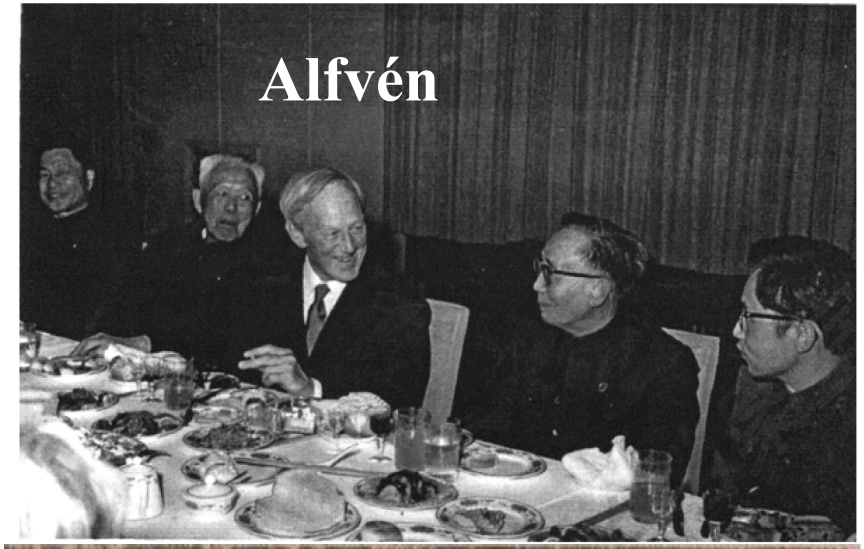
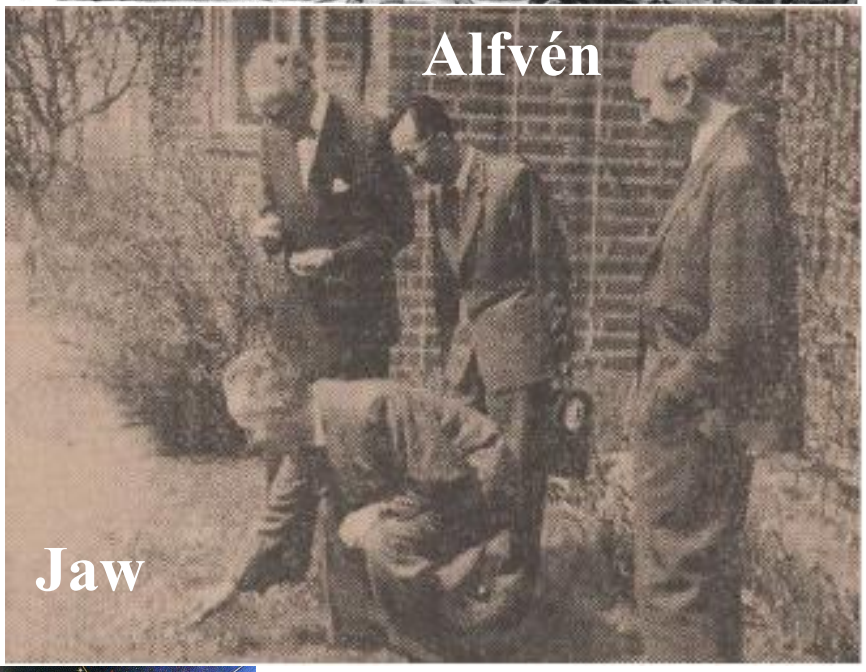
Magnetospheric Response to Solar Wind Forcing: ULF Wave-Particle Interaction Perspective

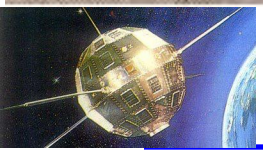
Q.-G. Zong

Peking University, China

Collaborators: X. Z. Zhou, Y. X. Hao, Z. Y. Liu, Y. Liu, J. Ren, X. R. Chen, S. Y. Fu
R. Rankin, D. N. Baker, H. E. Spence, J. B. Blake, G. D. Reeves, and S. G. Claudepierre







Alfvén's visits to China

① 19 Sep. -19 Oct. 1963

② 11 Mar.-02 Apr. 1972

My supervisor's supervisor

Prof. Jeoujang Jaw is the founder of the Chinese Space Program



He spoke Swedish, English, German, French, and Russian, and some Spanish and Chinese.

(https://en.wikipedia.org/wiki/Hannes_Alfvén)

THE ROYAL INSTITUTE OF TECHNOLOGY
Department of Plasma Physics

Stockholm, April 20, 1972

To Academia Sinica
Peking

To Academia Sinica we wish to forward our best thanks for a most interesting and pleasant visit to the People's Republic of China. The president of the Academy Professor Kuo Mo-Jo kindly invited us to a banquet at the People's Congress Hall, the vice-president Professor Wu You-Shung was our host both at a welcome and a farewell banquet, and the vice secretary general Chin Li-Shing received us with a luncheon. Mr Pan Chin and mr Su Feng-Lin arranged an interesting and agreeable journey to Nanking, Shanghai, and Canton in the pleasant company of Mr Hsu Chao-Hsiang and Professor Koo Chen-Chao. At these places as well as in Peking we were received with much hospitality and cordiality. We have had good opportunities to study science, education and family planning in China, and exchange views in a friendly atmosphere.

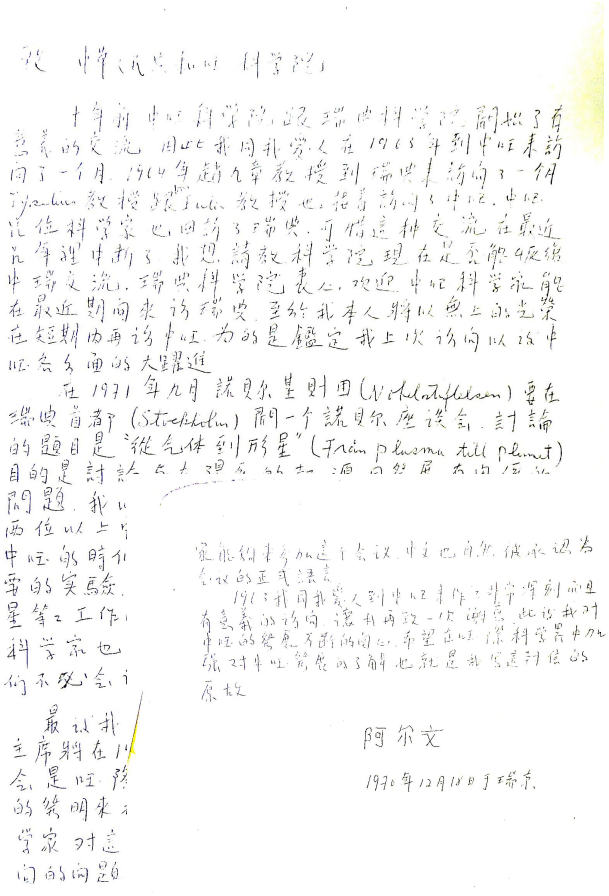
We should like to ask you to forward our best thanks to the large number of Chinese friends who most kindly have taken care of us.

It is our sincere hope that our visit will strengthen the friendship between China and Sweden, and also the contact between Chinese scientists and scientists all over the world. Especially we hope that many of our colleagues and friends in China will visit Sweden and study our work in different fields.

With cordial greetings,
Hannes + Kerstin Alfvén
Hannes and Kerstin Alfvén
阿尔文

Address S-100 44 STOCKHOLM 70 | Street address Teknikringen 31-33 | Telephone 08 - 23 63 20 | Cable address Technology | Telex 103 89 kthh STOCKHOLM

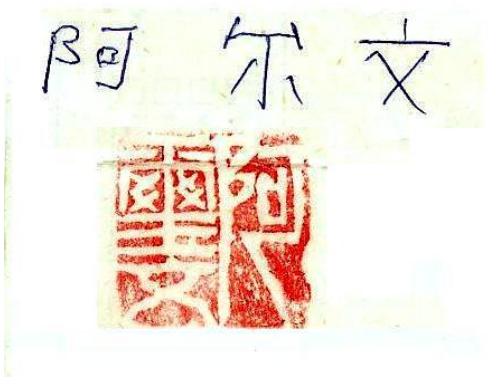
中国科学院



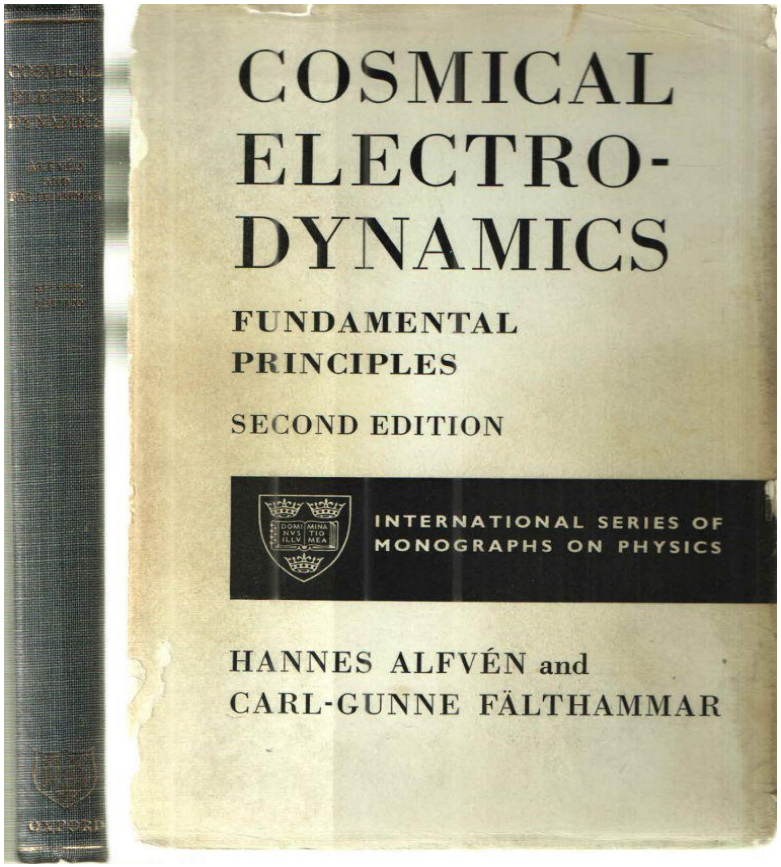
阿尔文

1972年12月18日于瑞典

Name Seal



My First Space Physics Book

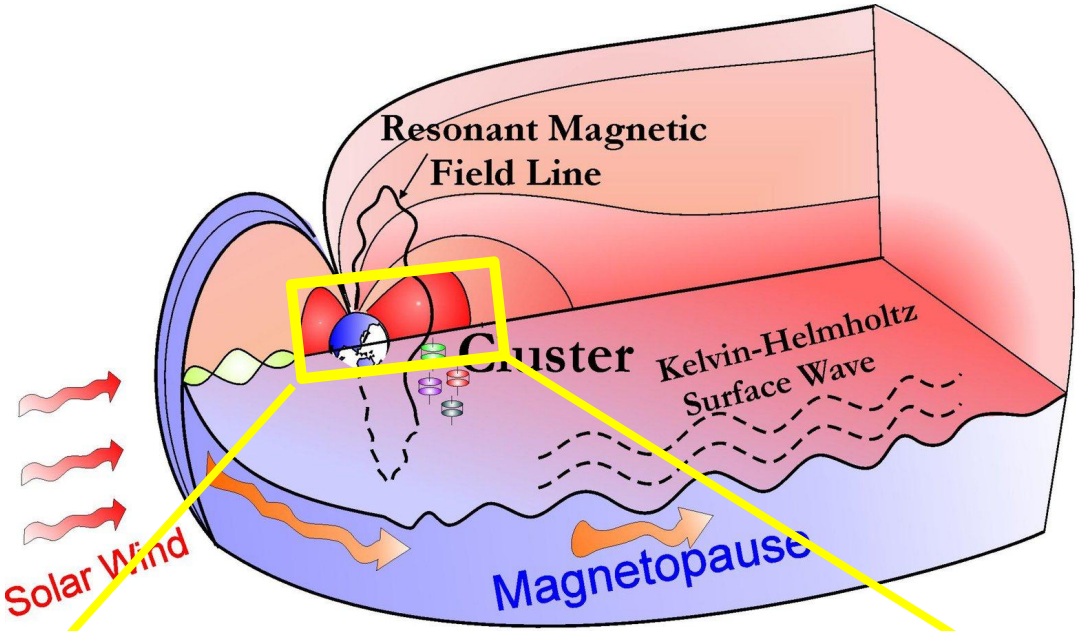


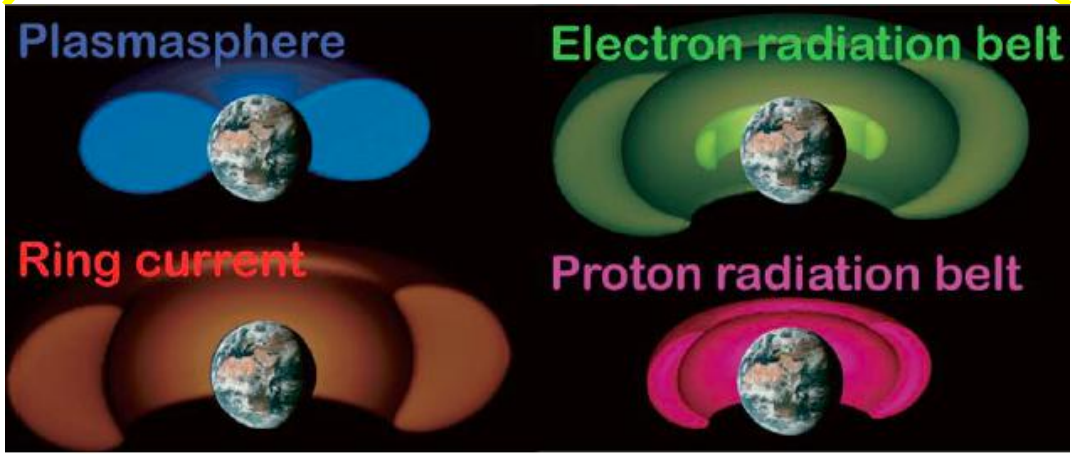
"When we try to apply to cosmic phenomena the laws in which this experience is condensed, we make an enormous extrapolation, the legitimacy of which can be checked only by comparing the theoretical results with observations."

Outline

- Introduction
- Magnetospheric response: “one-kick” & ULF wave scenarios
- Generalized theory of ULF wave-particle interactions
  - Drift resonance: radiation belt electrons
  - Drift-bounce resonance: ring current ions
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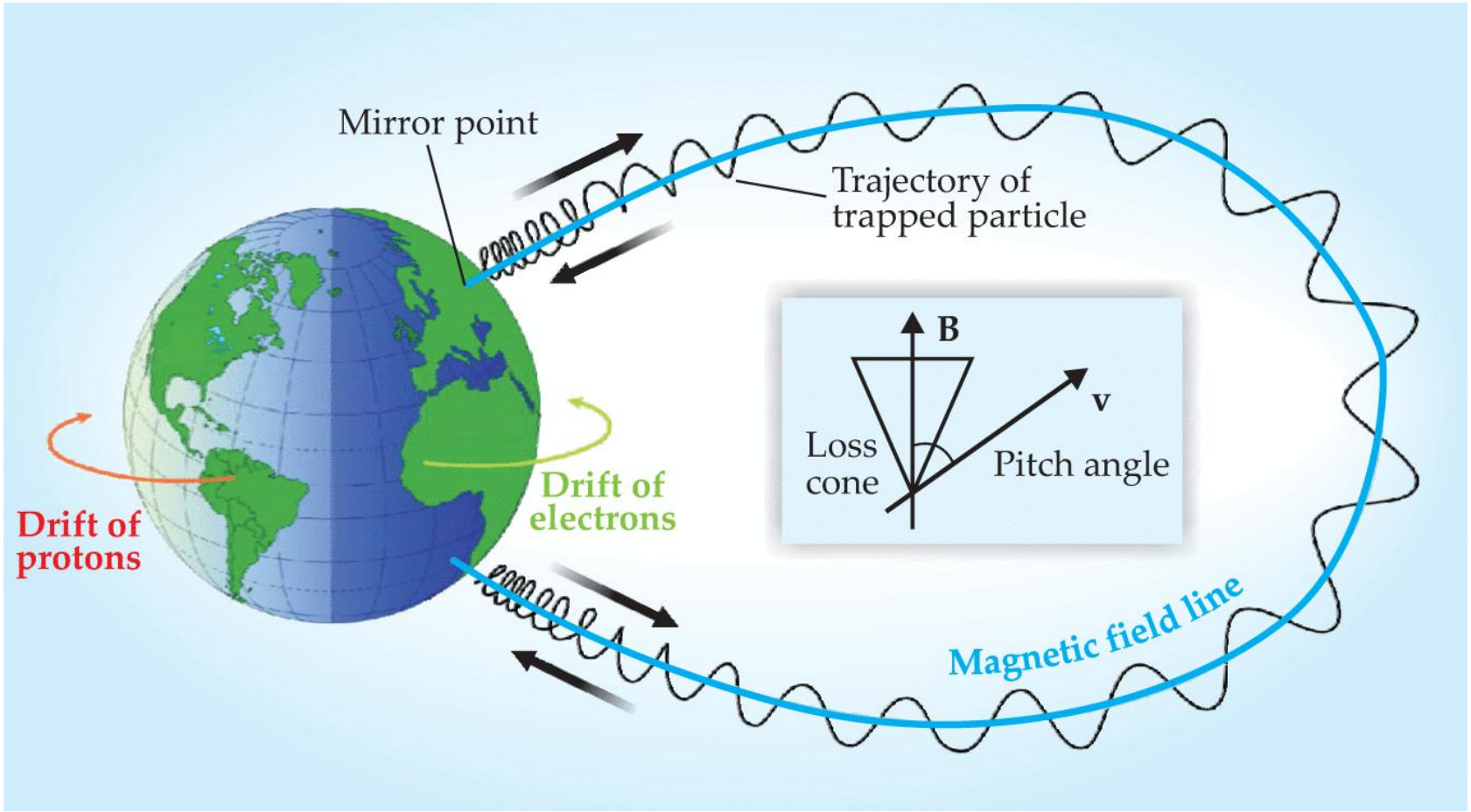
Inner Magnetosphere





- **Plasmasphere**
  T ~ 1 eV plasma
  N ~ 10-10000 cm^{-3}
- **Ring Current**
  E ~ 10s-100s keV ions
- **Radiation Belt**
  E ~ 10-100 MeV H^+
  E ~ keV-MeV Electrons

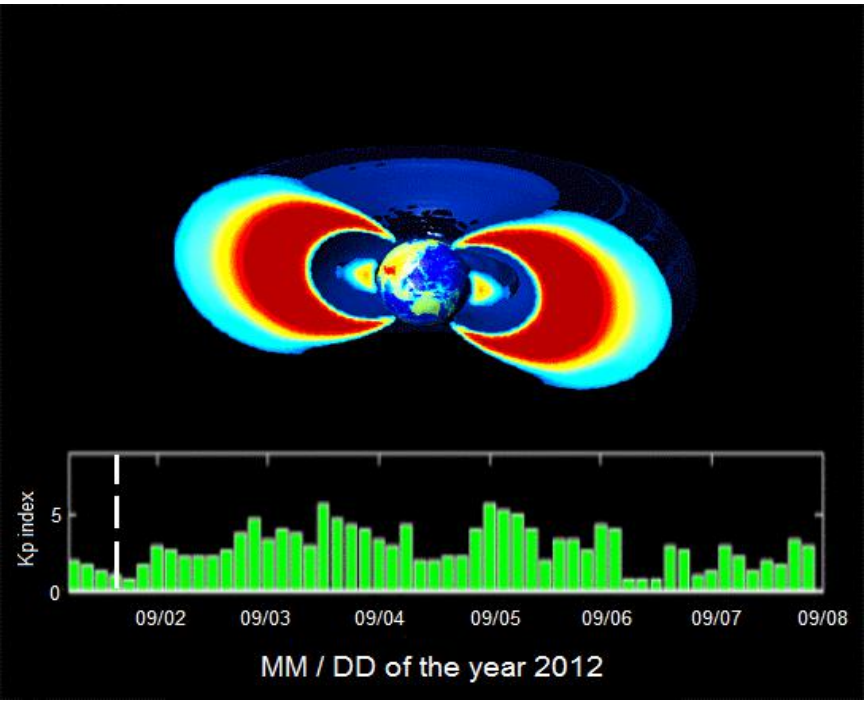
Particle Motion in the Inner Magnetosphere

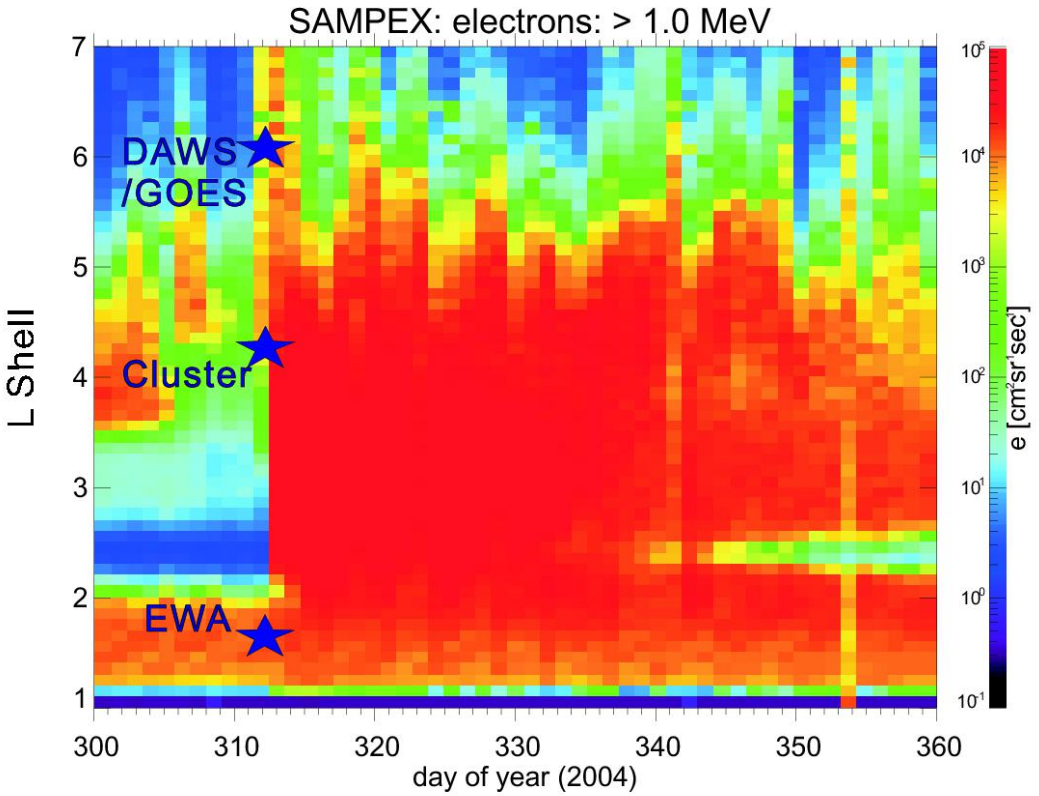


Characteristic time scales for **1 MeV electrons**

- Gyro: ~ millisecond
- Bounce: ~ 0.1-1.0 s
- Drift: ~ 1-10 minutes

Radiation Belt & Ring Current: Space Weather

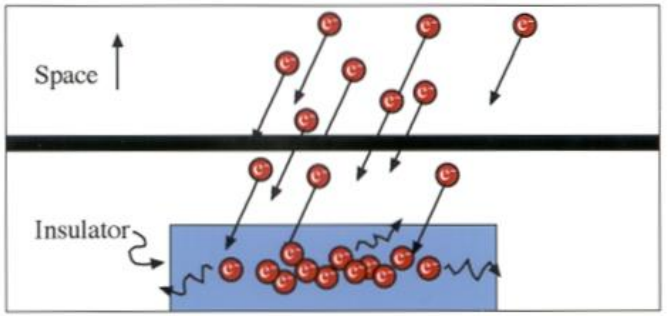


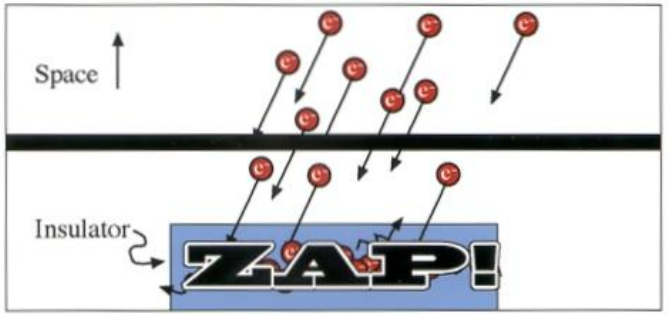


Zong et al., 2010

“Killer Electrons”: Deep-Dielectric Charging







On 5 April 2010, shortly after an IP shock impact, the geosynchronous spacecraft- Galaxy 15 has been found to be anomaly.

nergy > 100 keV

netrate satellite surface

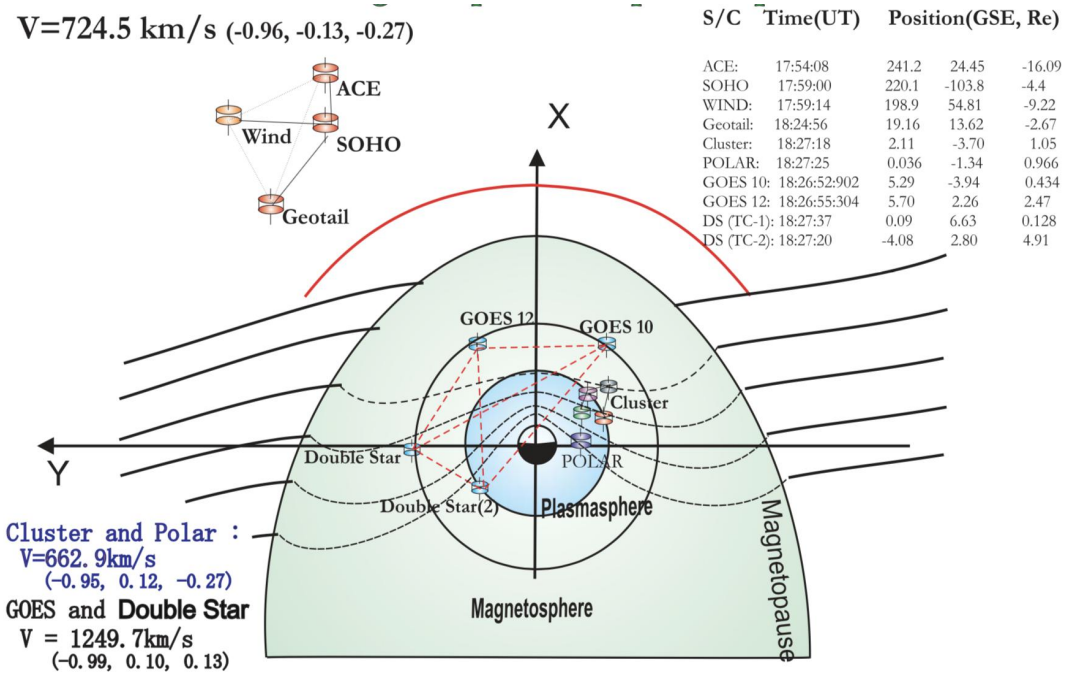
ep-dielectric charging

Baker et al., 2010

➢ **Permanent loss!**

Magnetospheric Response to IP shocks

are tractable from at least two obvious vantage points



1. It creates a significant and easily identified electromagnetic signal.
2. The specific energy source is clear.

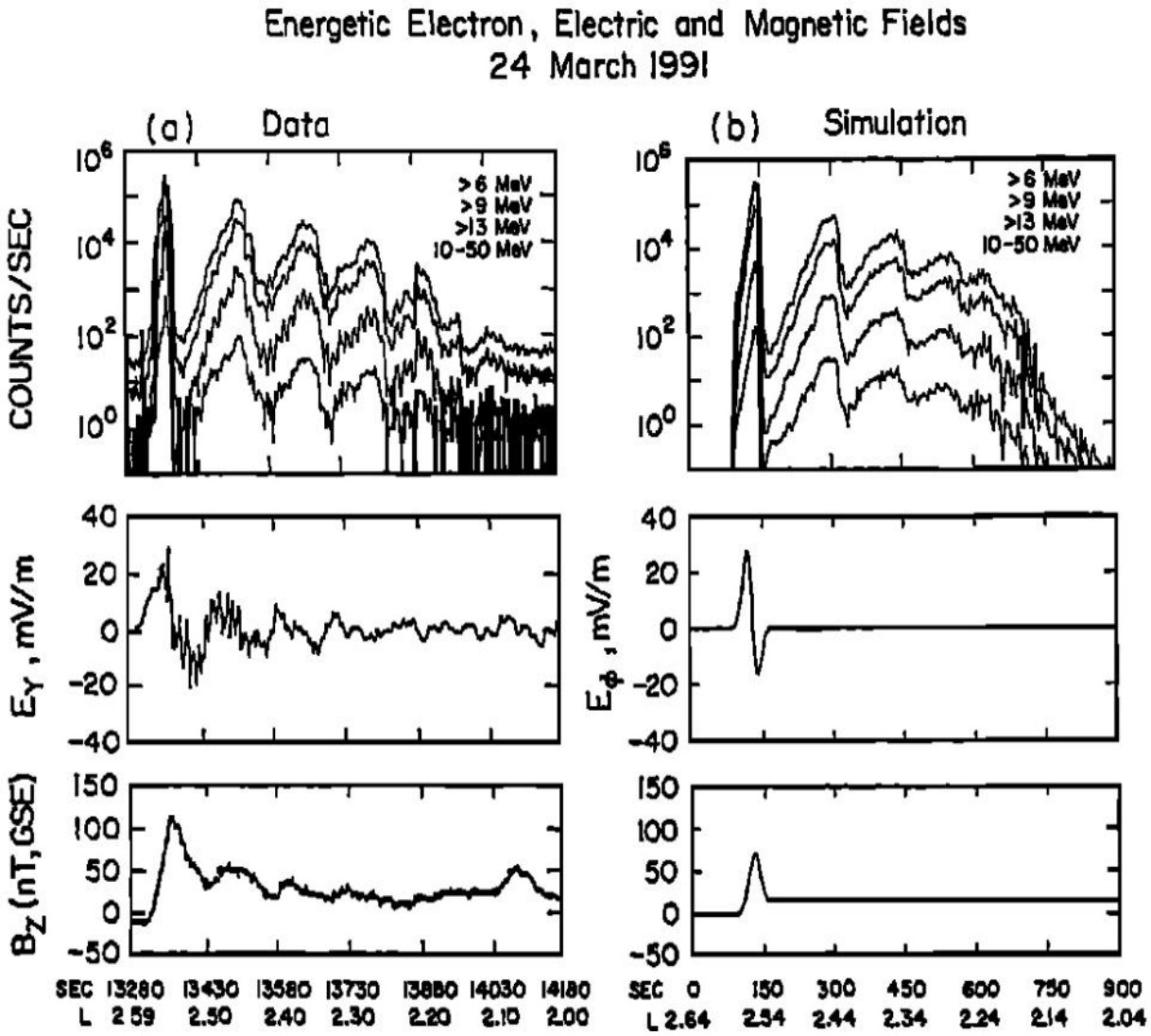
Tamao et al., 1964; Wilken et al., 1982; Zong et al., 2009

There is no temporal ambiguity for the IP shock related phenomena.

Outline

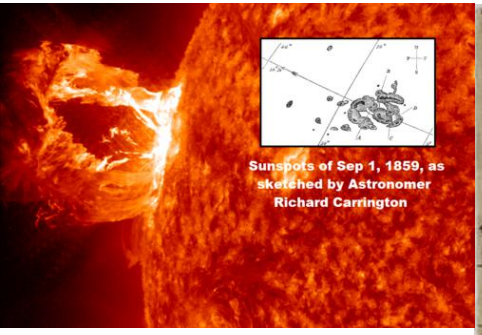
- Introduction
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Magnetosphere Response to IP Shock Impact: "One-kick" Scenario

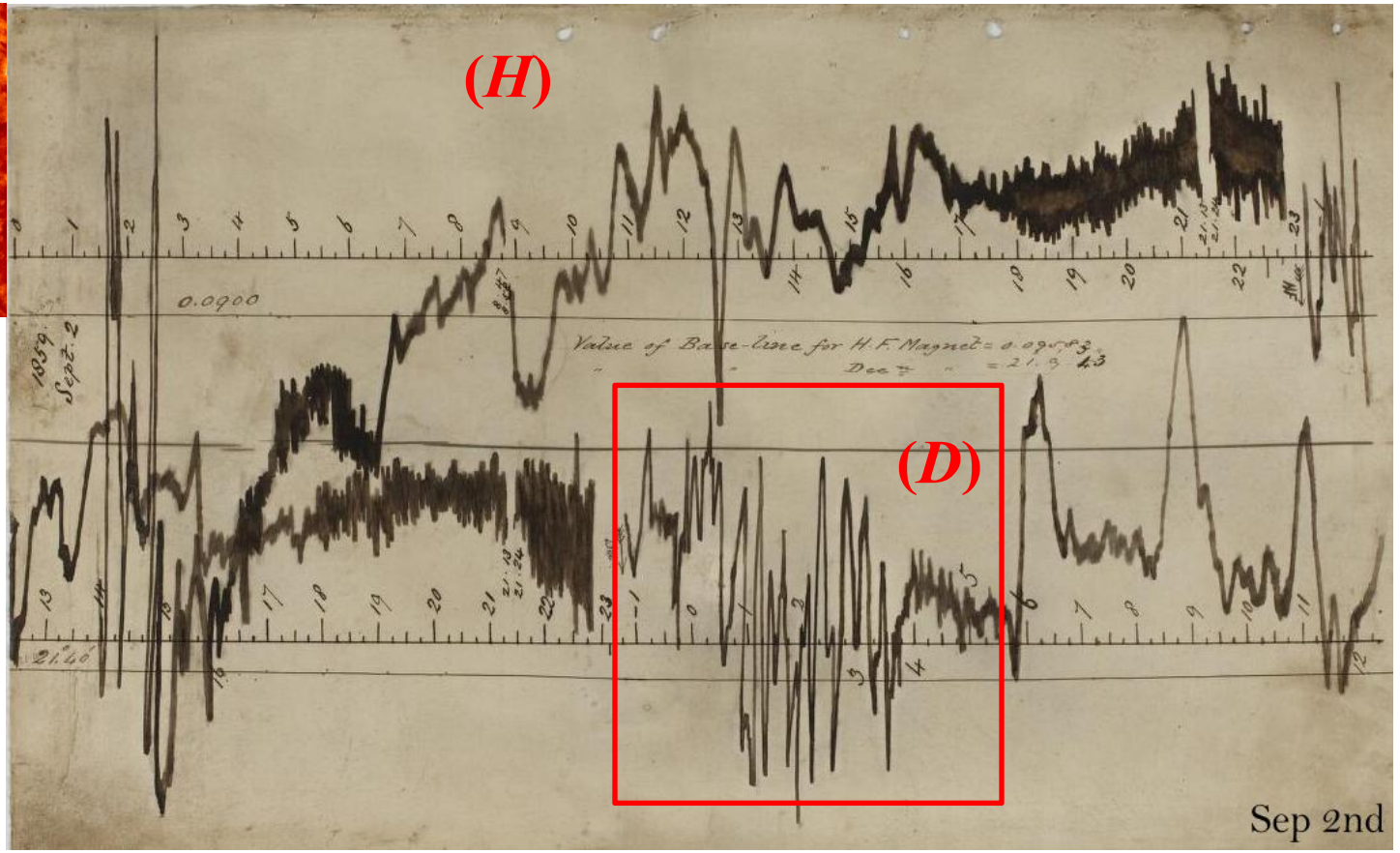


- Shock-induced injections followed by drift echoes.
  [Li et al., 1993]
- It remains unclear how these shock-related energetic particles are accelerated.
  [Friedel et al., 2002; Baker et al., 2004]

A magnetogram recorded at the Greenwich Observatory in London during the Carrington Event of 1859



Stewart, B, On the great magnetic disturbance which extended from August 28 to September 7, 1859, as recorded by photography at the Kew Observatory, *Philos. Trans. R. Soc. London*, 423, 1861

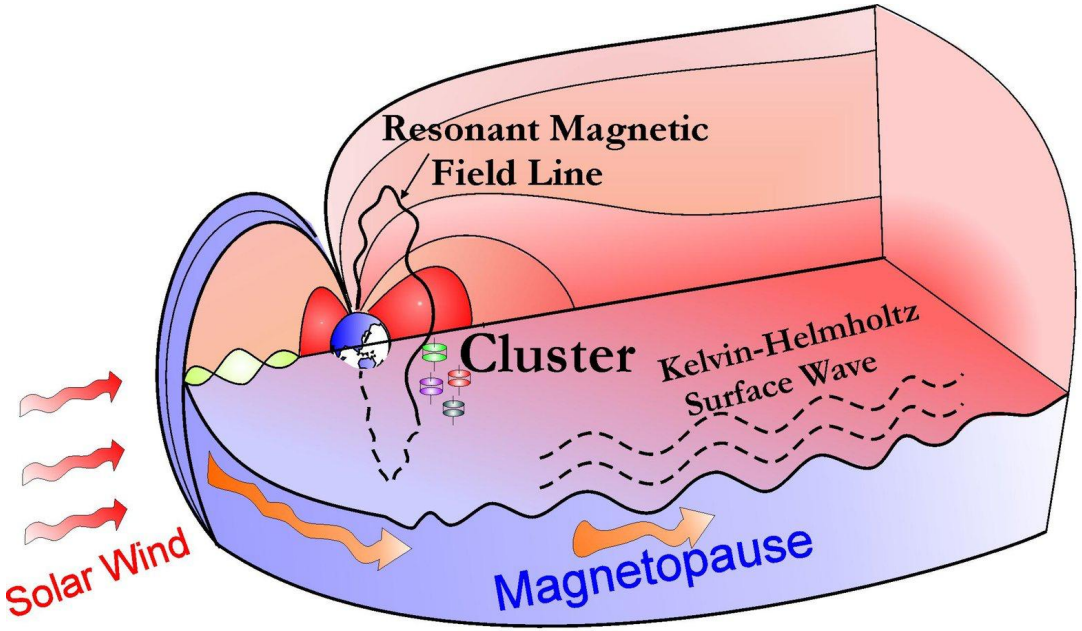


https://geomag.bgs.ac.uk/education/carrington.html

Field Line Resonance (FLR)

Drum





Guitar



DP_{SW}-Pc 3-5

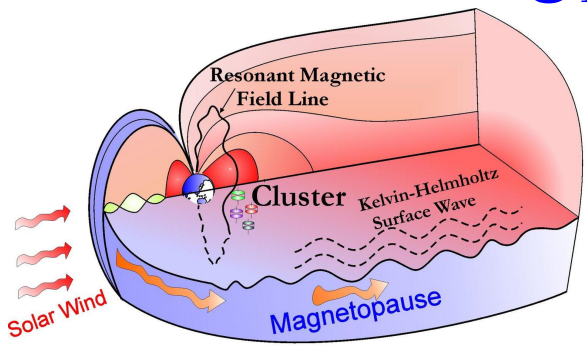
Poloidal ULF Waves

V_{SW}-Pc 3-5

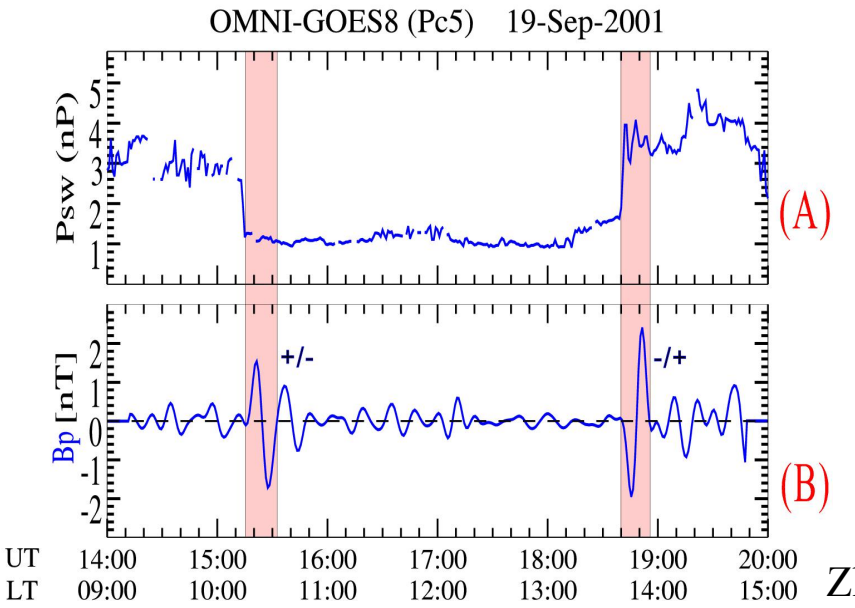
Toroidal ULF Waves

Zhang, Zong et al., 2010

Magnetosphere Response to IP Shock Impact: ULF Wave Scenario

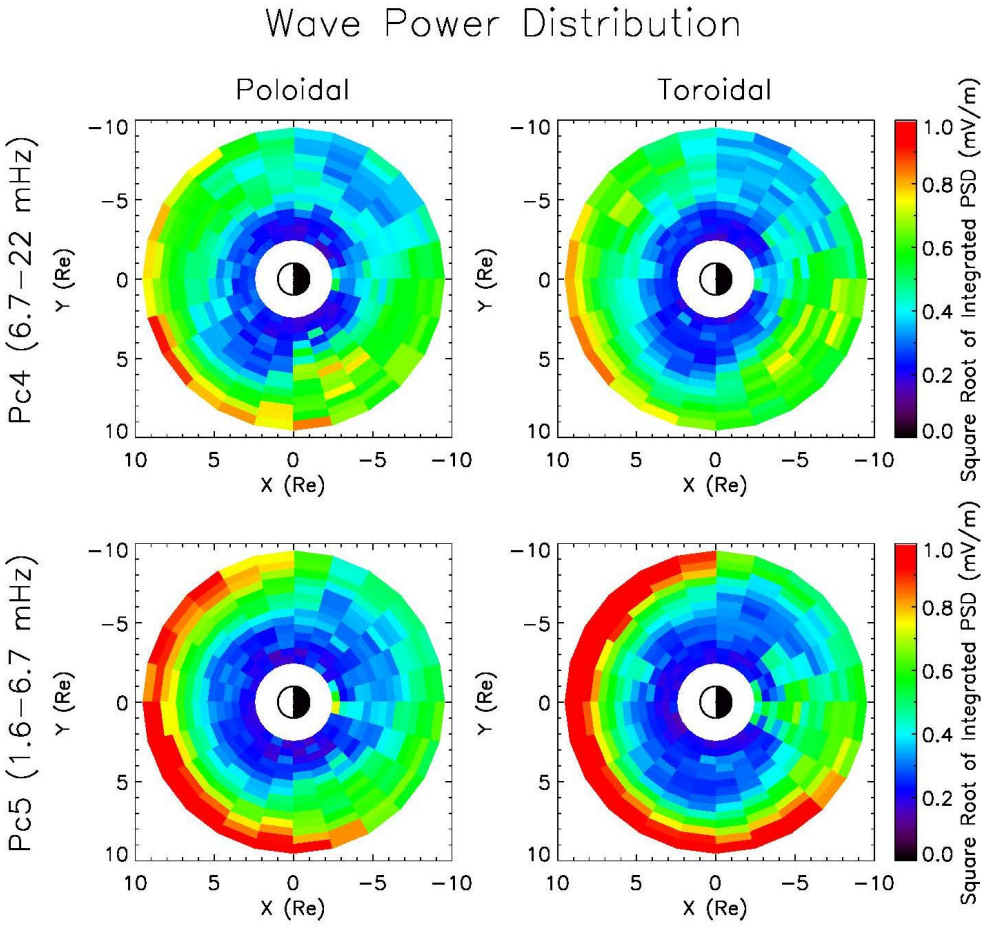


Pressure Pulses in 2001-2009:
524 = 270 positive + 254 negative



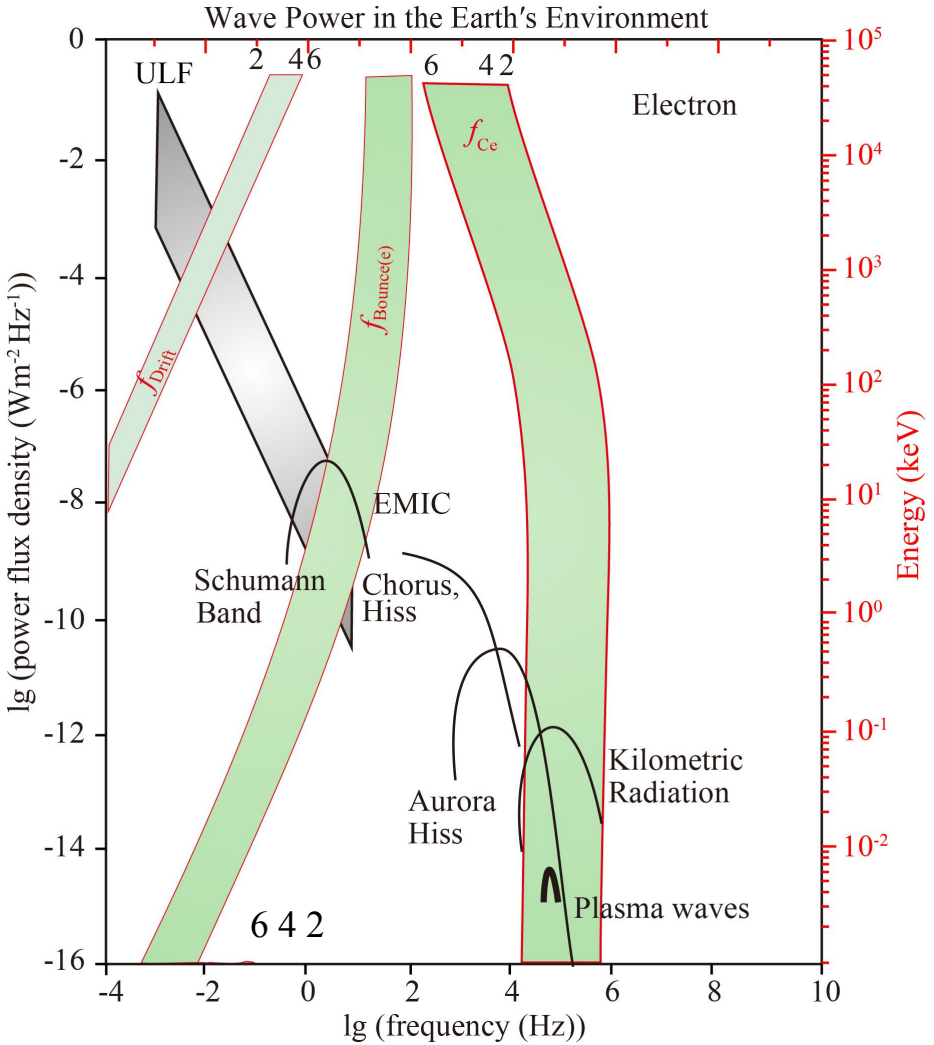
Zhang, Zong et al., 2010

2008-2019 THEMIS



Liu et al., 2019

Magnetosphere Response to IP Shock Impact: ULF Wave Scenario



Lanzerotti & Southwood, 1979

Ultra-low frequency:

$1\ \text{mHz} \le f \le 10\ \text{Hz}$

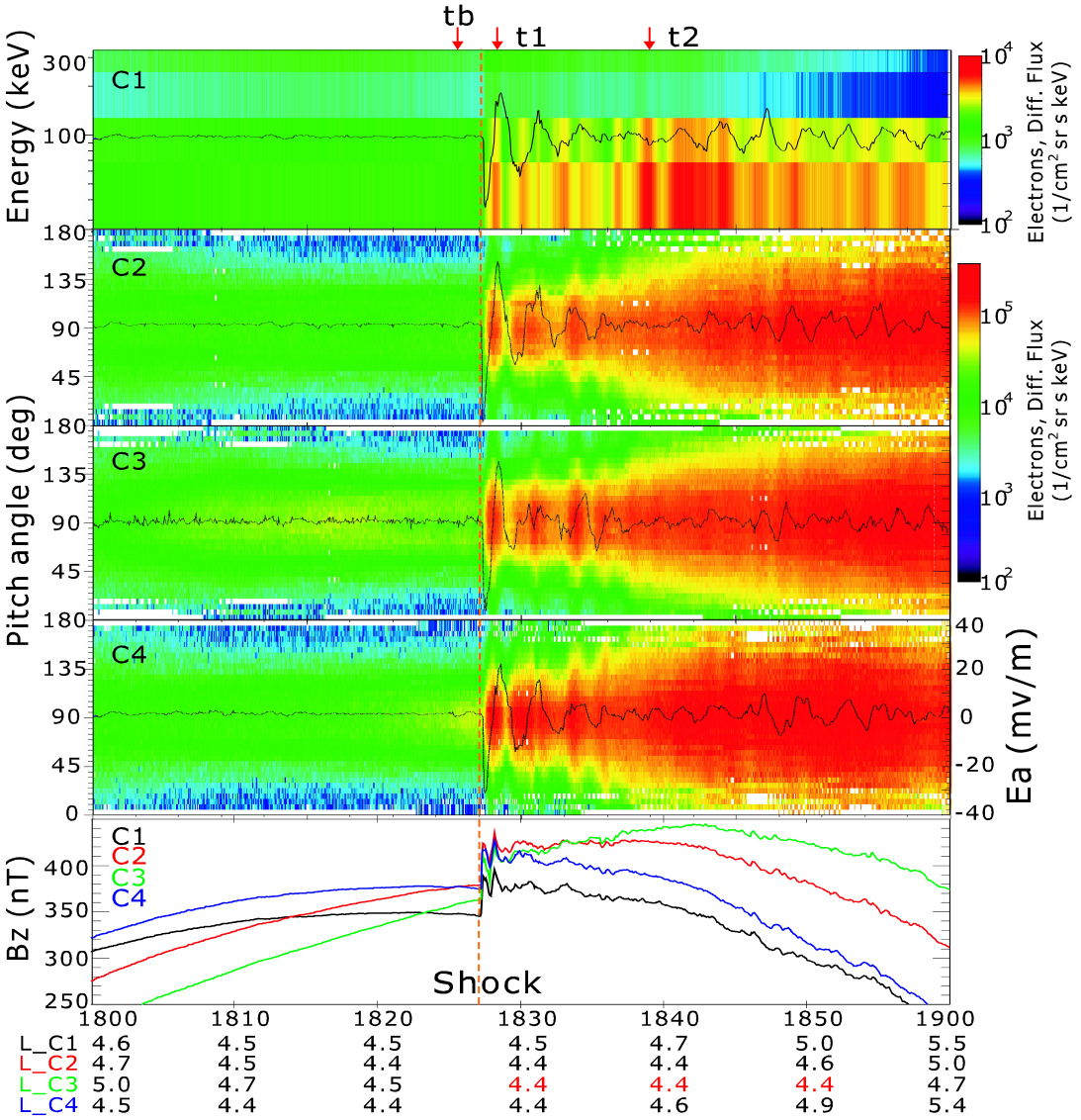
Particle measurements:

one to one correlation

- ✓ Drift resonance
- ✓ Drift-Bounce resonance

Zong et al., 2008, 2010, 2017

Magnetosphere Response to IP Shock Impact: ULF Wave Scenario

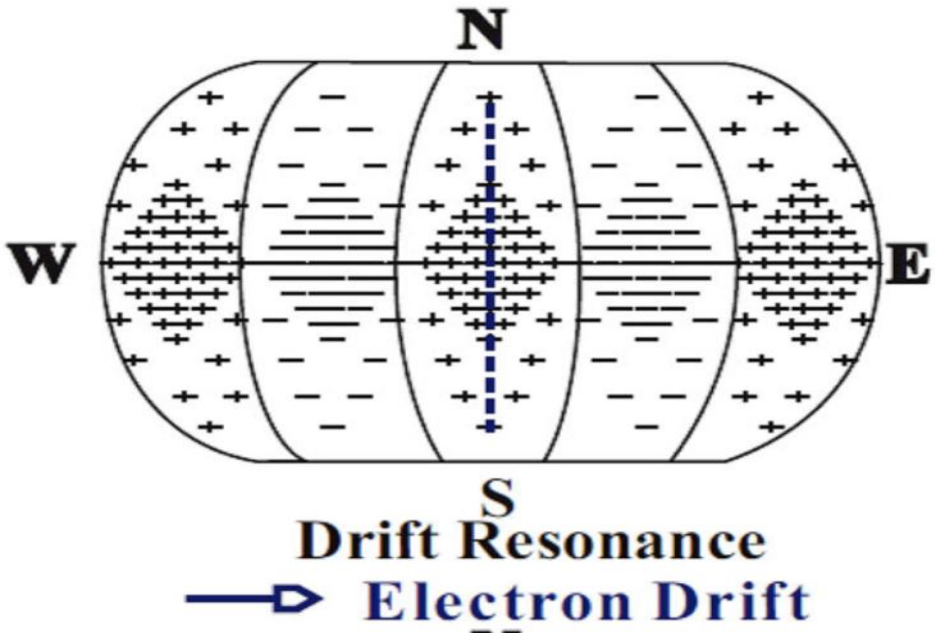


- Shocks can excite standing ULF waves in the magnetosphere.
- Outer belt electrons can be accelerated by ULF waves through drift resonance.

Zong et al., 2009

Drift-Bounce Resonance

ULF waves: $\mathbf{E} = E_\phi \exp i(m\phi - \omega t)\hat{\mathbf{e}}_\phi$

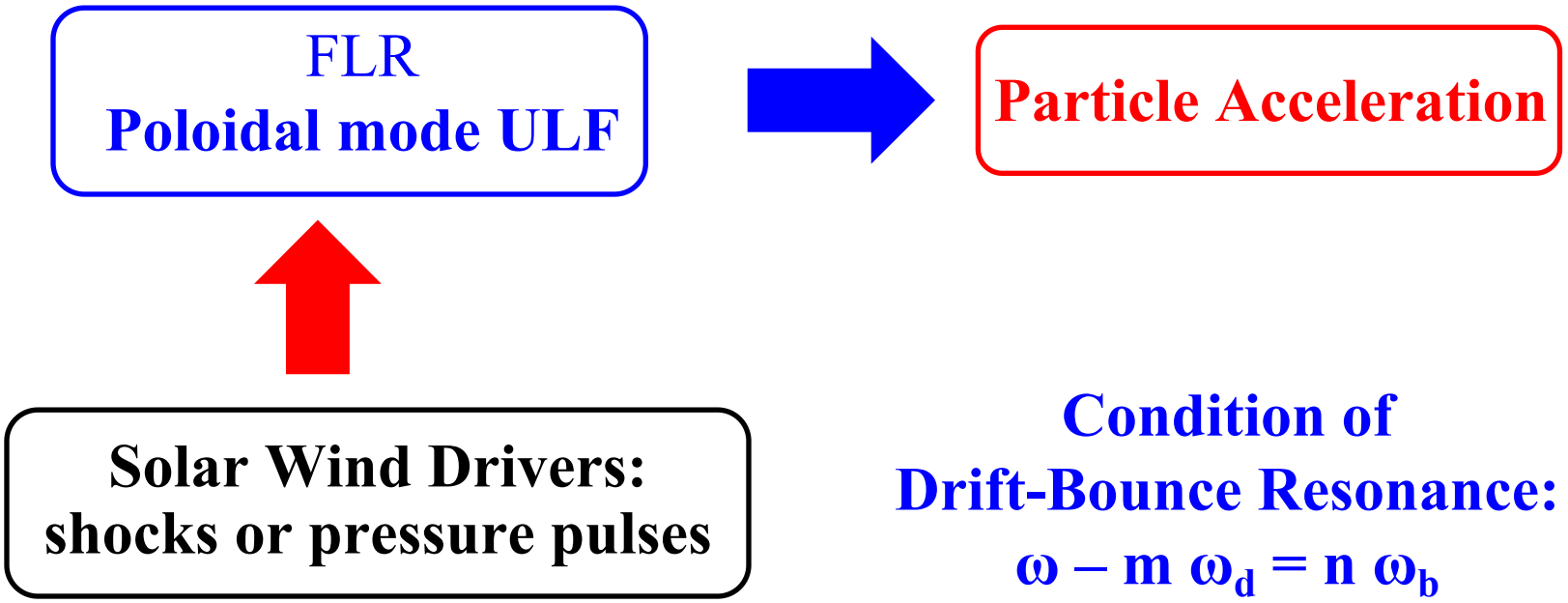


Analogous to wave-particle gyro-resonance, the particle's bounce and drift resonance could occur.
[Dungey,1964]

Condition of Drift-Bounce Resonance:

$$\omega - m\,\omega_d = n\,\omega_b$$

ULF Wave-Particle Interactions

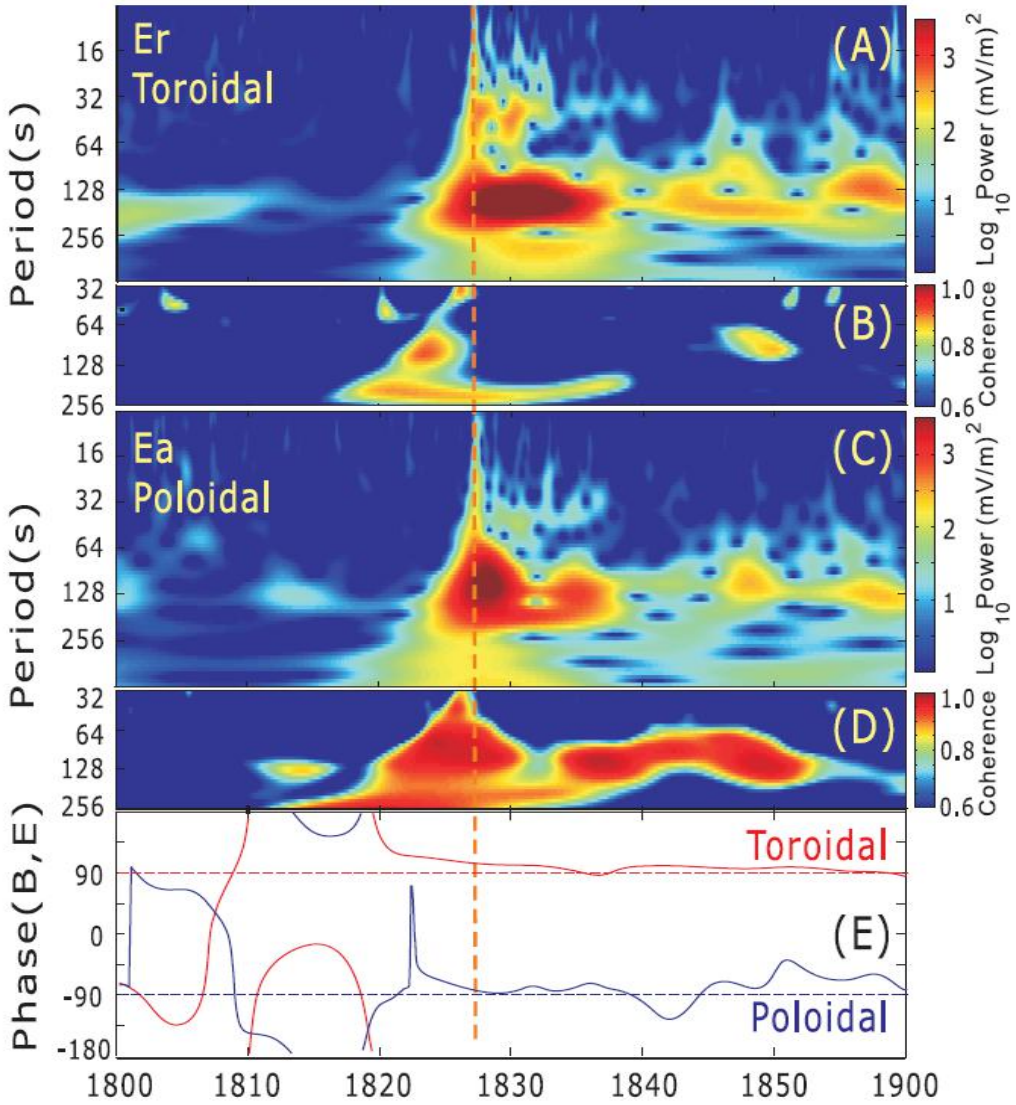


New View:

Electrons and ions can be accelerated by poloidal mode ULF waves.

Zong et al., 2007, 2009, 2012, 2017

Magnetosphere Response to IP Shock Impact: ULF Wave Scenario



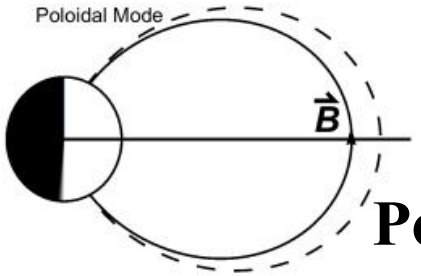
- Electron resonance with **Poloidal ULF** waves (~35 min)
- $m \sim 40$

$$\omega - m\,\omega_d = n\,\omega_b$$

$$\omega = m\,\omega_d$$

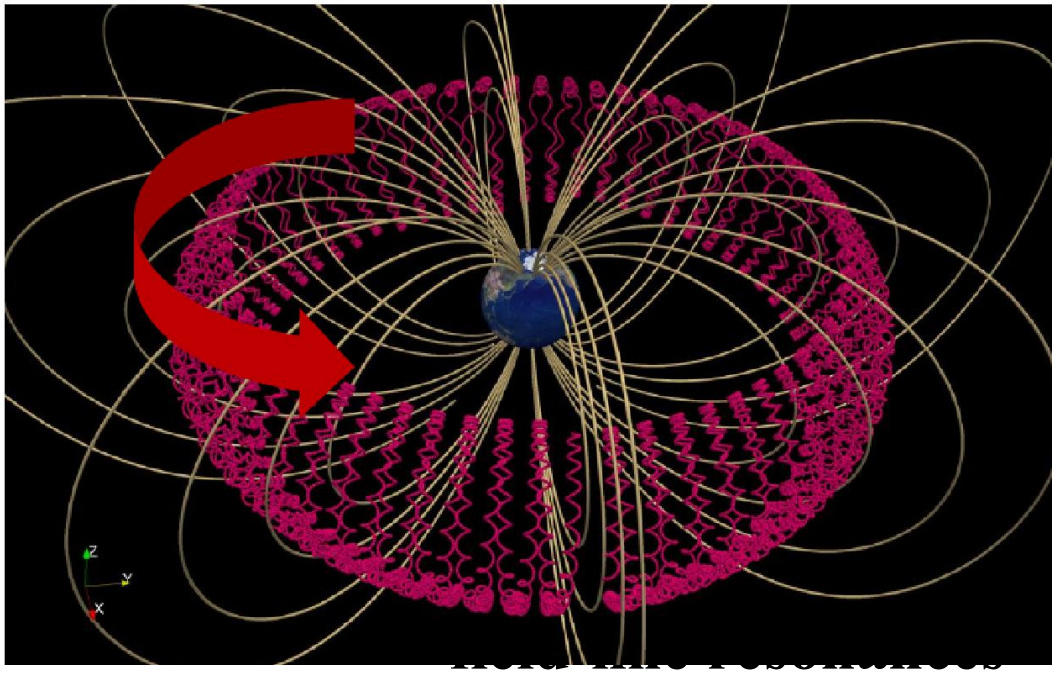
Zong et al., 2009, 2017

ULF Wave Modes



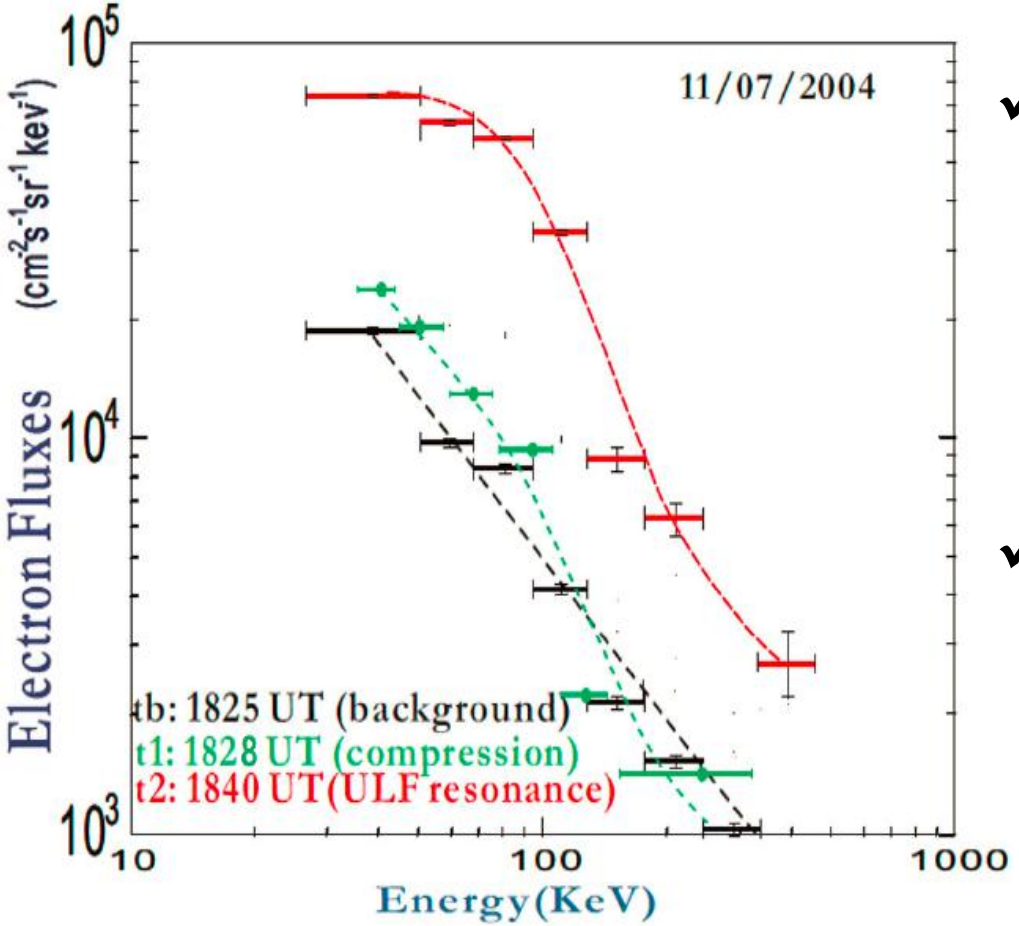
Dungey, 1955

Poloidal (outward) field-line resonances



- **Toroidal standing waves**
  - *B*_azimuthal
  - *E*_radial
  - Small wave number *m*
- **Poloidal standing waves**
  - *B*_radial
  - *E*_azimuthal
  - Large wave number *m*

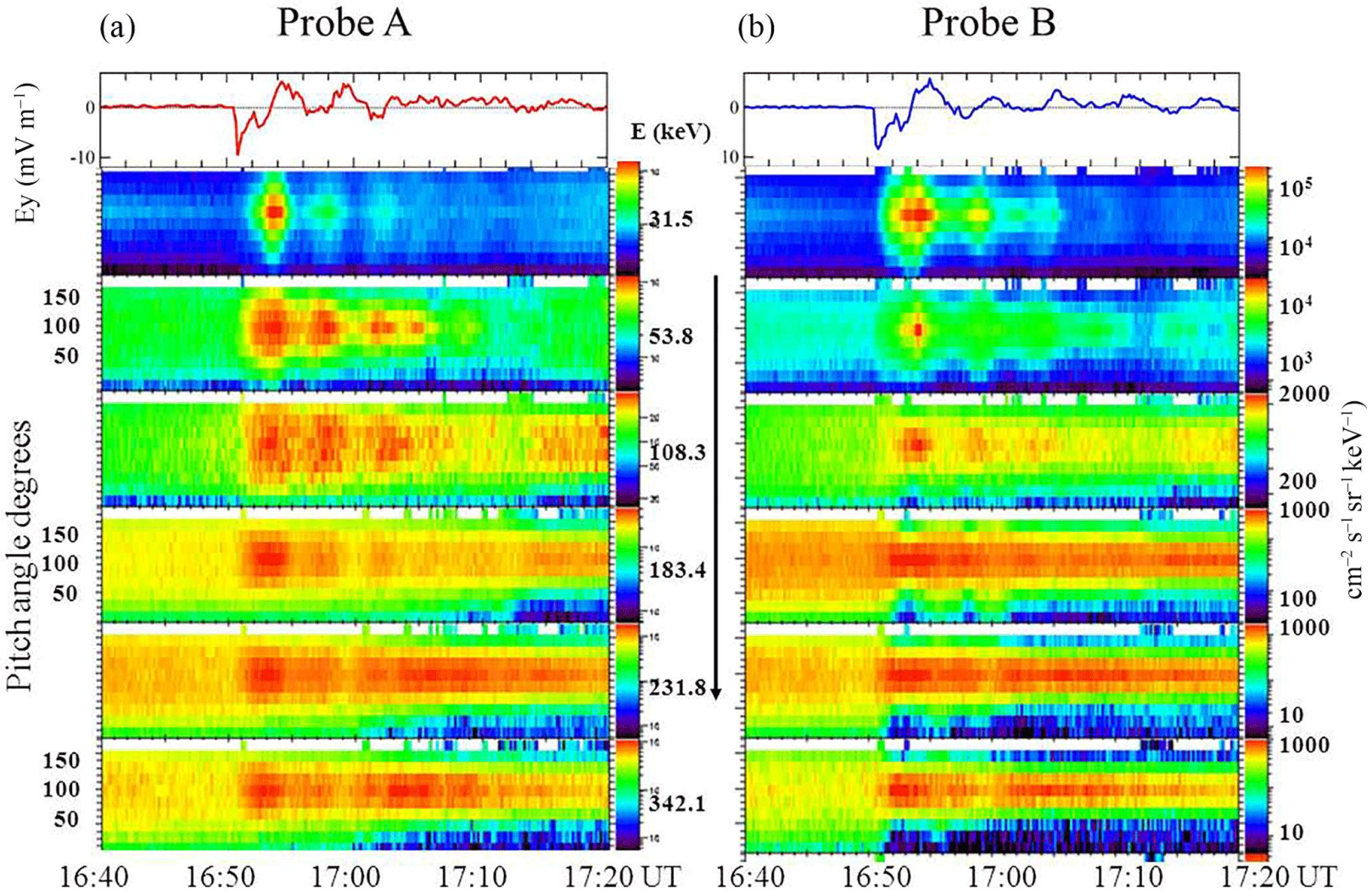
Magnetosphere Response to IP Shock Impact: ULF Wave Scenario



Zong et al., 2009

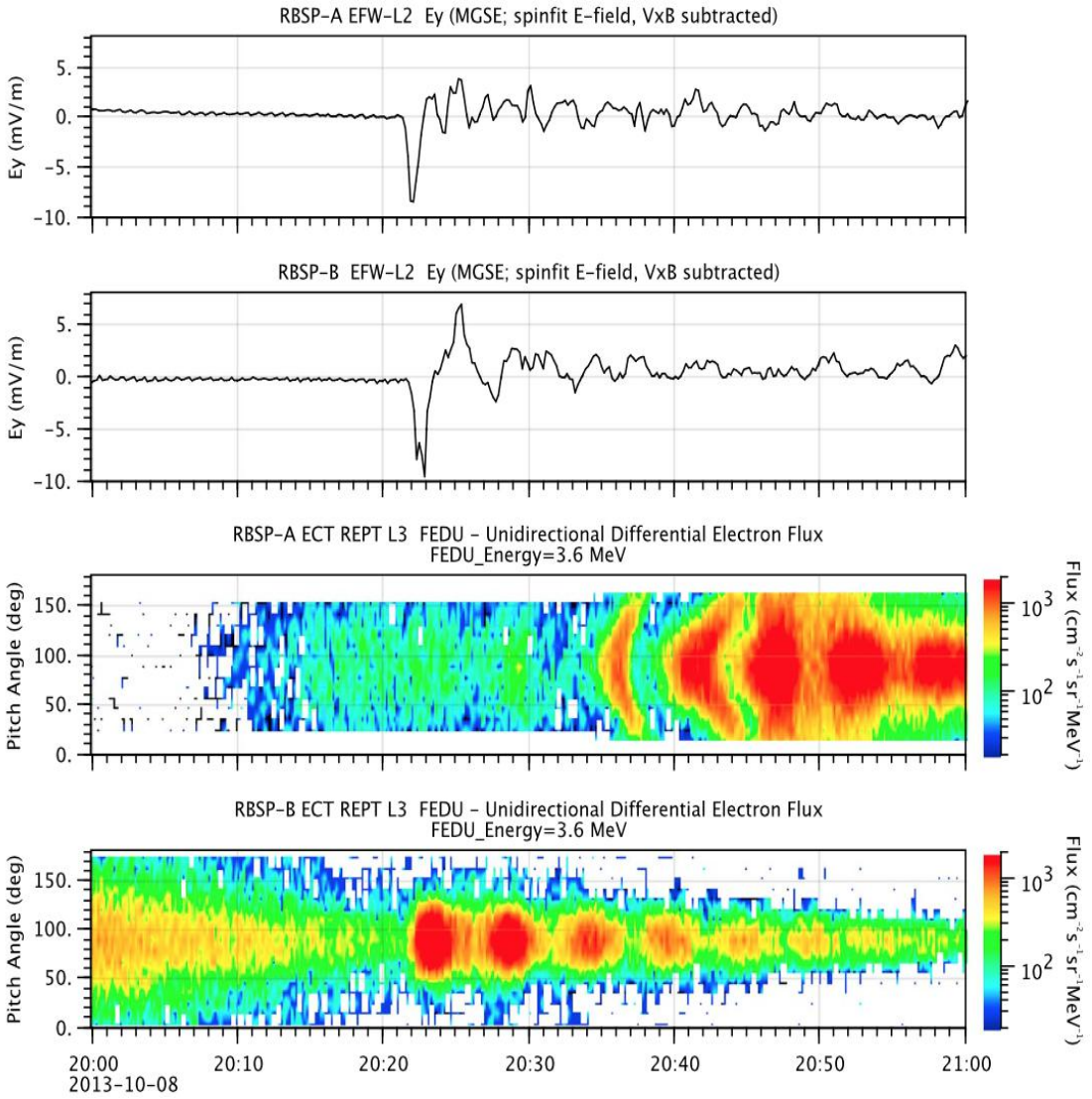
- ✓ Accelerated electrons after the first "Kick"
- ✓ Accelerated electrons after resonance with ULF waves (~15 min)

Magnetosphere Response to IP Shock Impact: ULF Wave Scenario



Korotova, Sibeck et al., 2018

Magnetosphere Response to IP Shock Impact: ULF Wave Scenario



~ 1 MeV

- Excited ULF waves
- Prompt acceleration of MeV electrons in the outer belt by the IP shock

Foster et al., 2015

IP Shocks Create Killer Electrons

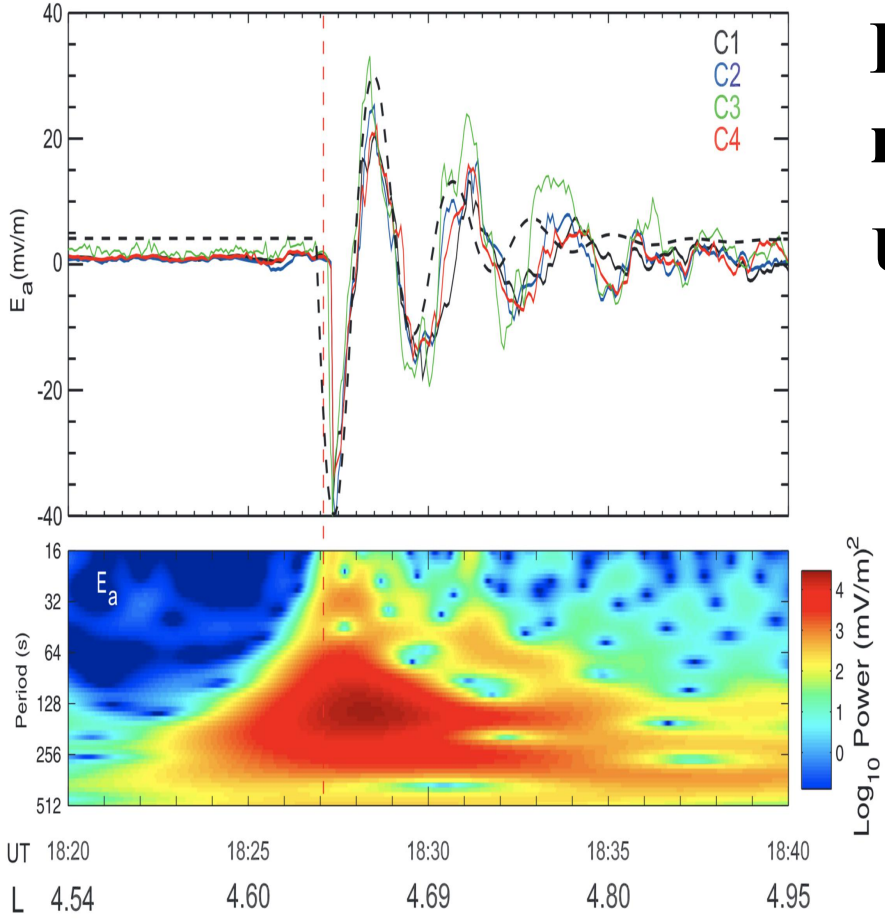


Copyright: ESA

Outline

- Introduction
- Magnetospheric response: “one-kick” & ULF wave scenarios
- **Generalized theory of ULF wave-particle interactions**
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Generalized Theory of ULF Wave-Particle Interaction: (1) Growing or Decaying ULF Waves



In the conventional drift resonance theory

ULF waves: $\mathbf{E} = E_\phi \exp i(m\phi - \omega t)\hat{\mathbf{e}}_\phi$

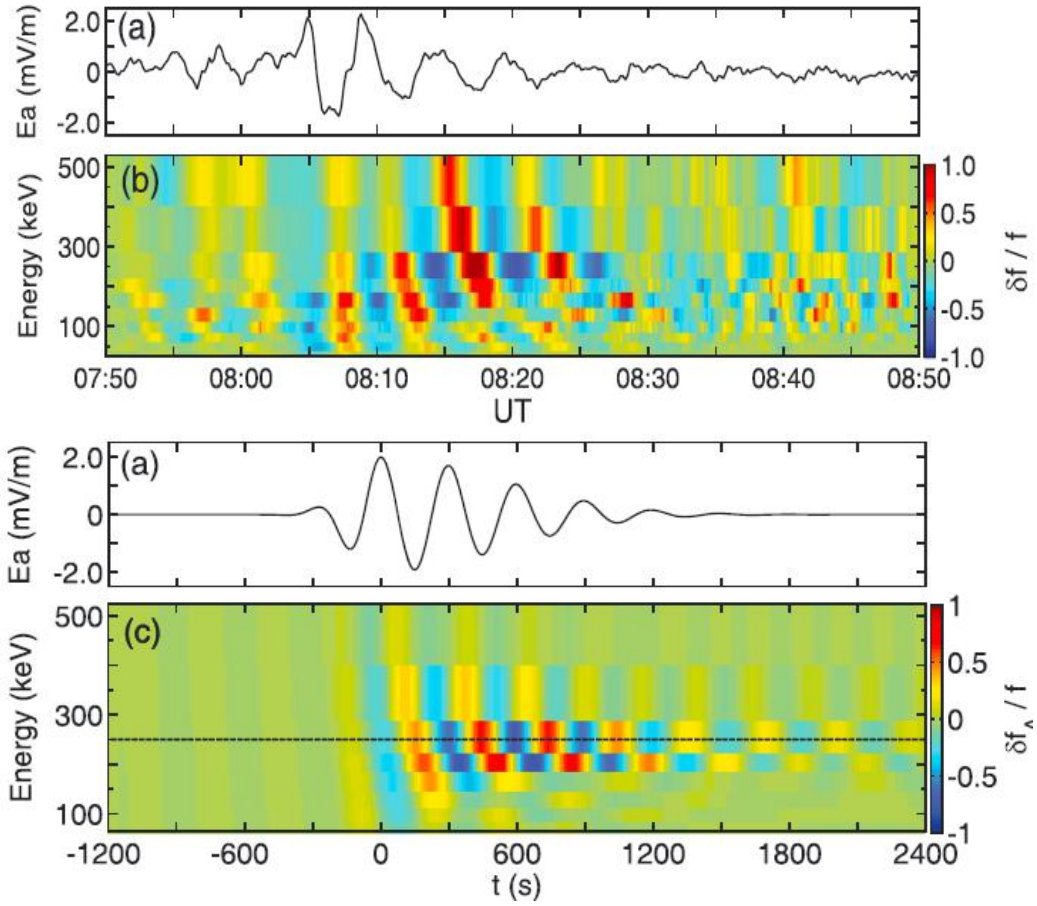
- **Small & constant amplitude**
- **Globally distributed**
- **Monochromatic wave**
- **Unperturbed particle trajectories**

Wang, C., R. Rankin, and Q. Zong (2015), **Fast damping of ultralow frequency waves** excited by interplanetary shocks in the magnetosphere, J. Geophys. Res. Space Physics, 120,Doi:10.1002/2014JA020761.

Generalized Theory of ULF Wave-Particle Interaction: (1) Growing or Decaying ULF Waves

ULF waves: $\mathbf{E} = E_\phi \exp(-t^2/\tau^2)\exp i(m\phi - \omega_r t)\hat{\mathbf{e}}_\phi$

Growing ULF waves followed by decaying ULF waves



Drift Resonance:

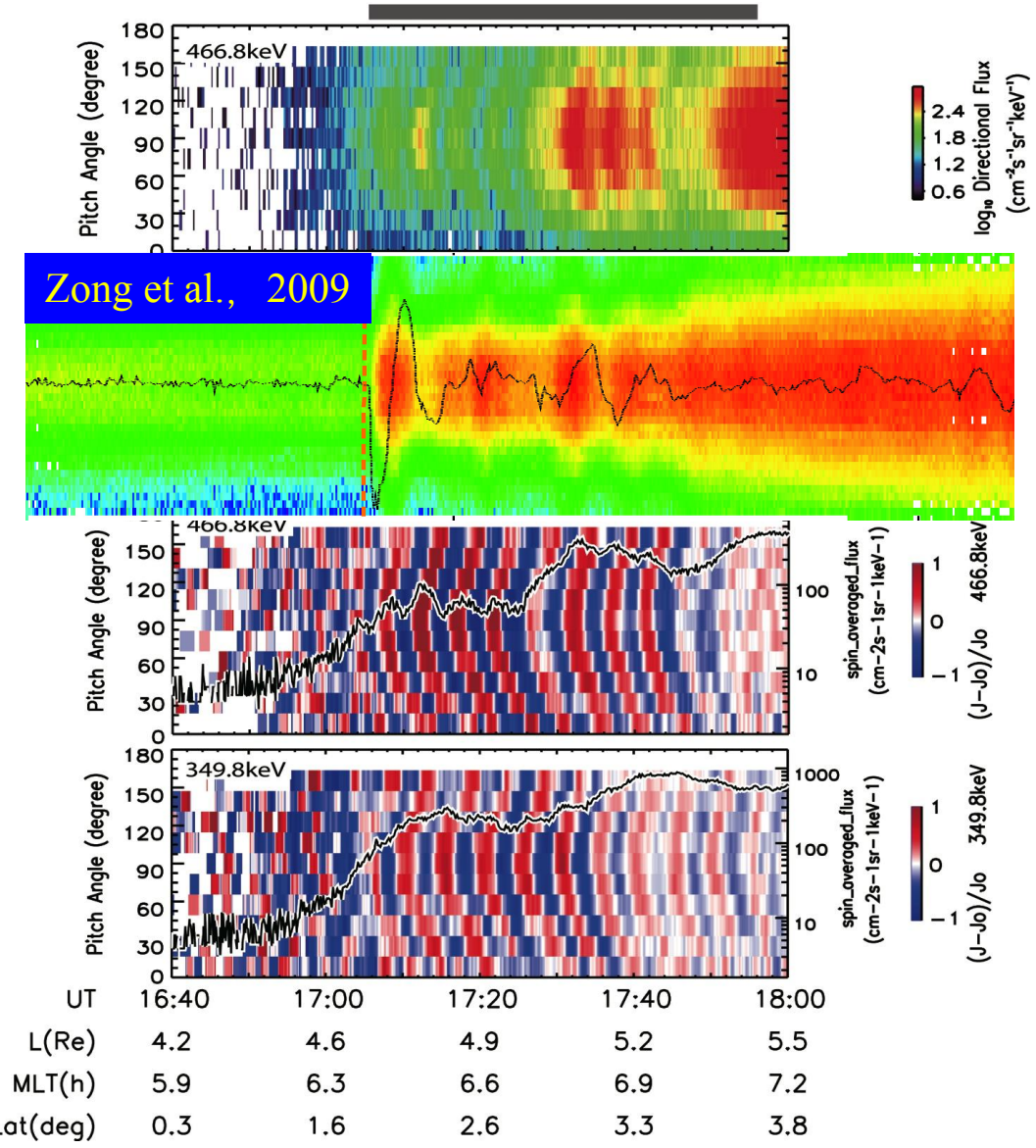
$\omega = m\,\omega_d$

Observations

Theory

Zhou et al., 2015, 2016;
Li, Zhou et al., 2017a, 2017b

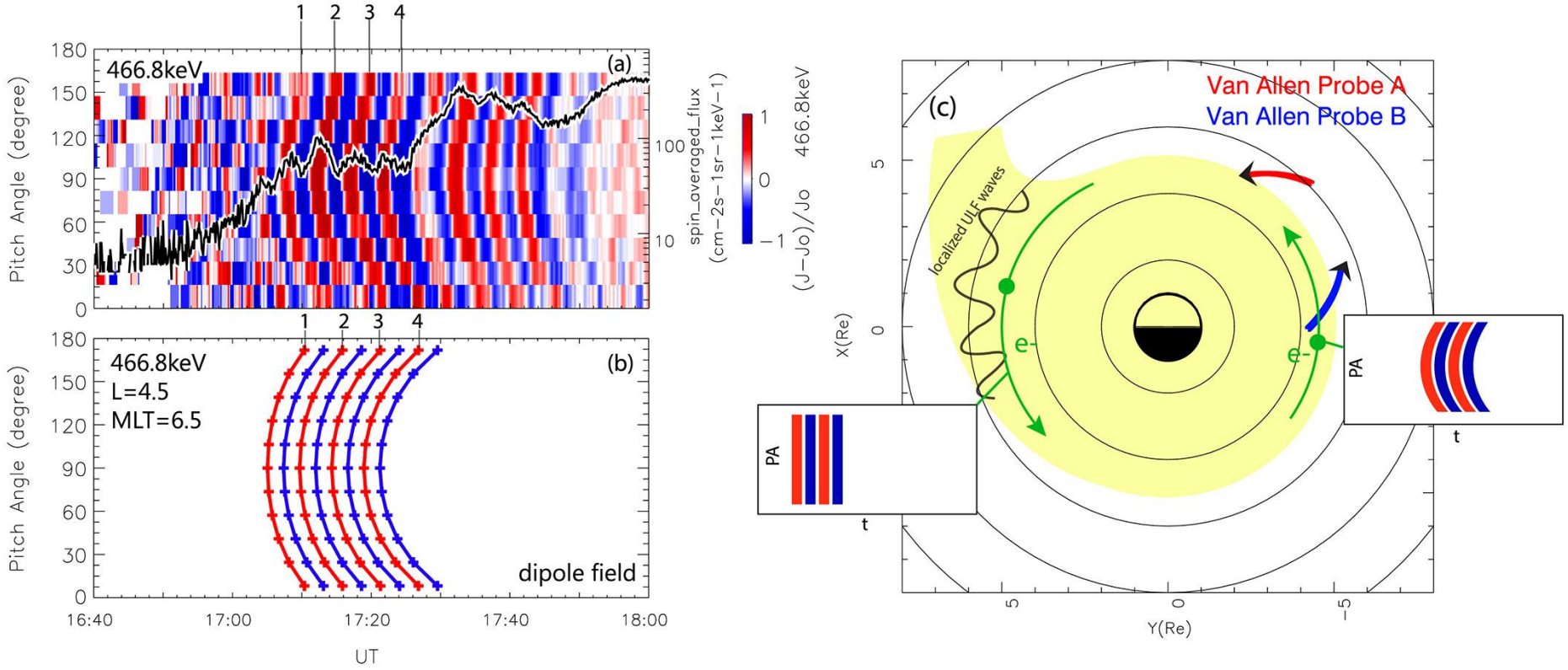
New Findings: Boomerang-shaped Pitch Angle Spectrogram





Hao et al., 2017; Zhao et al., 2019; Zong et al., 2017

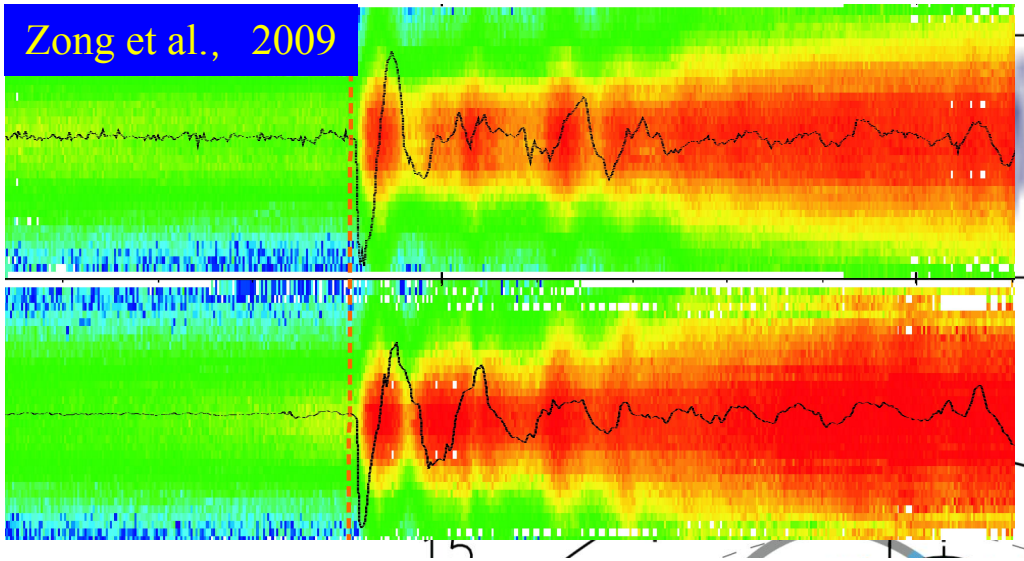
Generalized Theory of ULF Wave-Particle Interaction: (2) Localized ULF Waves

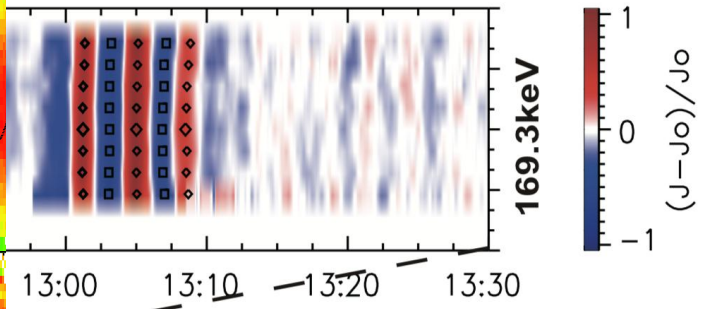


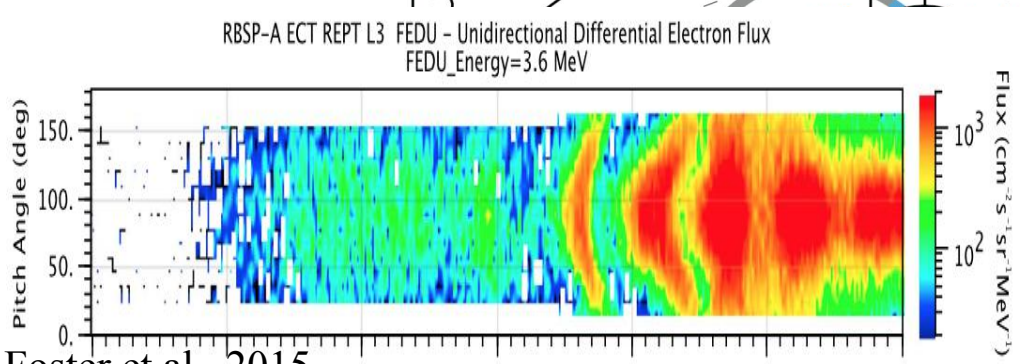
Hao et al., 2017; Zong et al., 2017

ULF waves: $$E(t,\phi) = \frac{E_{\phi 0}\exp(-t^2/\tau^2)}{2\pi I_0(\xi)}\exp[\xi\cos(\phi-\phi_0)]\cdot\exp\, i(m\phi-\omega t)\hat{e}_\phi,$$

Generalized Theory of ULF Wave-Particle Interaction: (2) Localized ULF Waves



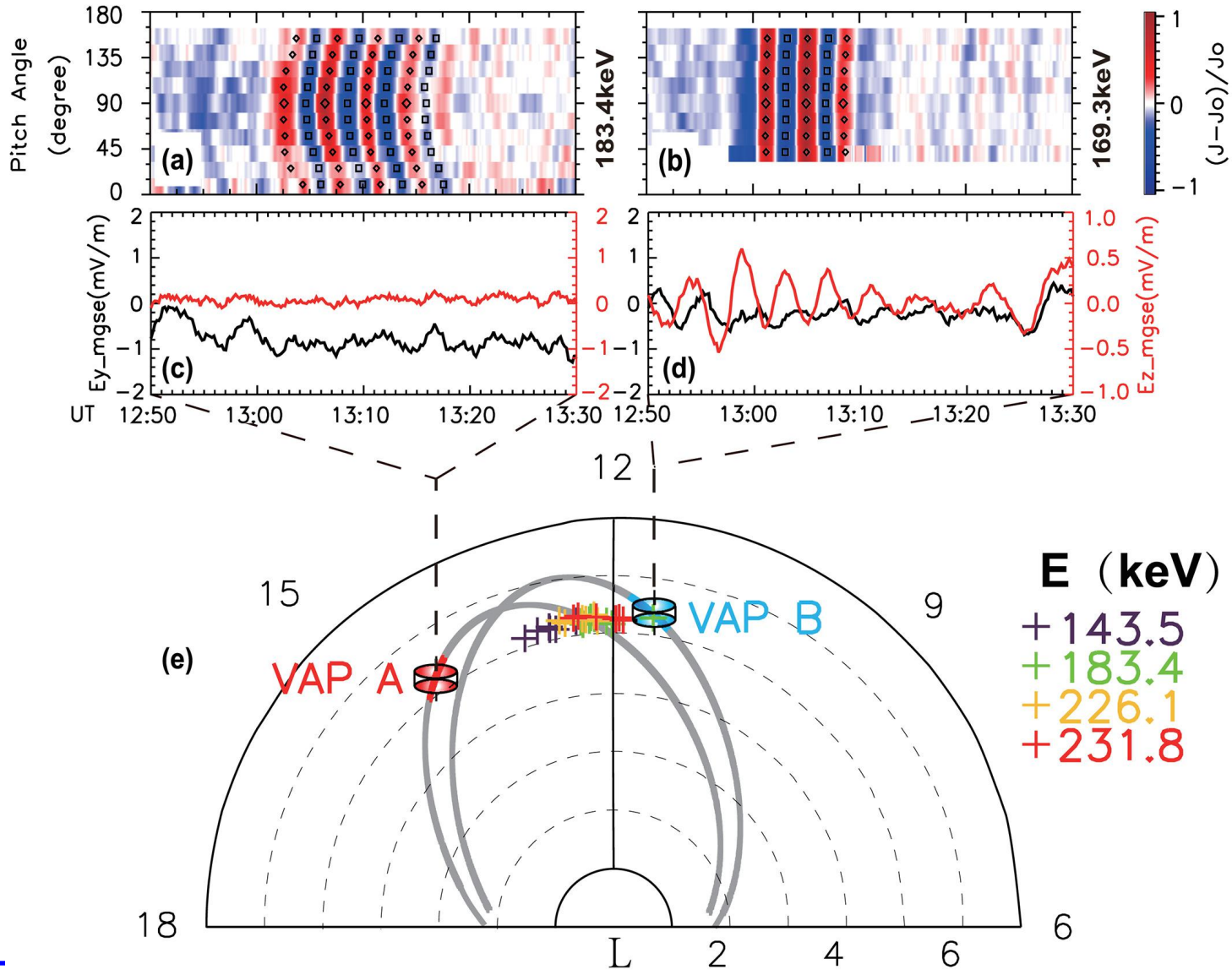




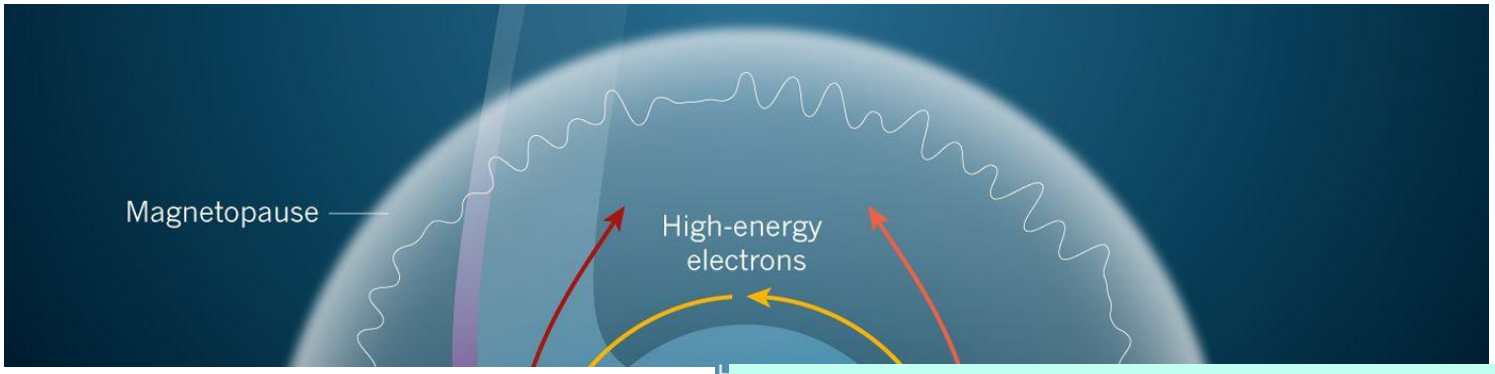
Foster et al., 2015

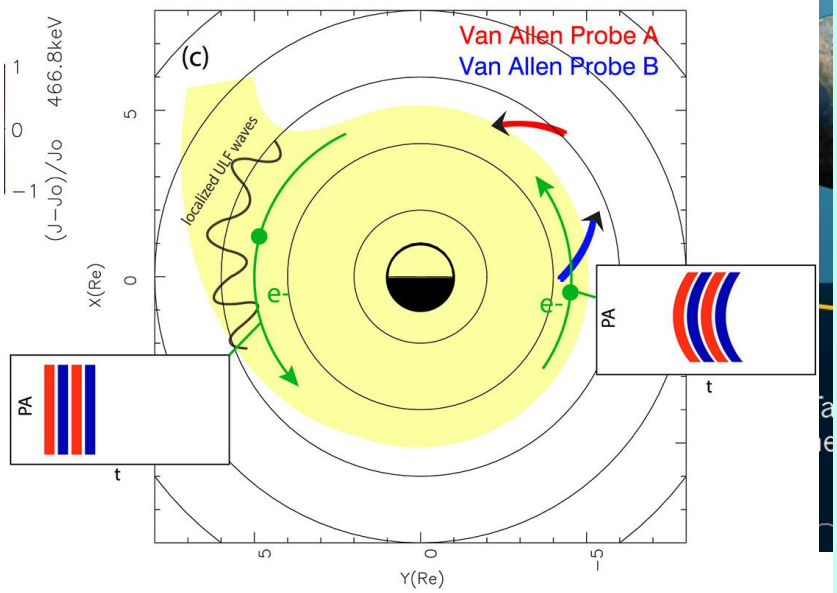
Zhao, Zong et al., GRL 2020

Generalized Theory of ULF Wave-Particle Interaction: (2) Localized ULF Waves



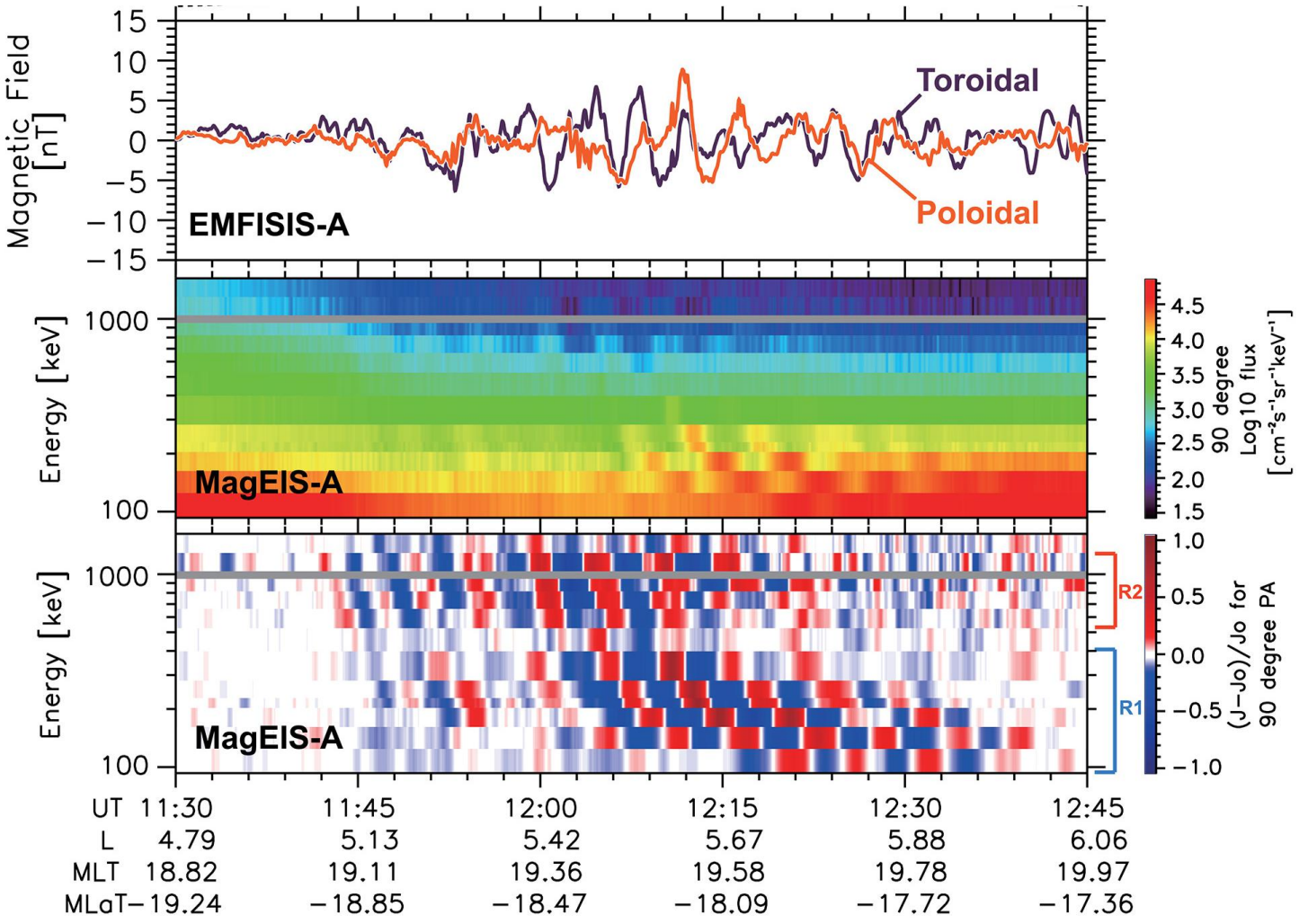
Generalized Theory of ULF Wave-Particle Interaction: (2) Localized ULF Waves





- **Novel periodic stripes in Pc 4-5 band in relativistic electrons' pitch angle spectrogram after shock impact.**
- **The Boomerang-shaped pitch angle spectrogram can be used in remote sensing of the ULF wave-particle interaction region.**

Generalized Theory of ULF Wave-Particle Interaction: (3) Global and Localized ULF Waves



m = 3

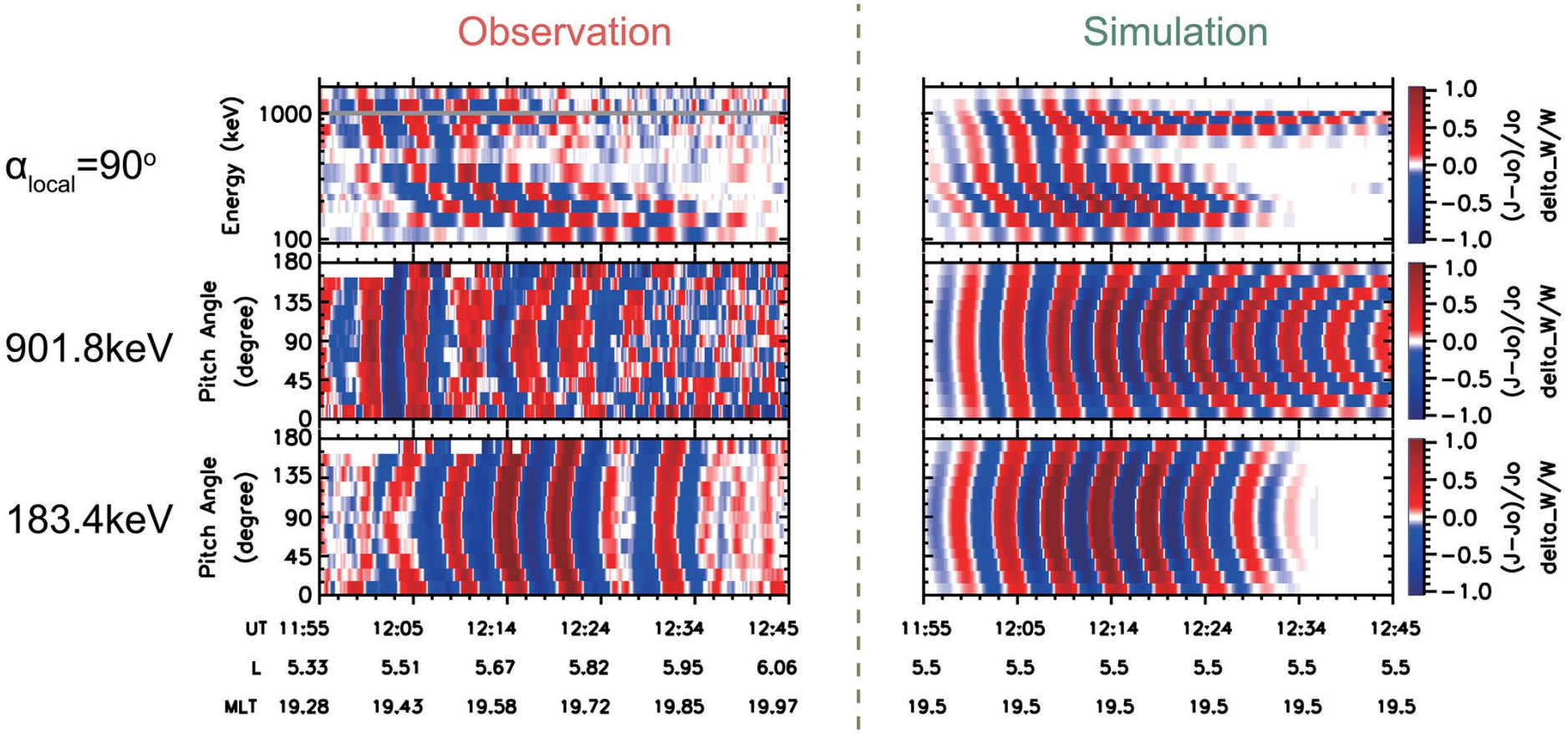
m = 10

Hao et al., 2020

Drift Resonance with multiple m number waves

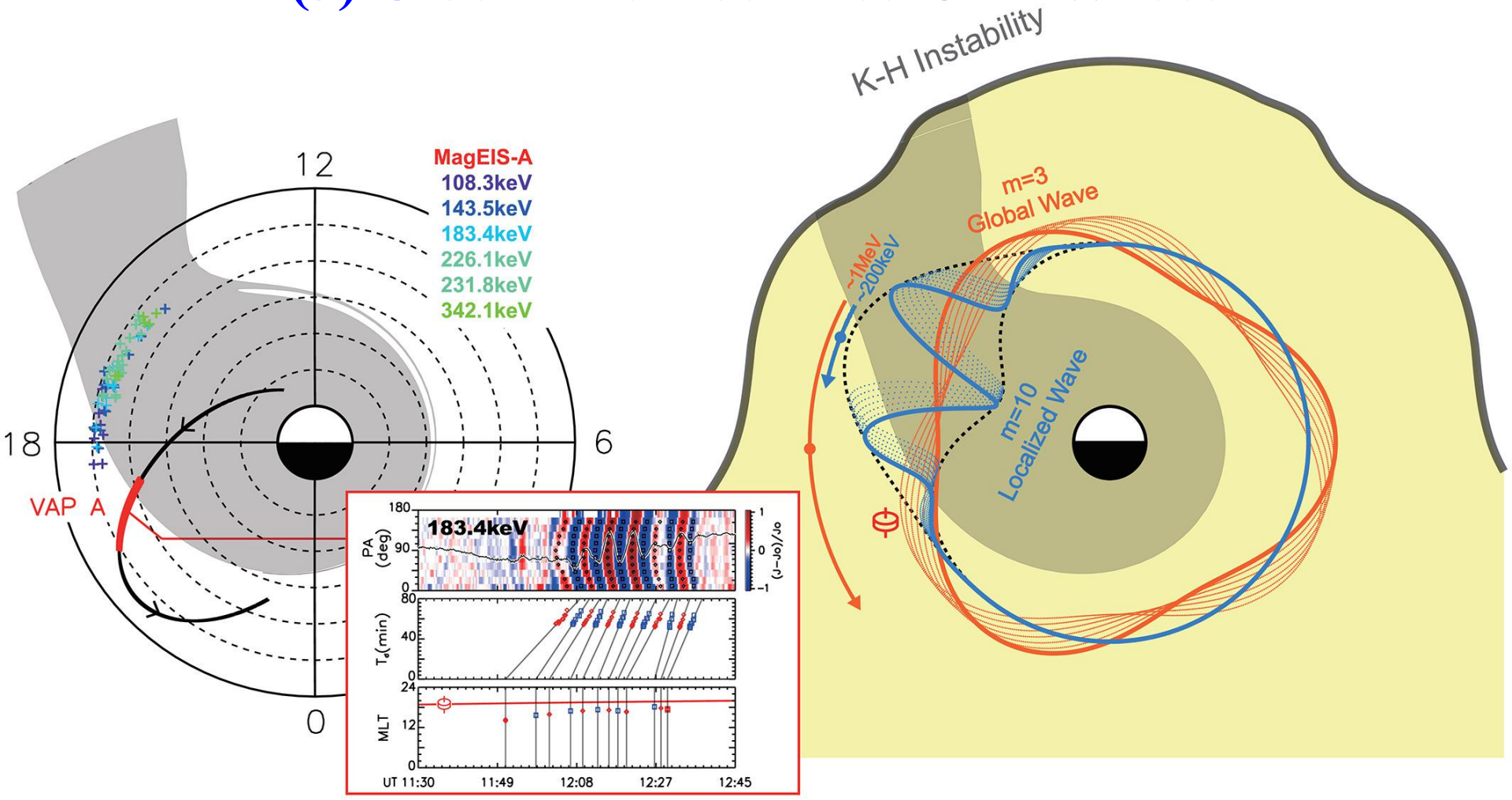
Generalized Theory of ULF Wave-Particle Interaction: (3) Global and Localized ULF Waves

Waves: m = 3, m = 10



Hao, Y. X., Zhao, X. X., Zong, Q.-G.,Zhou, X.-Z., Rankin, R., Chen, X. R., et al. (2020). Simultaneous observationsof localized and global drift resonance. Geophysical Research Letters, 47,e2020GL088019.

Generalized Theory of ULF Wave-Particle Interaction: (3) Global and Localized ULF Waves

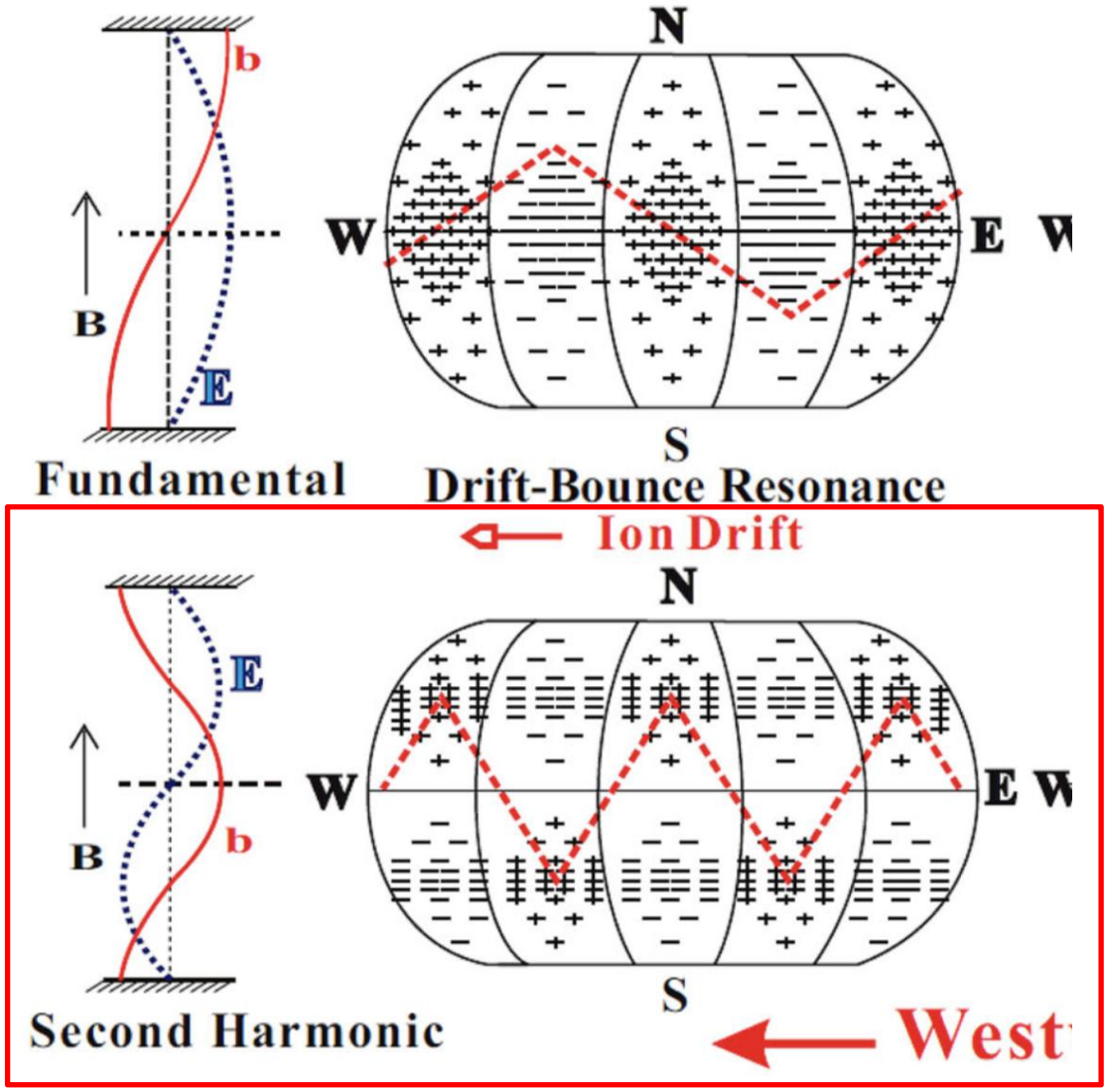


Hao, Y. X., Zhao, X. X., Zong, Q.-G.,Zhou, X.-Z., Rankin, R., Chen, X. R., et al. (2020). Simultaneous observationsof localized and global drift resonance. Geophysical Research Letters, 47,e2020GL088019.

Outline

- Introduction
- Magnetospheric response: “one-kick” & ULF wave scenarios
- **Generalized theory of ULF wave-particle interactions**
  - Drift resonance: radiation belt electrons
  - **Drift-bounce resonance: ring current ions**
- Concluding remarks and outstanding questions

Interaction of ULF Waves with Ring Current Ions



Drift-Bounce Resonance Condition:

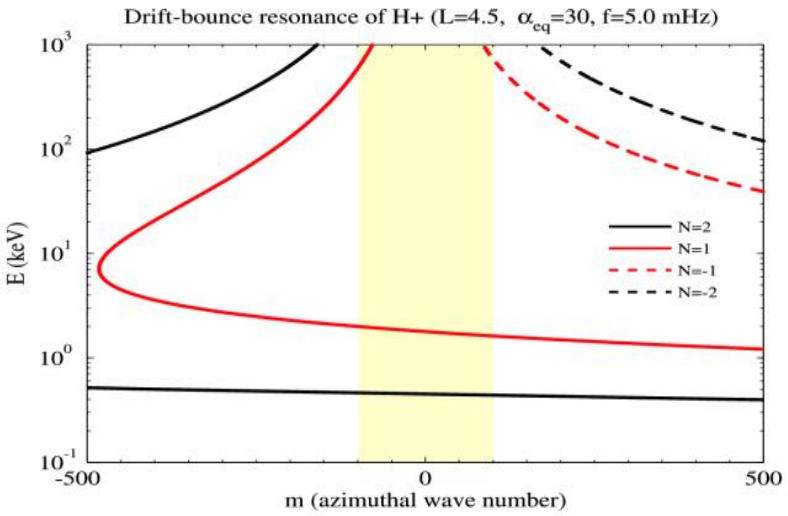
$$\omega - m\,\omega_d = n\,\omega_b$$

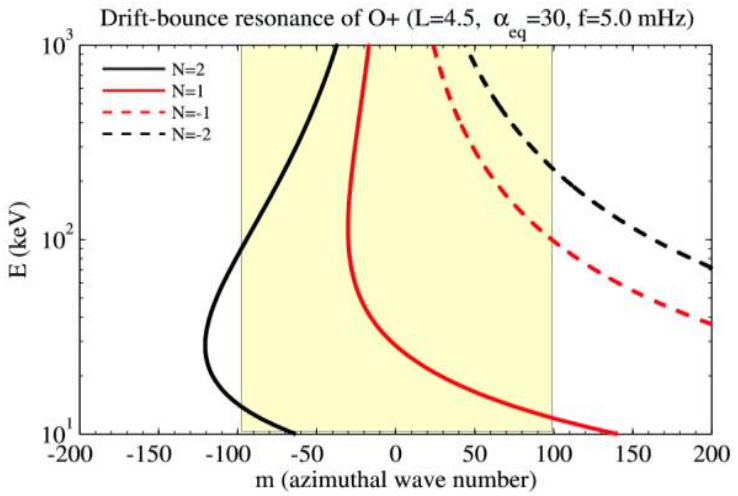
Zong, Q., Rankin, R.,&Zhou, X. (2017). The interaction of ultra-low-frequency Pc3-5 waves with charged particles in Earth's magnetosphere. *Reviews of Modern Plasma Physics*,*1*(1), 10.

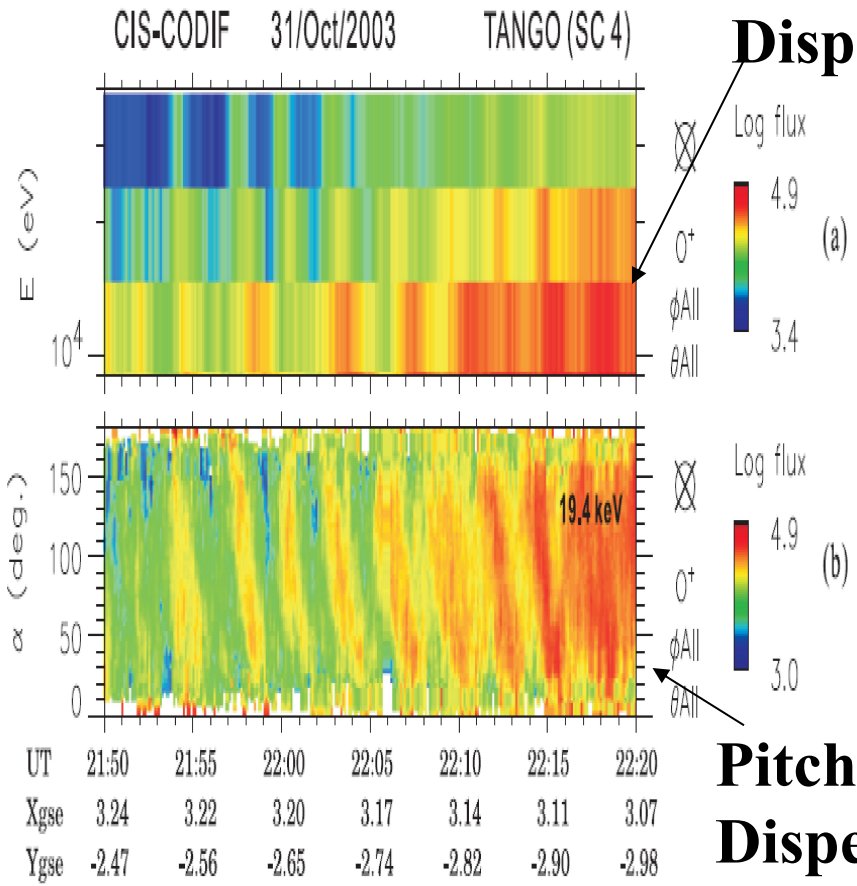
Interaction of ULF Waves with Ring Current Ions

Drift-Bounce Resonance Condition:

$$\omega - m\,\omega_d = n\,\omega_b$$





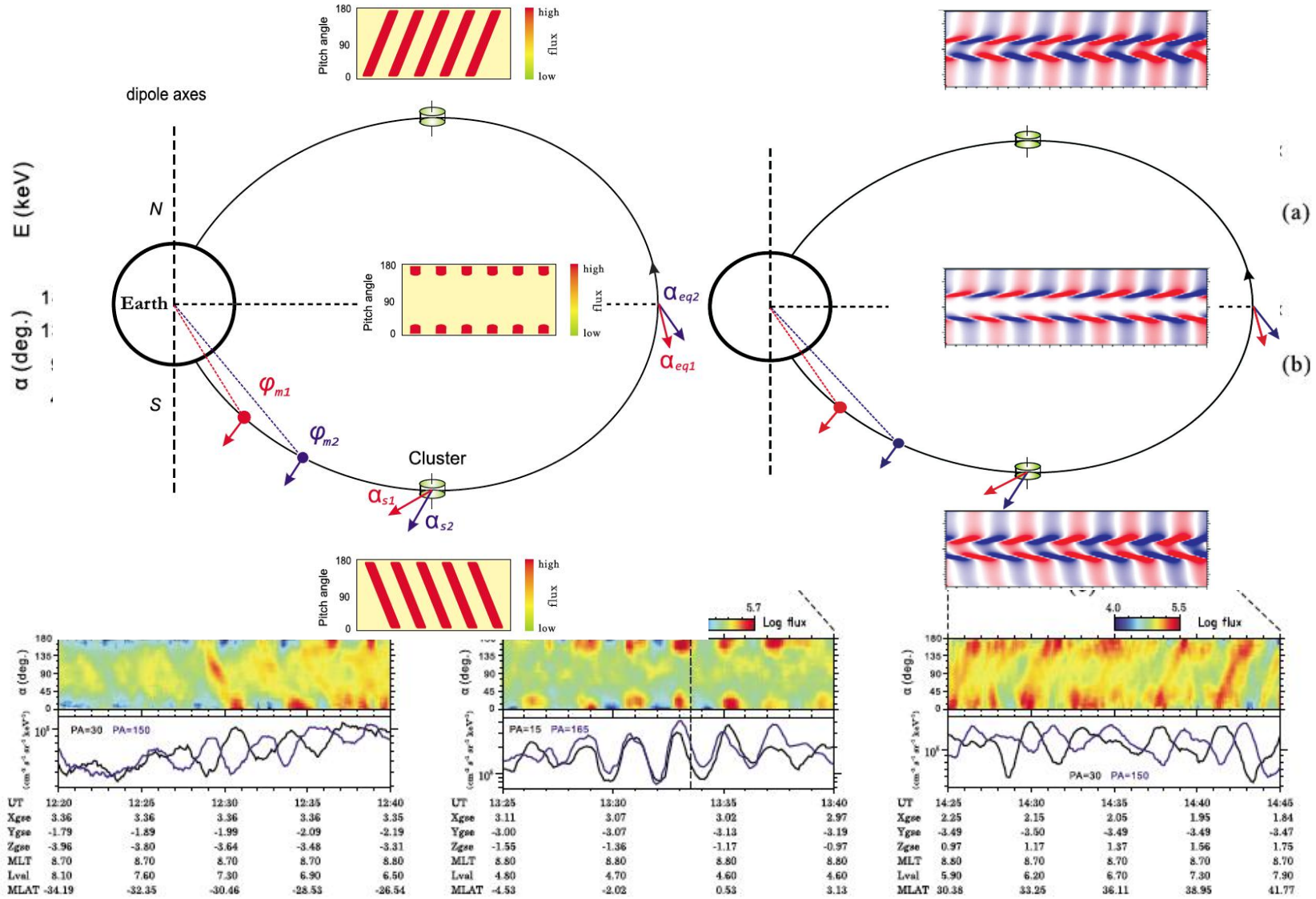


Energy Dispersion

Pitch Angle Dispersion

Zong et al., 2011, 2012, 2017

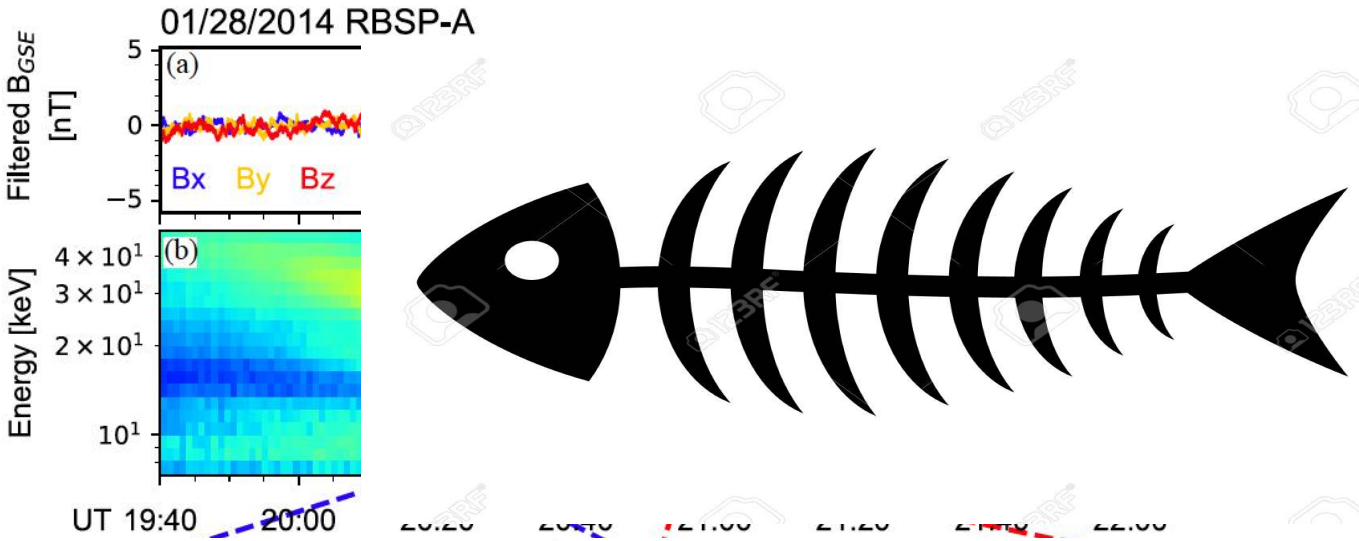
Interaction of ULF Waves with Ring Current Ions

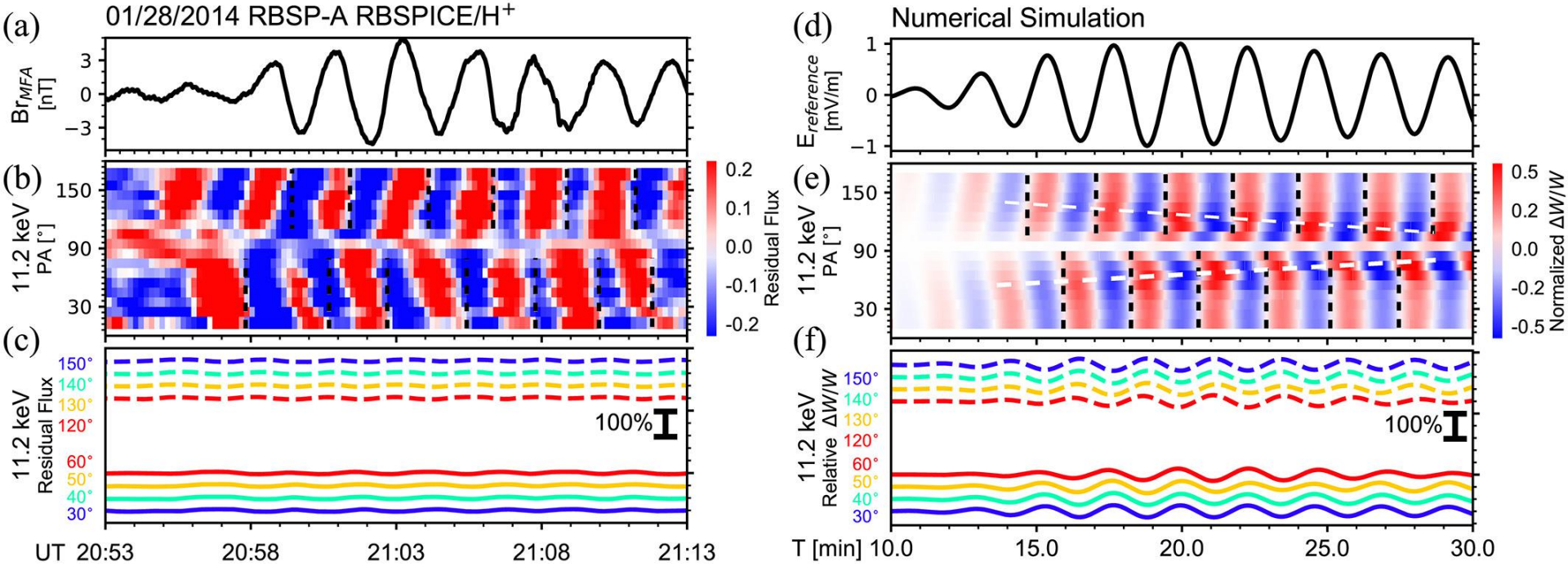


Yang, Zong et al., 2011; Zong et al., 2017, 2021

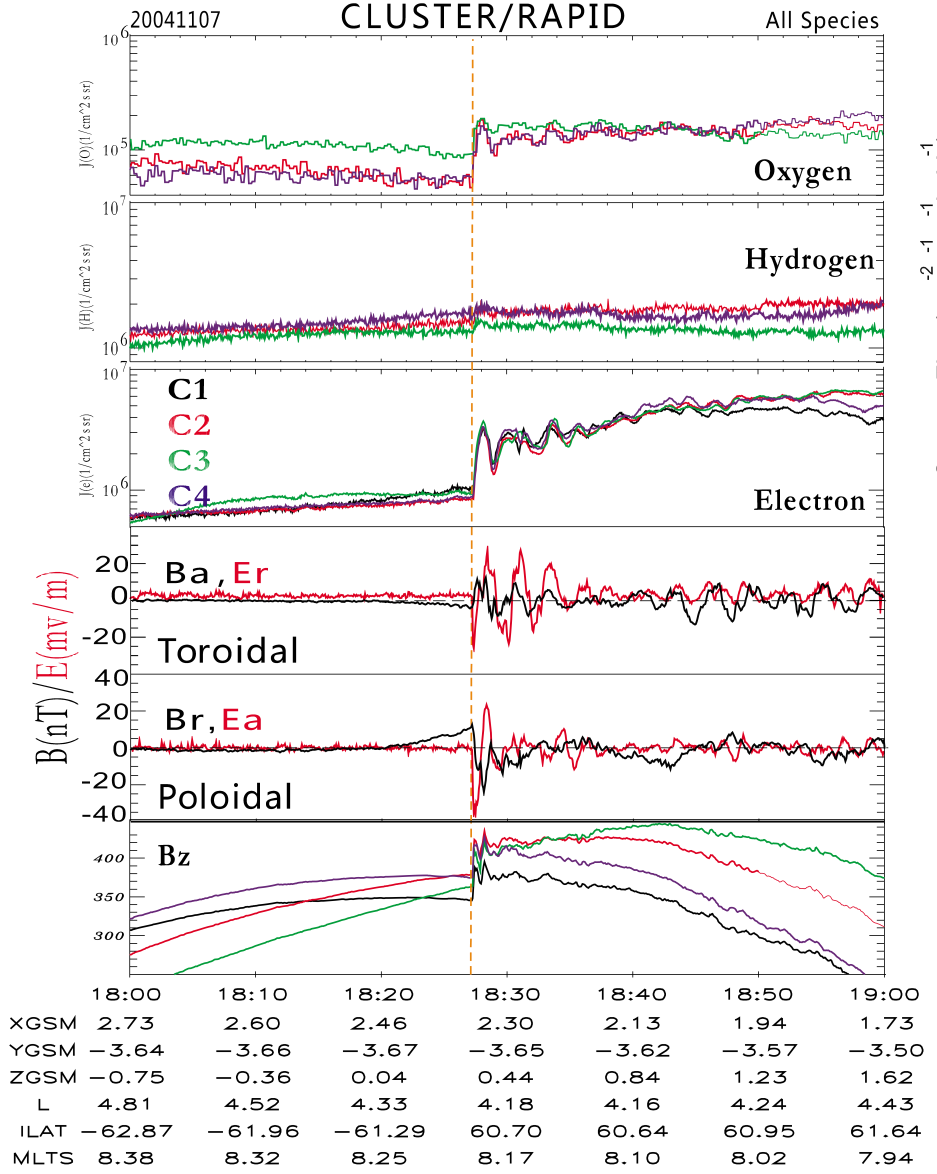
$\omega - m\,\omega_d = n\,\omega_b$

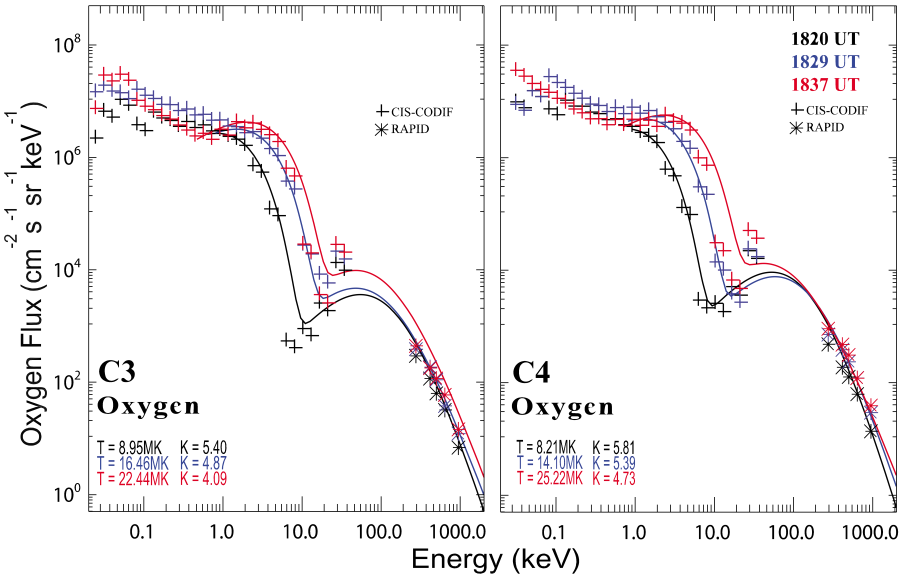
Ring Current Ion Drift-bounce Resonance with Growing or Decaying ULF Waves: Fishbone Distribution





Interaction of ULF Waves with Ring Current Ions





Zong et al., 2012

Concluding Remarks

- Magnetosphere response to interplanetary shocks is not a “one-kick” scenario. Instead, the impact generates different types of waves including poloidal mode ULF waves in the magnetosphere. Energetic particle acceleration starts nearly immediately and can last several hours.

- A generalized theory of drift-bounce resonance with growing or decaying localized ULF waves has been developed to explain observations.

- Energy and pitch angle dependent behavior (e.g. Boomerang) for both resonant and non-resonant electrons are well predicted by generalized drift-bounce resonance theory.

- This generalized theory can also be explained to resonant ion features when they interact with ULF waves (e.g. Fishbone), oxygen ions can be accelerated more efficiently by the poloidal mode ULF waves.

Outstanding Questions

- What is the significance of high-m poloidal mode ULF waves for the energization of storm-time ring current ions (see, e.g., Zong et al. 2012)? Is this a prerequisite for a super magnetospheric storm?
- Do ULF waves mediate coupling between plasmasphere and ring current ion species and high-energy electrons in the radiation belts? If so, is energization of radiation belt electrons caused by ring current ion-excited second-harmonic poloidal ULF waves of moderate m-number (Ozeke and Mann, 2008)?
- How common are high-m poloidal mode waves at the plasmapause and are the signature of the existence of the plasmapause? What is the role of the plasmaspheric ion constituency?
- Are high-m poloidal mode ULF waves generated principally by an exterior solar wind driver or do ring current ions predominantly excite these wave?
- What is the role of ULF waves in other planetary magnetospheres?