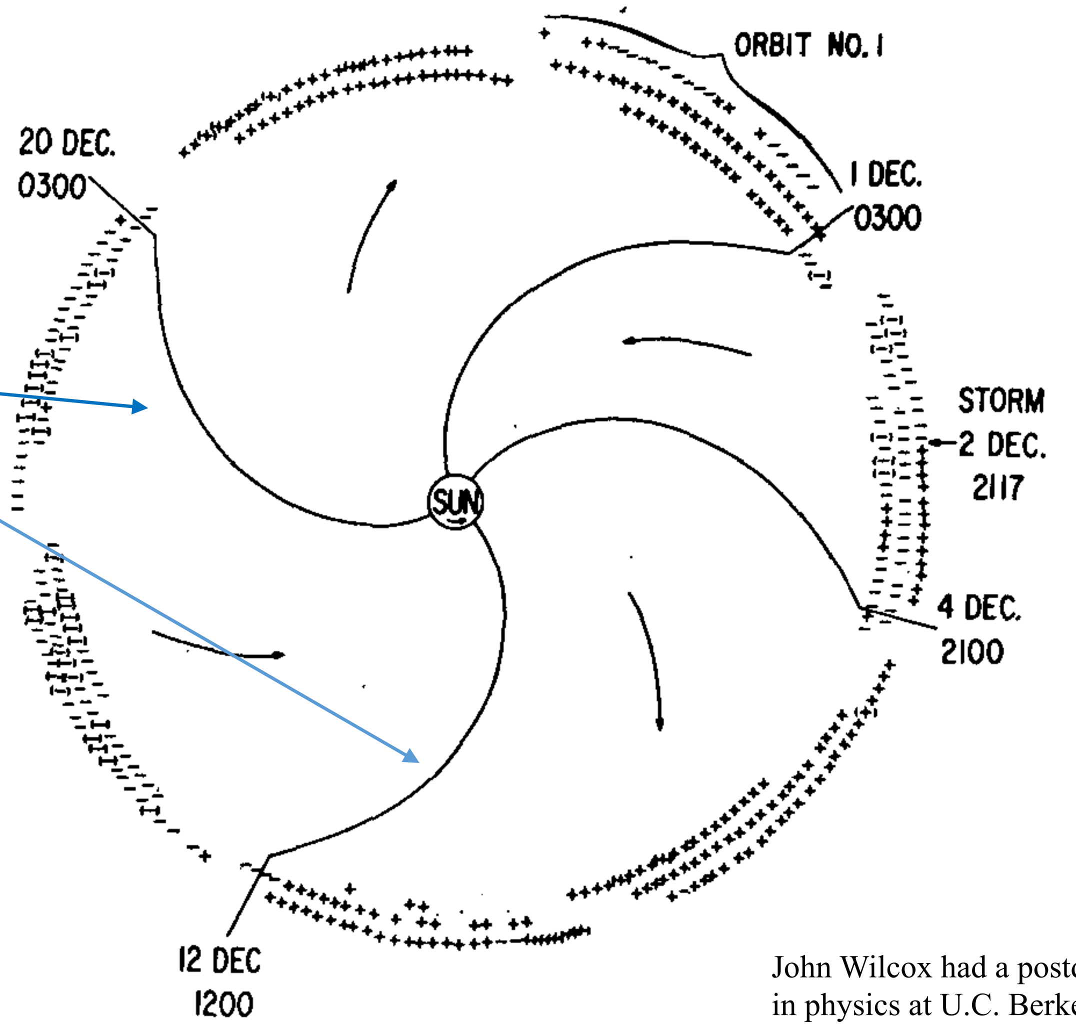
What are interplanetary “sector boundaries”?

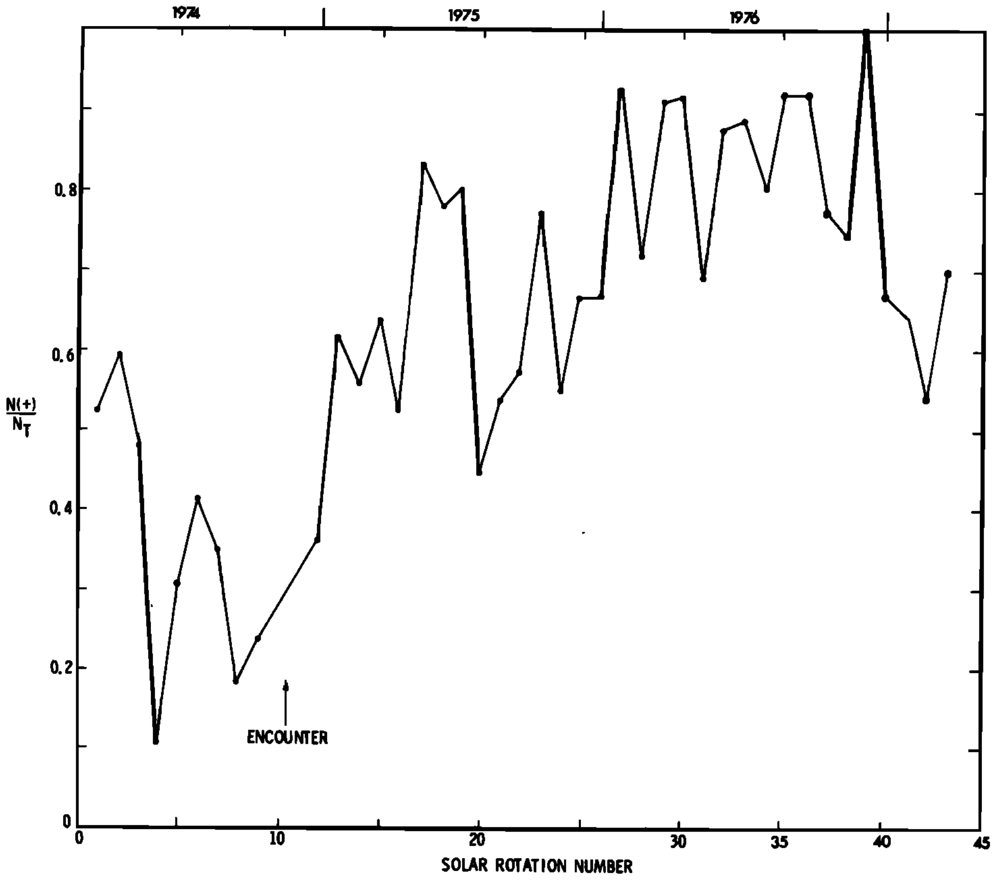
From measurements in the ecliptic plane, the interplanetary magnetic field typical has 4 magnetic field sectors.



Ness and Wilcox PRL 1964

John Wilcox had a postdoc with H. Alfvén, became a professor in physics at U.C. Berkeley and later moved to Stanford Univ. and set up the Wilcox Solar Observatory there.

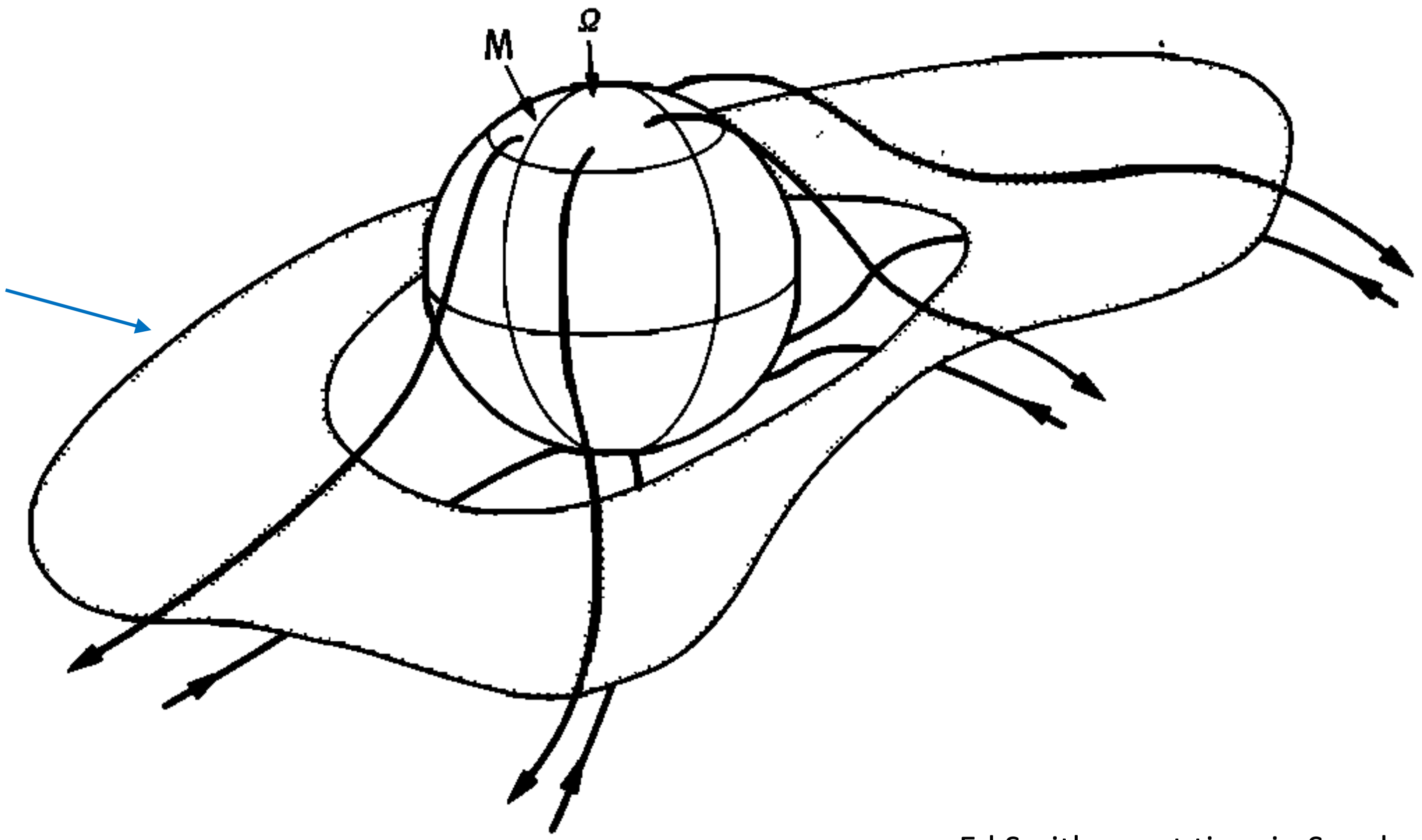
Pioneer 11 was the first spacecraft to go out of the ecliptic plane



Smith, Tsurutani and Rosenberg, JGR 1978

Alfven's "Ballerina Skirt"

Heliospheric current
Sheet (HCS)



Smith, Tsurutani and Rosenberg, JGR 1978

Ed Smith spent time in Sweden with Hannes Alfvén. Smith knew of Hannes' (somewhat obscure) model of heliospheric plasmas. Hannes was credited in our paper for predicting the magnetic field 3-d configuration.

"Solar Magnetic Sector Structure: Relation to Circulation of the Earth's Atmosphere"

Abstract. The solar magnetic sector structure appears to be related to the average area of high positive vorticity centers (low-pressure troughs) observed during winter in the Northern Hemisphere at the 300-millibar level. The average area of high vorticity decreases (low-pressure troughs become less intense) during a few days near the times at which sector boundaries are carried past the earth by the solar wind. The amplitude of the effect is about 10 percent.

Wilcox et al. *Science, 180*, 186, 1973

Why are pressure changes in the stratosphere important?

It is known that occasionally stratospheric winds (near auroral zone latitudes) suddenly become disrupted or reverse direction.

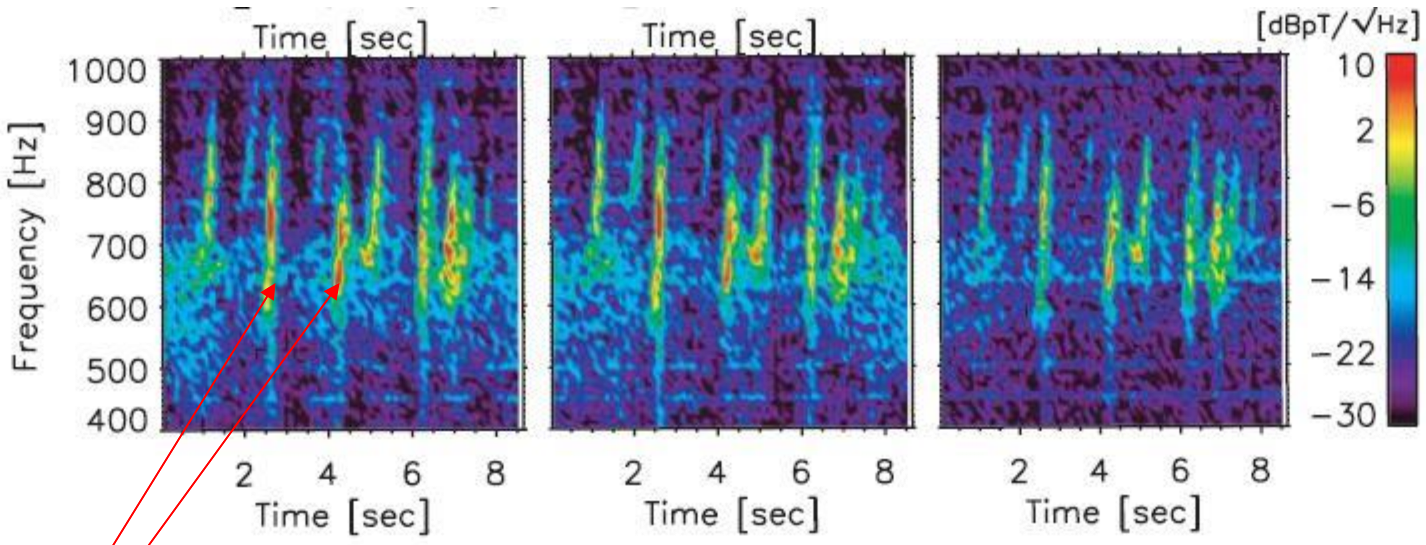
This changes our weather patterns at lower latitudes.

“Sudden Stratospheric Warmings” (SSWs) (originally called the “Berlin Effect”) are closely related.

Over the years, the statistics of heliospheric current sheets and pressure changes in the stratosphere has been verified as a substantial statistical result.

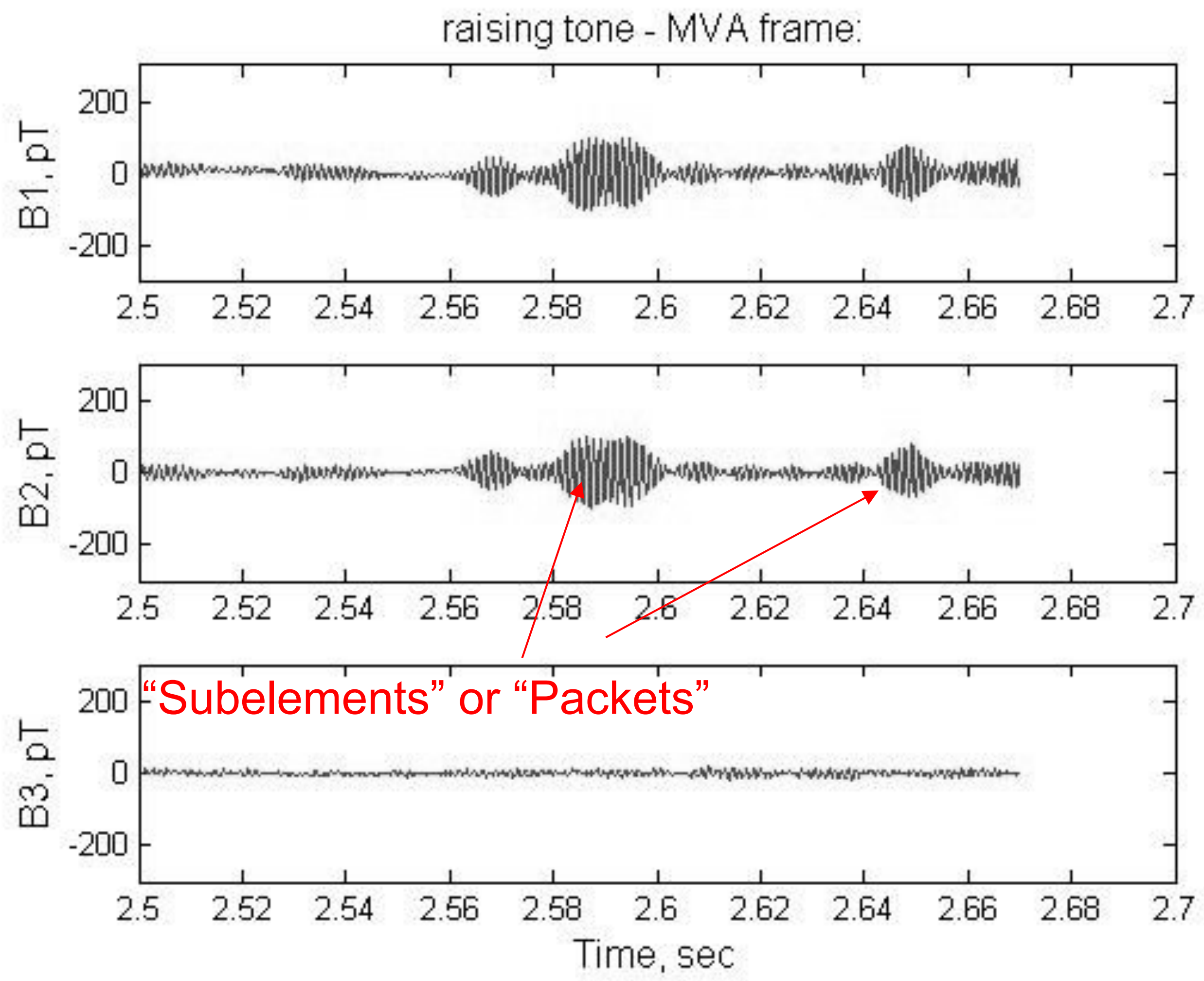
Magnetospheric Electromagnetic Whistler Mode Waves Called Chorus Generation Region Properties

Data from the Japanese Geotail Mission



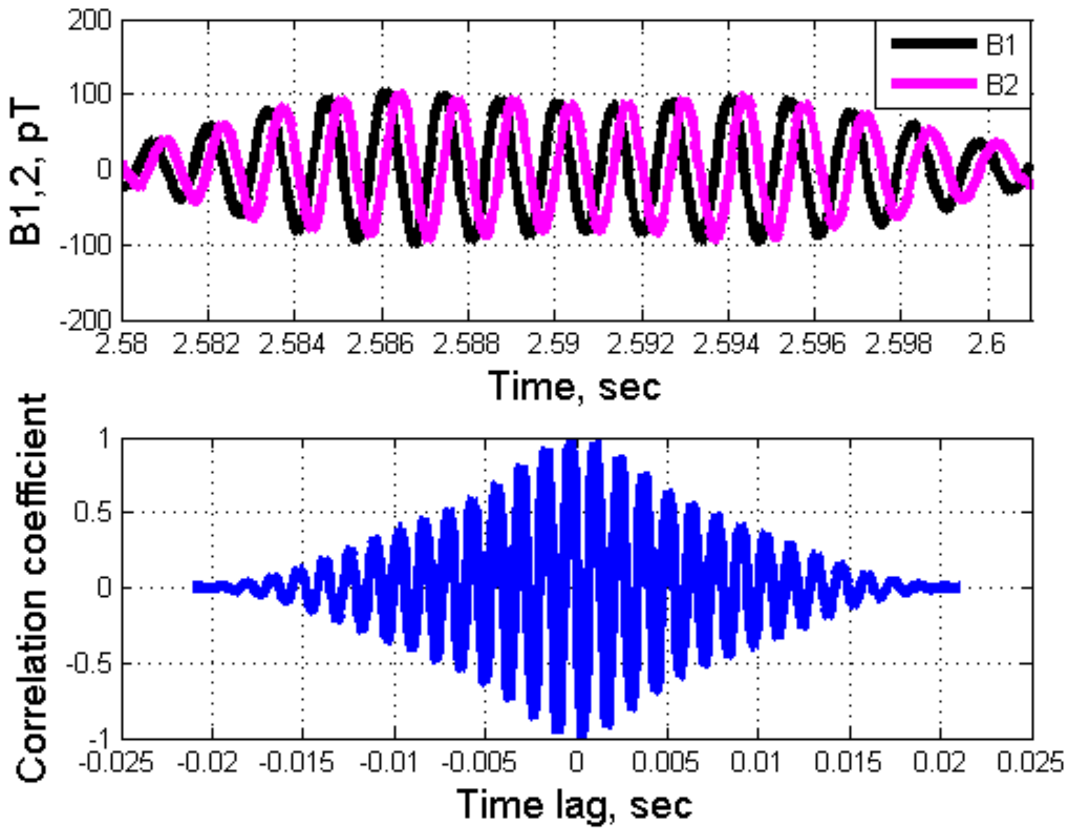
Chorus “elements”

Within One Chorus Rising Tone Element, There Are Many Coherent Subelements (from minimum variance analyses): "Frequency Stepping"

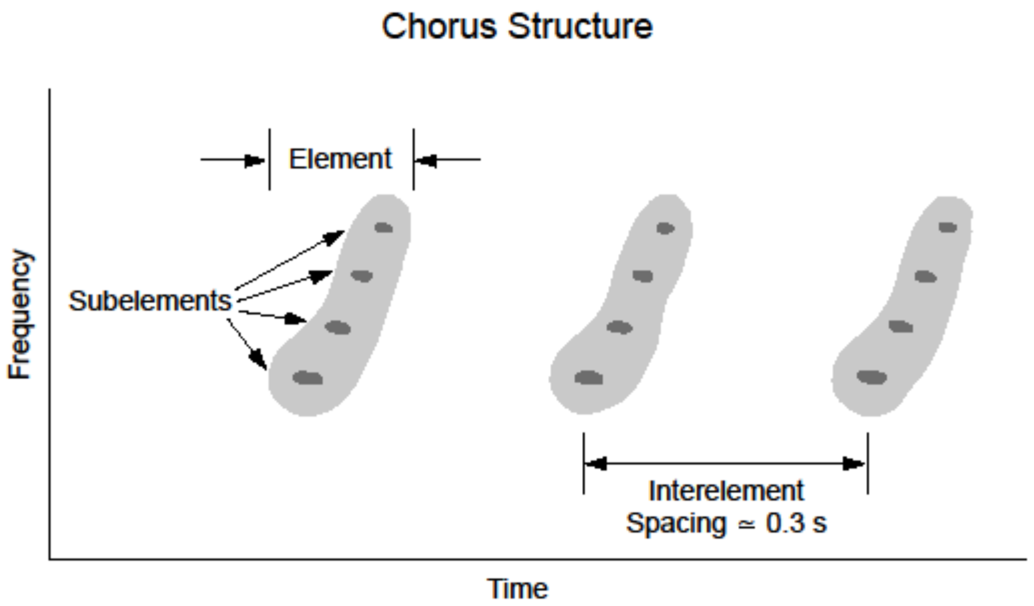


Tsurutani et al. JGR 2009

Coherent Chorus in Equatorial Generation Region



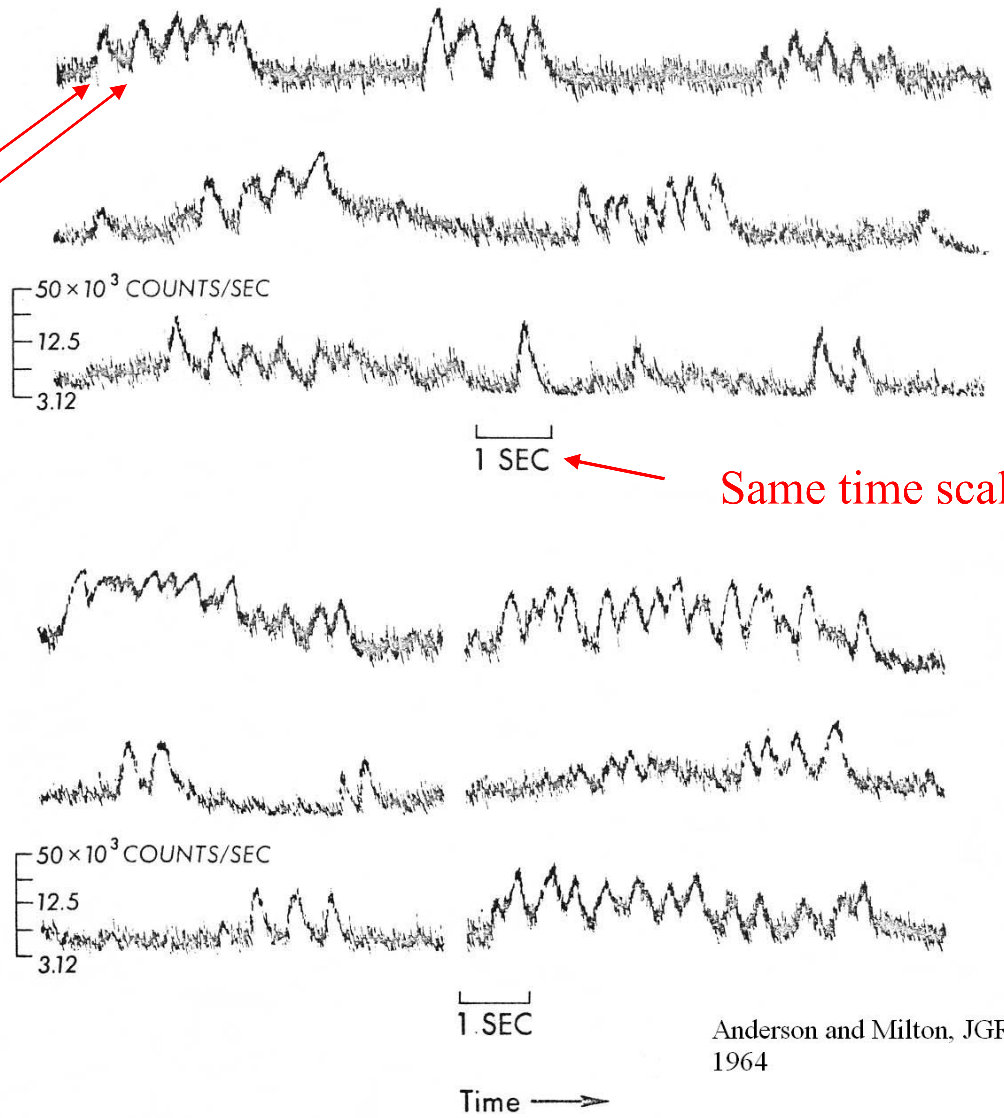
Tsurutani et al. JGR, 2011


Chorus Structure
Element
Subelements
Frequency
Interelement
Spacing ≃ 0.3 s
Time

Chorus Coherency in the Generation Region Explains Electron Microbursts

Ionospheric Energetic ~10 to 100 keV Electron Precipitation
High Altitude Balloon-Borne Auroral Zone Bremsstrahlung X-ray Measurements

“microbursts”

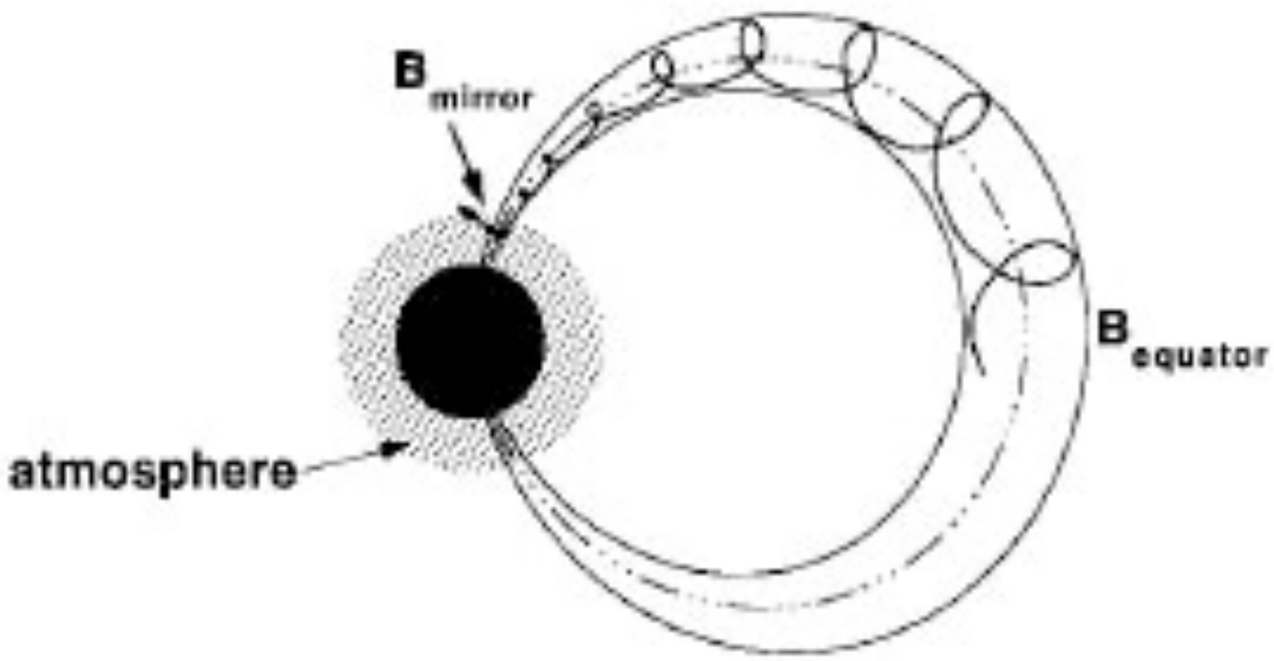


Same time scale as chorus elements

Anderson and Milton, JGR, 1964

Tsurutani et al. JGR 2013

Earth's Radiation Belts: Loss Cone



Auroras

Back of the Envelope Calculation: Pitch Angle *"Transport"* near the Loss Cone

- Assumptions: B_0 = 125 nT, f_w = 800 Hz, B_w = 0.2 nT , $\Delta t = 10^{-2}$ sec, $\theta_{kB} = 0°$
- V_{llR} = 65 keV (first order)
- Pitch angle *"transport"* is 7°

- Particles within 7° of the loss cone are coherently *"transported"* into it (not diffused)
- This scattering rate is 10^3 times faster than Kennel-Petschek (JGR, 1966)/ Tsurutani-Lakhina (RG 1997) which assumes incoherent waves.

(Tsurutani et al., JGR 2009)

Full theoretical analyses (with diffusion): Lakhina et al. JGR 2010

PHYSICS OF PLASMAS **20**, 042117 (2013)

Pitch angle scattering of an energetic magnetized particle by a circularly polarized electromagnetic wave

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(Received 7 February 2013; accepted 26 March 2013; published online 19 April 2013)

The interaction between a circularly polarized wave and an energetic gyrating particle is described using a relativistic pseudo-potential that is a function of the frequency mismatch. Analysis of the pseudo-potential provides a means for interpreting numerical results. The pseudo-potential profile depends on the initial mismatch, the normalized wave amplitude, and the initial angle between the wave magnetic field and the particle perpendicular velocity. For zero initial mismatch, the pseudo-potential consists of only one valley, but for finite mismatch, there can be two valleys separated by a hill. A large pitch angle scattering of the energetic electron can occur in the two-valley situation but fast scattering can also occur in a single valley. Examples relevant to magnetospheric whistler waves show that the energetic electron pitch angle can be deflected 5°towards the loss cone when transiting a 10 ms long coherent wave packet having realistic parameters.
[http://dx.doi.org/10.1063/1.4801055]

Room for several PhD theses on this topic.

An Attempt to Understand the Cause of Magnetospheric Relativistic Electron Decreases

All low speed-high speed solar wind intervals without magnetic storms during solar cycle 23: 8 Events

#	Event	Start (DOY UT)	End (DOY UT)	Duration (h)	Peak pressure (nPa)	HCS time (DOY UT)
1	1995_150	150 02:39	150 05:37	3.0	26.6	150 04:44
2	1998_202	202 02:38	202 06:45	4.1	18.6	202 04:27
3	2000_027	027 14:04	027 21:35	7.5	20.3	027 18:03
4	2000_052	052 01:11	052 08:13	7.0	14.8	----
5	2003_258	258 16:32	259 03:16	10.7	8.0	258 20:43
6	2007_056	056 12:00	057 05:32	17.3	12.2	057 03:21
7	2007_243	243 13:43	243 20:52	7.2	5.1	243 21:37
8	2008_058	058 14:07	058 19:48	5.7	9.6	058 17:51

Relativistic Electron Decreases (REDs)

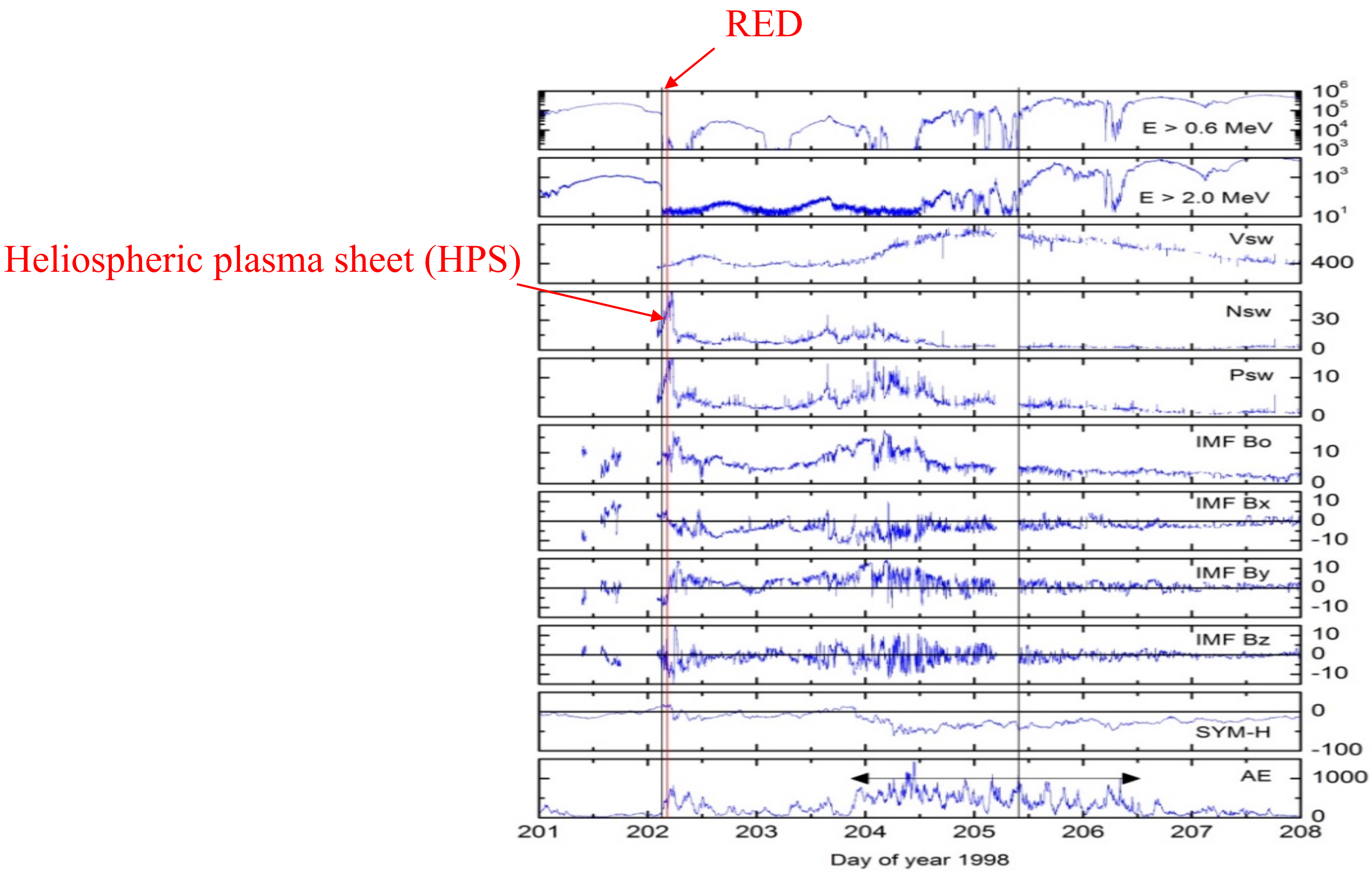


Table 1. Eight HPS Pressure Pulse Events From SC23 That Were Not Followed by Magnetic Storms[a]

Number	Event	Start (DOY UT)	End (DOY UT)	Duration (h)	Peak Pressure (nPa)	HCS Time (DOY UT)
1	1995_150	150 02:39	150 05:37	3.0	26.6	150 04:44
2	1998_202	202 02:38	202 06:45	4.1	18.6	202 04:27
3	2000_027	027 14:04	027 21:35	7.5	20.3	027 18:03
4	2000_052	052 01:11	052 08:13	7.0	14.8	—
5	2003_258	258 16:32	259 03:16	10.7	8.0	258 20:43
6	2007_056	056 12:00	057 05:32	17.3	12.2	057 03:21
7	2007_243	243 13:43	243 20:52	7.2	5.1	243 21:37
8	2008_058	058 14:07	058 19:48	5.7	9.6	058 17:51

[a]All eight HPS impacts on the magnetosphere were associated with REDs.

All 8 intervals had relativistic electron decrease (RED) events. The typical RED decay time ~ 1 hr

Our original goal to understand the disappearance of relativistic electrons was solved. So we could have terminated our work there.

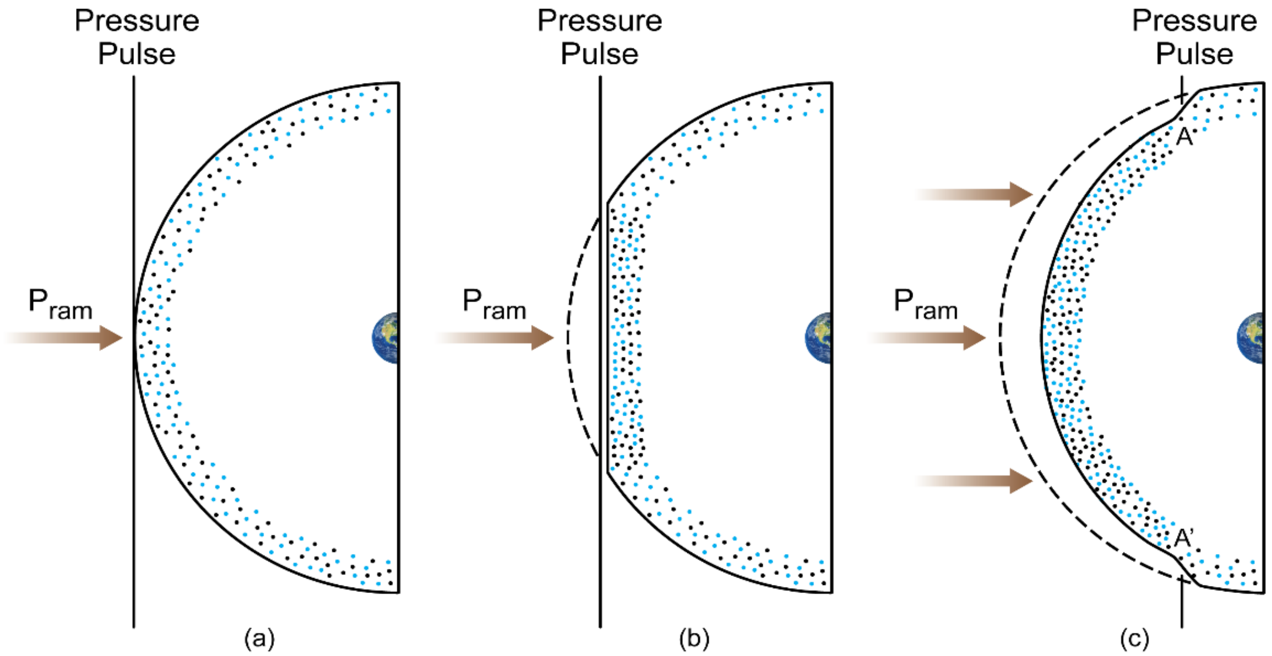
Gradient drift of the electrons to the dayside magnetopause can explain the electron losses.

However there are other possibilities.

Title of 2016 JGR paper:

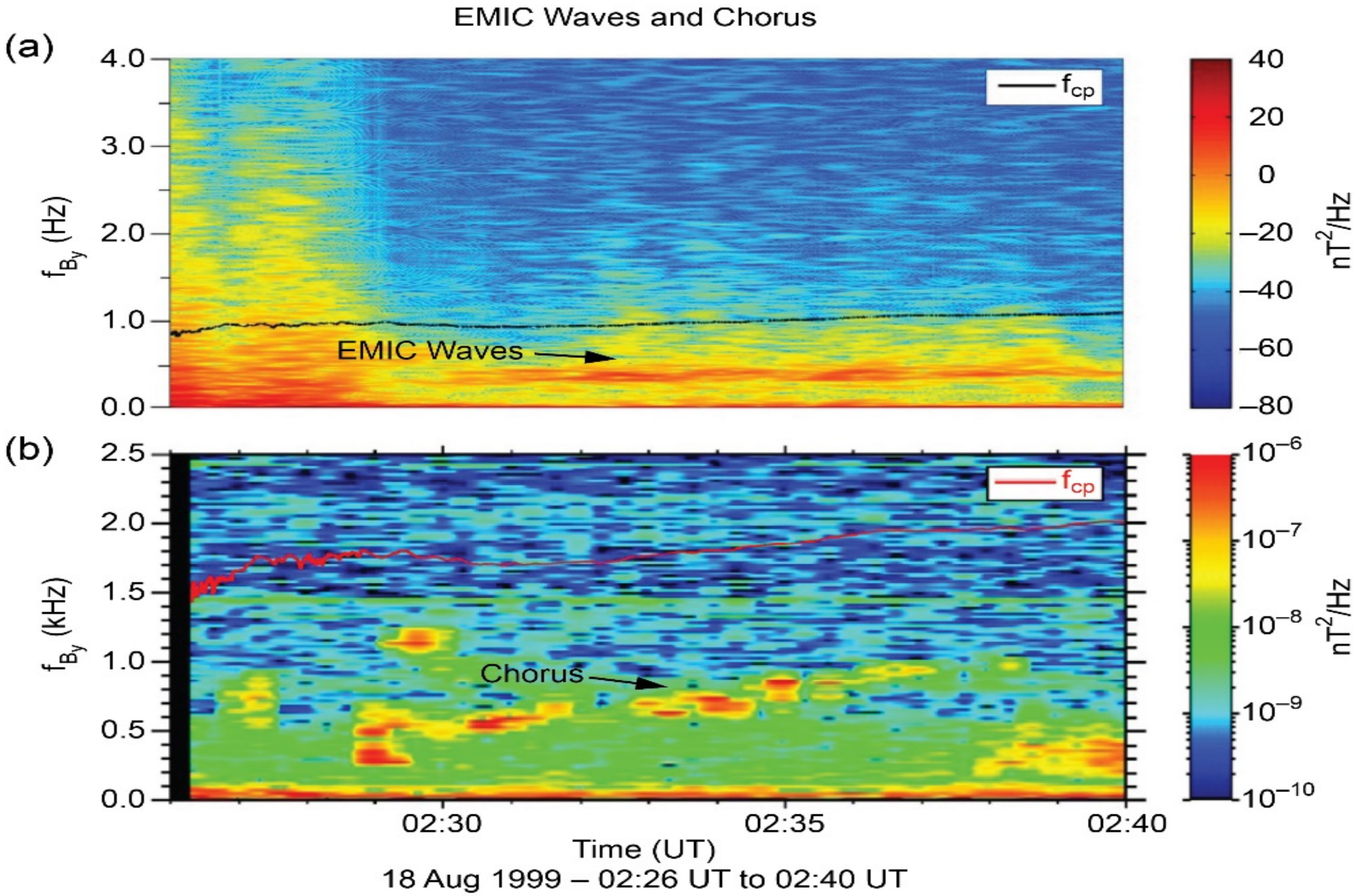
"Heliospheric Plasma Sheet (HPS) Impingement onto the Magnetosphere as a Cause of Relativistic Electron Dropouts (REDs) via Coherent EMIC Wave Scattering with Possible Consequences for Climate Change Mechanisms"

The Solar Wind HPS Will Compress the Dayside Magnetosphere



The solar wind pressure pulse will cause betatron acceleration of preexisting ~10-100 keV electrons and protons in $T_\perp$, causing $T_\perp / T_{||} > 1$. Thus instability in both particle species and wave generation.

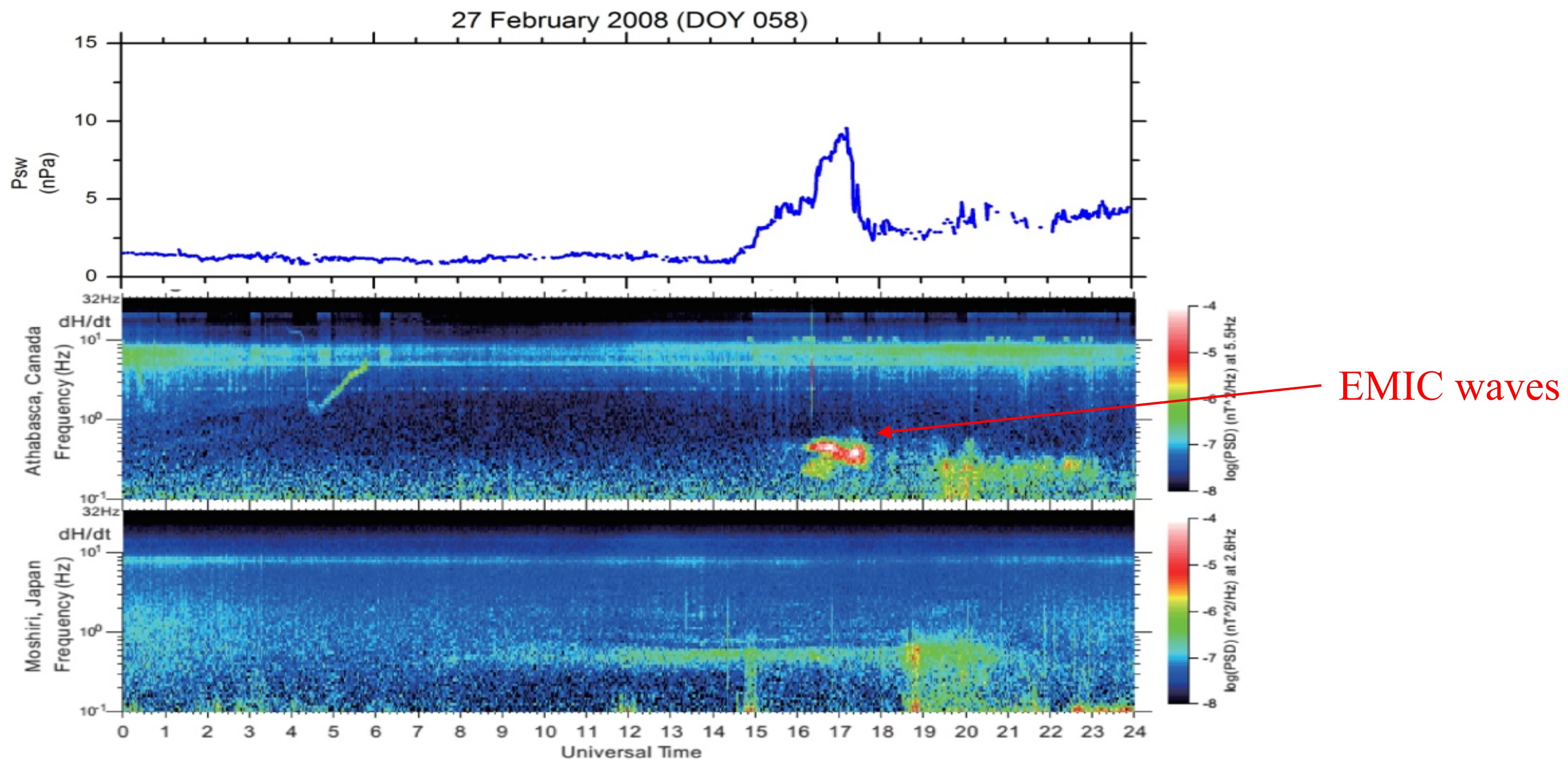
Simultaneous EMIC and Chorus Waves from L = 10 to 7 in Wave Generation Region During a Solar Wind Pressure Pulse (Cassini Near-Earth Swing-By)



Simultaneous HPS Impingement and Nagoya Univ. ISEE Ground Magnetometer EMIC Waves

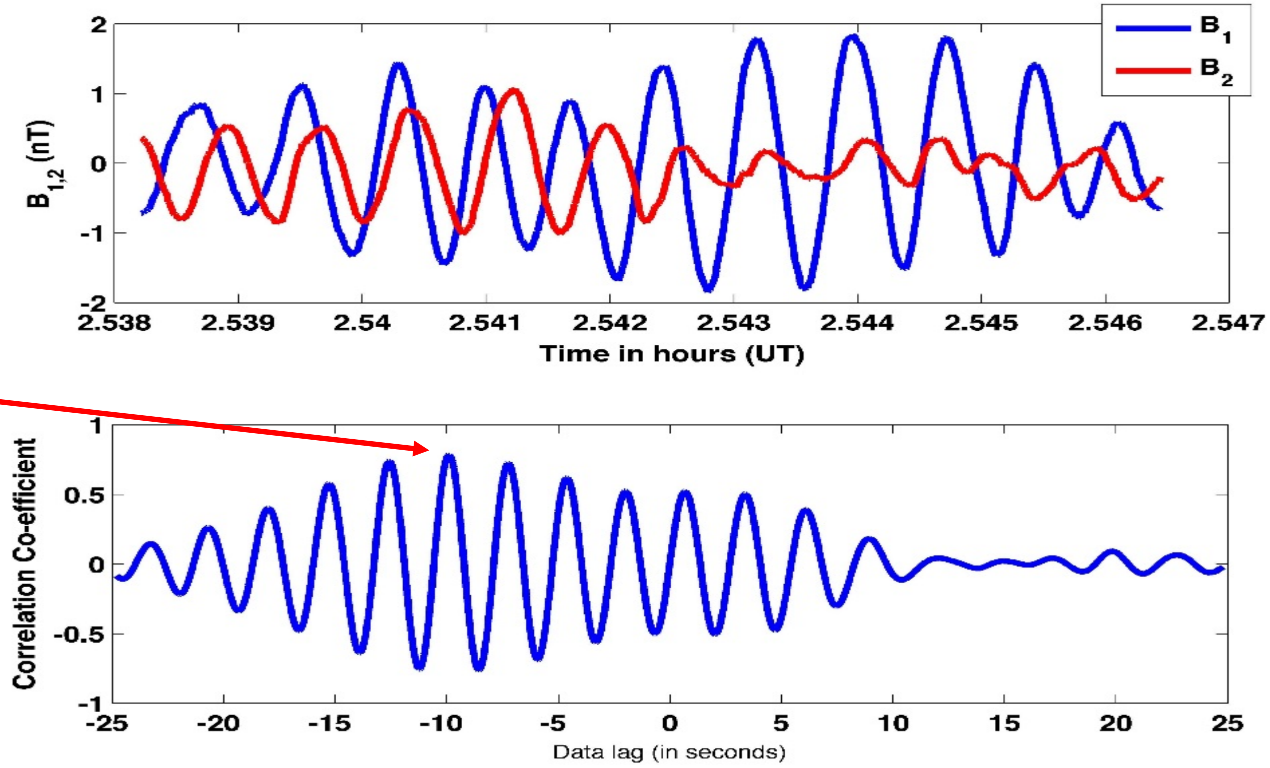
Athabasca, Canada
61.7° MLAT, ~09 MLT

Moshiri, Japan
35° MLAT, ~02 MLT



What Do the EMIC Waves Look Like in Detail?

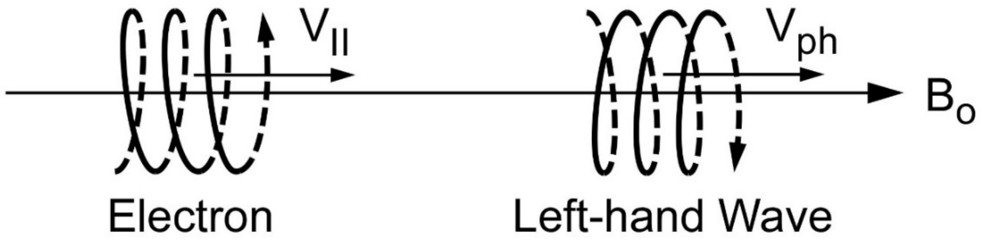
EMIC waves
are **"coherent"**



With coherent waves, the pitch angle transport of resonant particles will be 3 orders of magnitude larger than standard (Kennel-Petschek JGR, 1966; Tsurutani and Lakhina, RG 1997) theory.

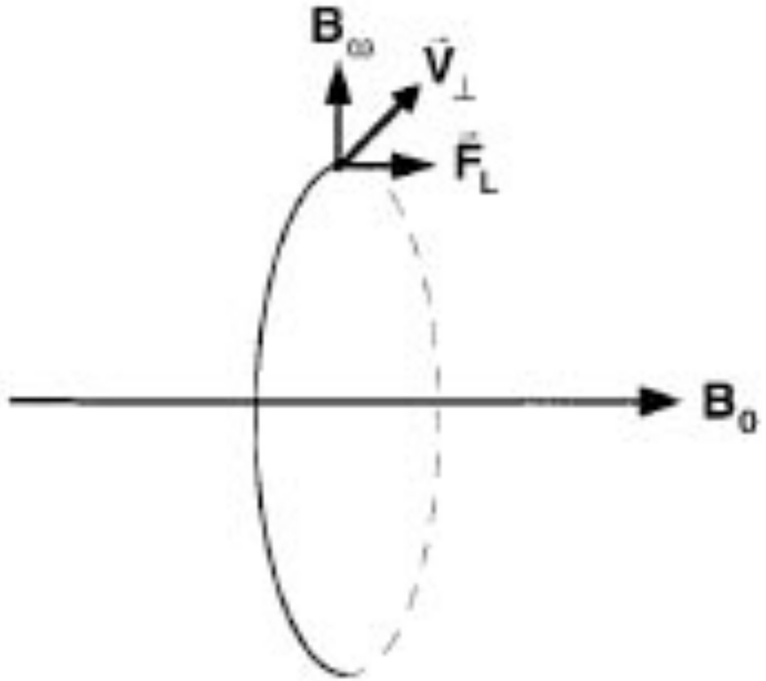
A Parasitic Interaction

Anomalous Cyclotron Resonance



$$\omega - k_{||}V_{||} = \Omega^{-}$$

Wave-Particle (Cyclotron) Interaction



Tsurutani and Lakhina, RG, 1997

EMIC Waves Resonate with 0.6 to 0.9 MeV Electrons

Table 3. Electron Anomalous Cyclotron Resonance With Two Cycles of an EMIC Wave of Conservative Amplitude 2.0 nT at a Variety of Different L Shells[a]

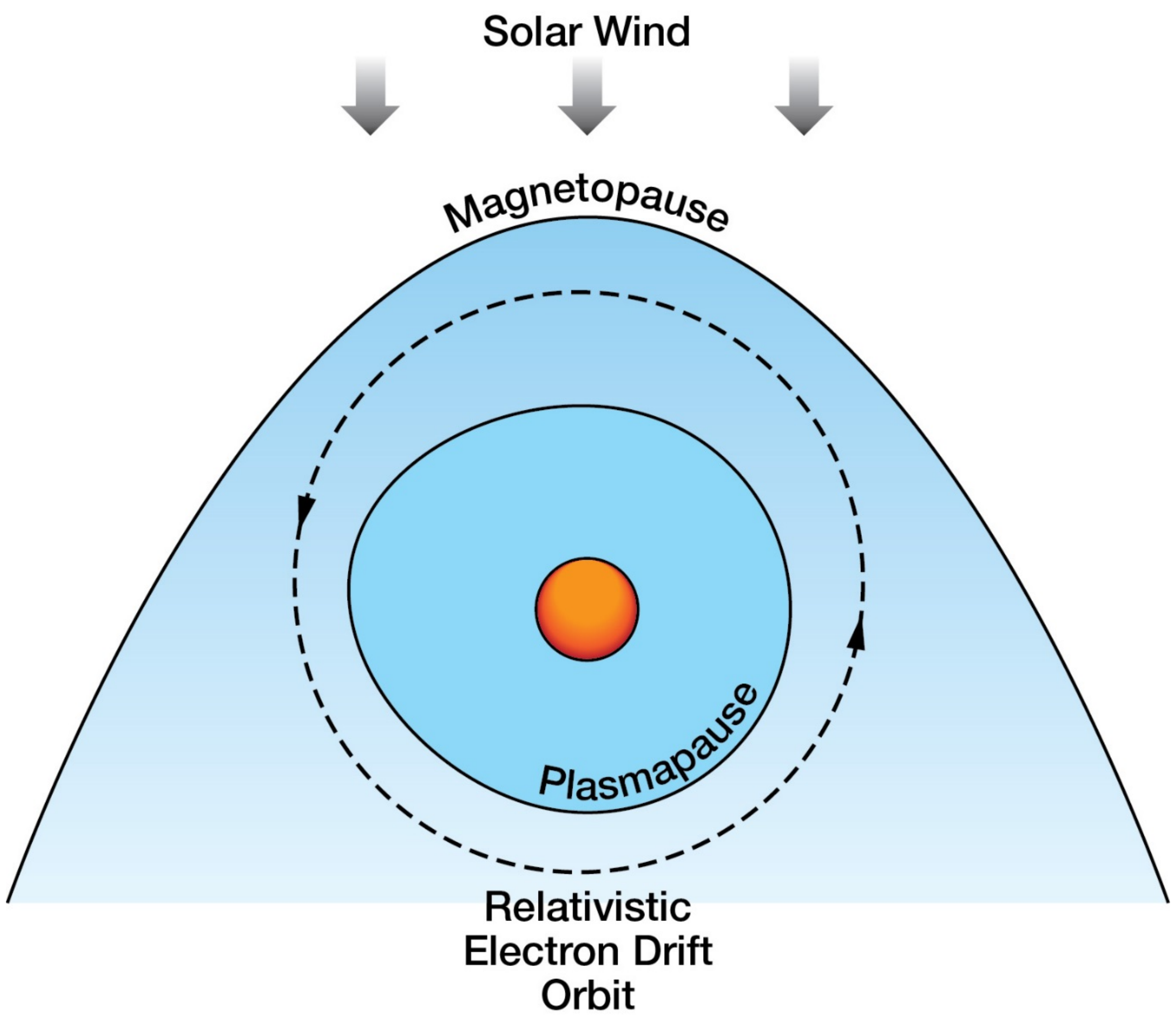
Parameters	$L = 10$	$L = 9$	$L = 8$	$L = 7$	$L = 6$
V_{ph} (*10^5 m/s)	2.2643	2.1946	2.3163	2.3732	3.499
Ωe (*10^4 rad/s)	1.077	1.0873	1.2956	1.4756	3.4274
ω (rad/s)	3.107	2.255	2.6	3	3
$V_{\|\|}$ (* 10^8 m/s)	2.8025	2.886	2.9037	2.9057	2.9916
γ	2.8	3.66	3.98	4.019	13.37
$E_{\|\|}$ (MeV)	0.625	0.87	0.954	0.964	3.4
Δt (ms)	4.357	4.11	4.37	4.41	6.32
$\Delta\alpha$ (deg)	31.5	22.6	22.2	22.1	9.5
D (s^{-1})	34.65	18.87	17.08	16.85	2.18
T (ms)	28.9	53	58.5	59.3	457.8

[a]The rows, from top to bottom, are the wave phase velocity, the electron cyclotron frequency at the equator, the parallel speed of the electron along B_0, the parallel kinetic energy of the electron, the time of wave-particle interaction, the amount of particle pitch angle transport, the diffusion coefficient D, and the time for particle pitch angle diffusion T.

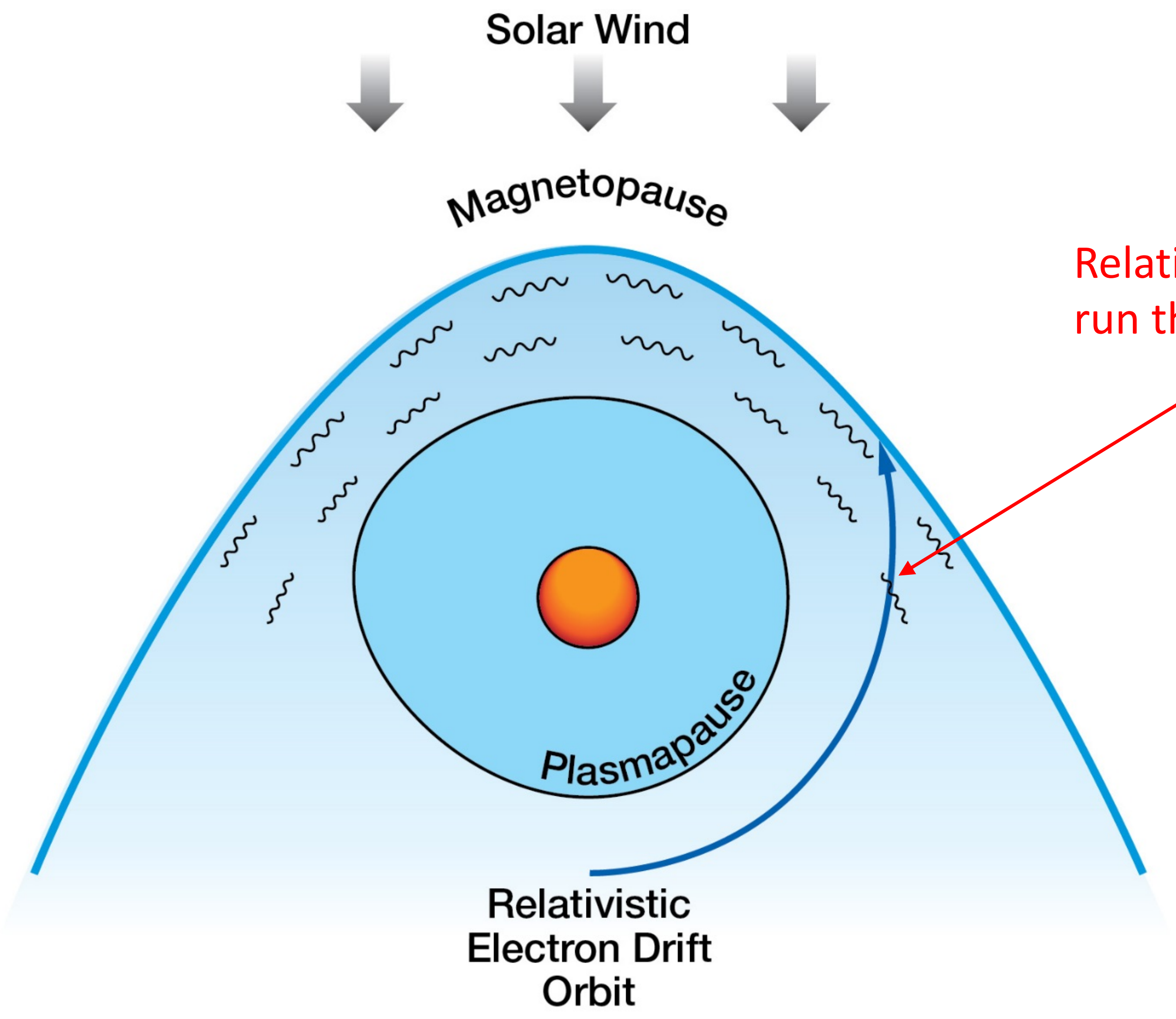
The change $\Delta\alpha$ in particle pitch angle for arbitrary α is obtained as: $\Delta\alpha = \frac{B}{B_0}\Omega\Delta t$

For interaction with only 2 wave cycles, T = 4.1 ms, Δα = 23°

“Before”

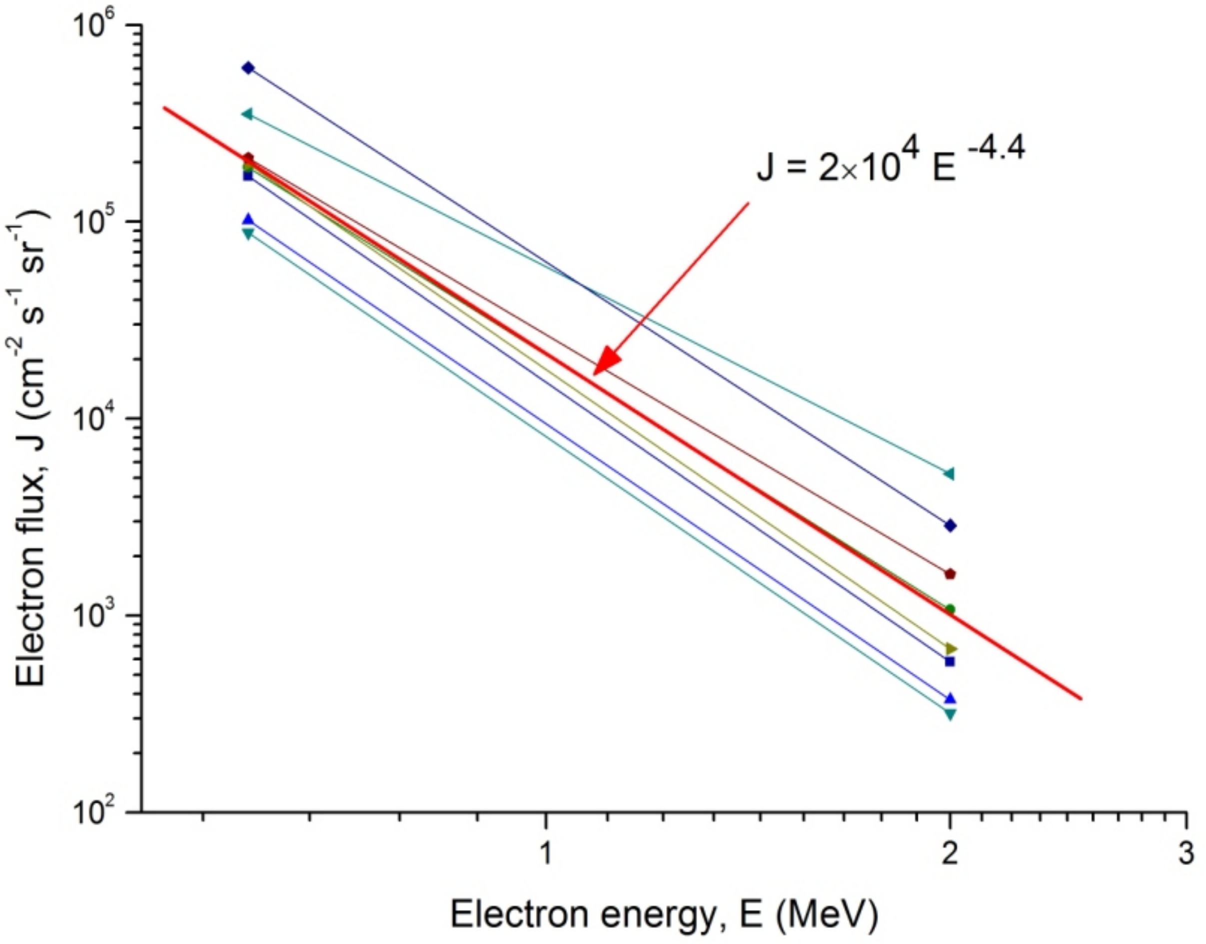

Solar Wind
Magnetopause
Plasmapause
Relativistic
Electron Drift
Orbit

“After”



Relativistic electrons will have to run the EMIC wave gauntlet

2-Point Power Spectra for the Eight Events



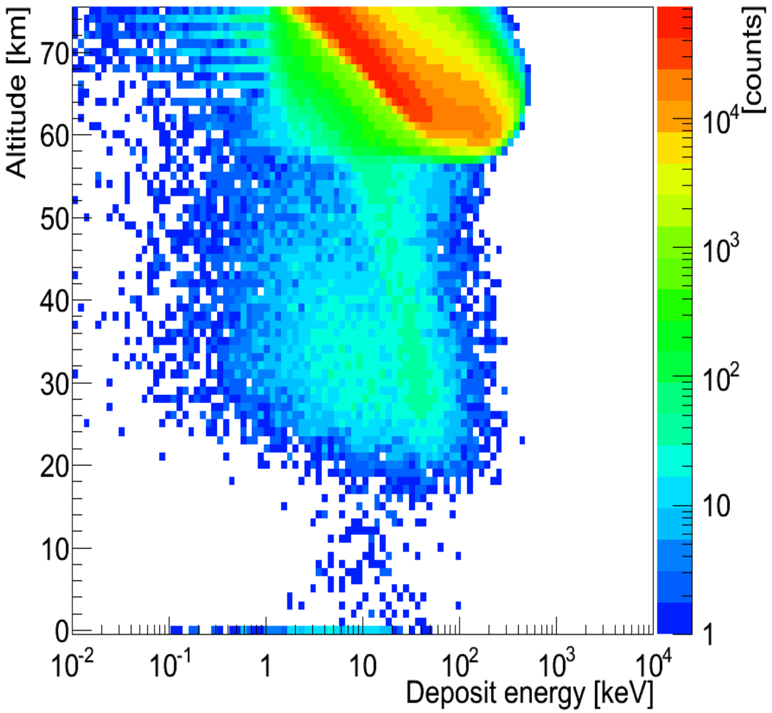
Total Magnetospheric Particle Energy Calculations

A flux decrease of ~10^5 particles cm^{-2} $s^{-1}ster^{-1}$ in the E > 0.6 MeV energy range (~1 MeV electrons) was determined from measurements.

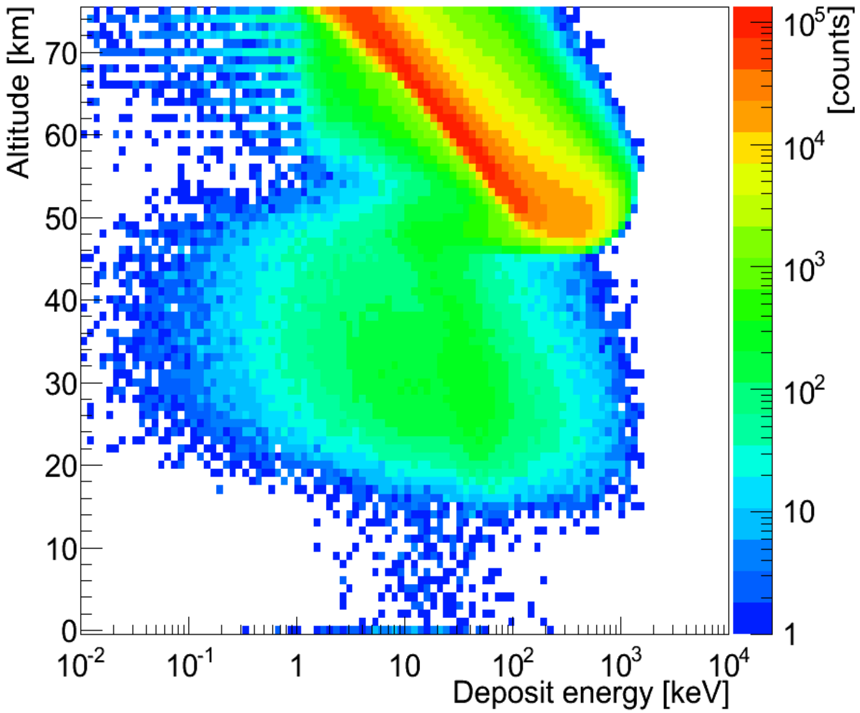
The bounce time of a charged particle is $T_B = L\ R_E\ (3.7 - 1.6 \sin \alpha)\ V_e$ (Baumjohann and Treumann, 2012). Assuming a 2π ster downward flux and a constant flux from L = 6 to 10,

The total energy of ~1 MeV electrons in the magnetosphere from L = 6 to 10 is ~ 3 x 10^{20} ergs.

The GEANT4 Monte Carlo Code Developed by CERN



E = 0.6 MeV



E = 2.0 MeV

Vertical magnetic fields assumed in simulations

HPS crossings and atmospheric winds

- *Wilcox et al.* [1973] believed that a relationship exists between interplanetary heliospheric current sheet (HCS) crossings and atmospheric winds.

- Our hypothesis is that it is the HPS crossings and REDS, and not the HCS crossings, that are causing the Wilcox et al. atmospheric effect.

Can the energy deposited in the mesosphere between 50 and ~80 km altitude be important?

Taking a 100 km x 100 km x 5 km volume and assuming the energy is distributed throughout the volume, a

+6 K temperature increase is obtained.

Clearly "hot spots" will give substantially higher temperatures.

Could this directly drive planetary and gravity waves?

Energy Deposition Between 50 and 30 km Altitude

For **E > 0.6 MeV** electrons a maximum of **~4 x 10^{17} ergs** deposited between **50 and 30 km** and **~ 3.0 x 10^{17} ergs** deposited **below 30 km** altitude

For **E > 2.0 MeV** electrons, a maximum of **~1.4 x10^{16} ergs** is deposited between **50 km and 30 km** altitude and a maximum of **~1.8 x 10^{16} ergs** is deposited **below 30 km** altitude.

This energy deposition is higher than those of Cosmic Rays or Solar Flare particles because of the higher RED flux and also because the deposition is in a limited region of space.

NOx Production, ozone depletion: Tropopause Instability?

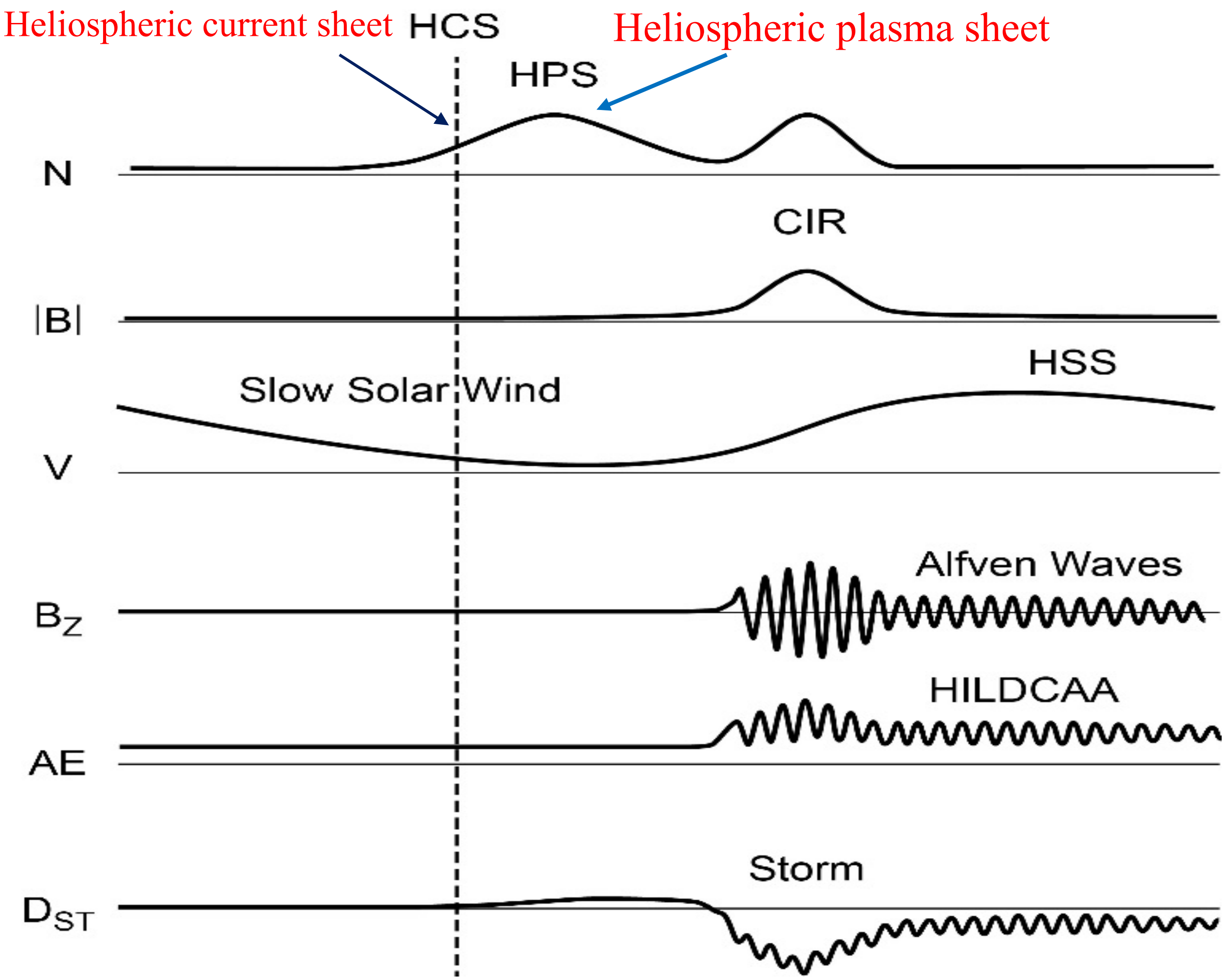
The secondary (~10 to 100 keV) electrons of the electron precipitation and energy cascade (γ-rays, X-rays, secondary electrons, etc.) will lead to N_2 dissociation and NOx production. This in turn will lead to ozone depletion.

With a reduction of ozone in the stratosphere, solar radiation will be absorbed at the tropopause.

Could the additional solar UV heating of the tropopause lead to instability of this structure?

At the present time, we don't have any answers to these questions (and other suggested mechanisms in Tsurutani et al. (2016), but we are still looking. If you are interested, please join in.

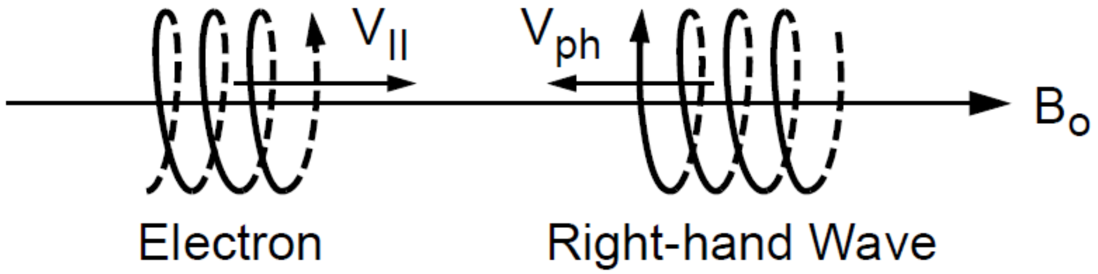
Thank You For Your Attention



HPS occurs before CIR and HSS

Normal Cyclotron Resonance

a) Parallel Propagating Waves



$$\omega + k_{ll}\, V_{ll} = \Omega^{-}$$