Wave-Particle Interaction Analyzer: Direct Measurements of Wave-Particle Interactions in the Jovian Inner Magnetosphere

Yuto Katoh [1] and Hirotsugu Kojima [2]

[1] Department of Geophysics, Graduate School of Science, Tohoku University
[2] Research Institute for Sustainable Humanosphere, Kyoto University

Abstract:

We present a new instrumentation "Wave Particle Interaction Analyzer (WPIA)" for measurement of the energy transfer process between energetic electrons and plasma waves in the magnetosphere. The WPIA measures a relative phase angle between the wave vector and velocity vector of each particle and computes an inner product W(t), while W(t) is equivalent to the variation of the kinetic energy of energetic electrons interacting with plasma waves [*Katoh et al.*, 2013]. The WPIA will be firstly realized by the Software-type WPIA in the ERG satellite mission to measure interactions between energetic electrons and whistler-mode chorus in the Earth's inner magnetosphere. In this talk we discuss scientific objectives of the WPIA in the Jovian inner magnetosphere and propose a possible plan of implementation for direct measurements of wave-particle interactions.

References:

Katoh, Y., M. Kitahara, H. Kojima, Y. Omura, S. Kasahara, M. Hirahara, Y. Miyoshi, K. Seki, K. Asamura, T. Takashima, and T. Ono, Significance of Wave-Particle Interaction Analyzer for direct measurements of nonlinear wave-particle interactions, *Ann. Geophys.*, **31**, 503-512, doi:10.5194/angeo-31-503-2013, 2013.

Symposium on Planetary Science
Kawauchi-Kita Campus, Tohoku University
February 20-22, 2013

Direct measurements of wave-particle interactions in the Jovian inner magnetosphere: Wave-Particle Interaction Analyzer (WPIA)

Y. Katoh [1] and H. Kojima [2]

[1] Department of Geophysics, Graduate School of Science, Tohoku University
[2] Research Institute for Sustainable Humanosphere, Kyoto University

Outline

1.Introduction

2.Science objectives of WPIA on JUICE

3.Implementation to realize WPIA

4.Summary

Breakthrough driven by the WPIA

[Fukuhara et al., EPS 2009]

In Wave-Particle Interactions, the phase relation of waves and particle velocity vectors determines the energy flow direction

$$\frac{d}{dt}\left(\frac{1}{2}mV^2\right) = \boldsymbol{E}\bullet\boldsymbol{V} = q|\boldsymbol{E}||\boldsymbol{V}|\cos\theta \quad \begin{cases} C(t) = \dfrac{dK}{dt} = q\mathbf{E}(t)\cdot\mathbf{v}(t) \\ K = m_0c^2(\gamma - 1) \end{cases}$$

Energy flow balance ⇒ Particle ⇒ Waves / Waves ⇒ Particle

We need the time resolution enough to detect the above phase relation.

Plasma waves: **Success of the Wave-Form capture in Geotail**
Particle: **a particle pulse detection with a few usec accuracy will be achieved in the ERG mission**

New attempt for identifying the phase relation of waves and particles

Difference of the WPIA and conventional observations

Conventional

$$\frac{d}{dt}\left(\frac{1}{2}mV^2\right) = q|\mathbf{E}||\mathbf{V}|\cos\theta \;?$$

Plasma waves (waveform) — ? — Energy flow — particles (velocity distribution)

No phase information = No energy flow information

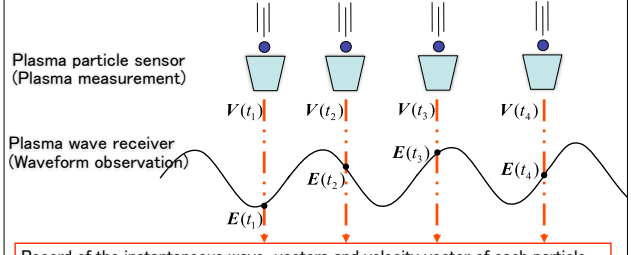
WPIA

$$\frac{d}{dt}\left(\frac{1}{2}mV^2\right) = q|\mathbf{E}||\mathbf{V}|\cos\theta$$

Plasma waves (waveform) — $\cos\theta > 0$ / Energy flow / $\cos\theta < 0$ — particle (in each particle)

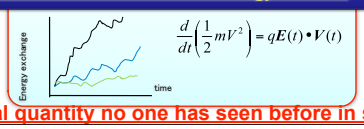
Detection of phase relation = Detection of energy flow

New measurement method – WPIA



Record of the instantaneous wave vectors and velocity vector of each particle

Possible direct measurement of energy transfer



Physical quantity no one has seen before in space

Representative algorithm of the S-WPIA

Waveform — 3 components selected among $E_1, E_2, E_3, B_1, B_2, B_3$ → FFT → Calibration → Band limited spectra → IFFT → Coordinate transformation ← Mag. Field (reference)

$$W(t) = \boldsymbol{E}(t)\cdot\boldsymbol{v}(t) \Rightarrow \sum W(t)$$

Particle — K, α, t → Coordinate transformation ← Mag. Field (reference)

Wave-Particle Interaction Analyzer
(WPIA)

- One-chip type WPIA (O-WPIA)
  - ✓ The algorithm is implemented inside the FPGA
  - ✓ The real time processing is realized.
- Software type WPIA (S-WPIA)
  - ✓ The algorithm is realized by the onboard software.
  - ✓ Difficulty in the real time processing
  - ✓ High flexibility in the data processing
  - ✓ Onboard the ERG satellite mission

ERG---Energization and Radiation in Geospace

Small satellite mission to Geospace

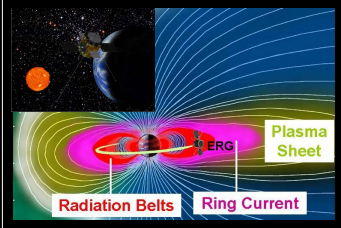
A mission to elucidate acceleration and loss mechanisms of relativistic electrons around Earth during space storms.

ERG mission will

- achieve comprehensive plasma observations with magnetic & electric field, wave, and particle detectors with a wide energy coverage (10eV~10MeV) to capture acceleration, transport, and loss of charged particles in Geospace
- establish plasma observatory under strong radiation environment.

- Launch: FY 2015
- Orbit :
  - apogee altitude 4.7Re / perigee altitude: 275km
  - inclination ≦31
  - spin-axis stabilized (sun oriented)
- Mission Life : > 1year
- Science Instruments:
  - PPE (Plasma/Particle)
    - electron detectors
      LEP-e: 12eV-20keV, MEP-e: 10-80keV
      HEP-e: 70keV-2MeV, XEP-e: 200keV-20MeV
    - ion detectors with mass discrimination
      LEP-i: 10eV-25keV, MEP-i: 5-180keV
  - PWE (DC Electric Field/Plasma Waves)
    - electric field (DC-10MHz)
    - magnetic field (1Hz- 500kHz)
  - MGF (DC Magnetic Field)

Software-type WPIA will be installed



ERG project office: ERG_adm@st4a.stelab.nagoya-u.ac.jp

Whistler-mode chorus

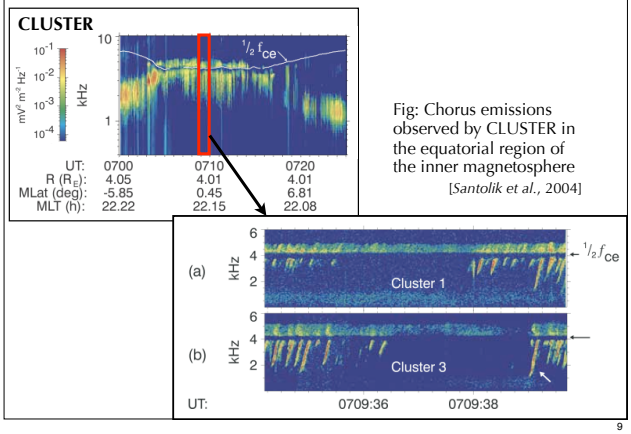
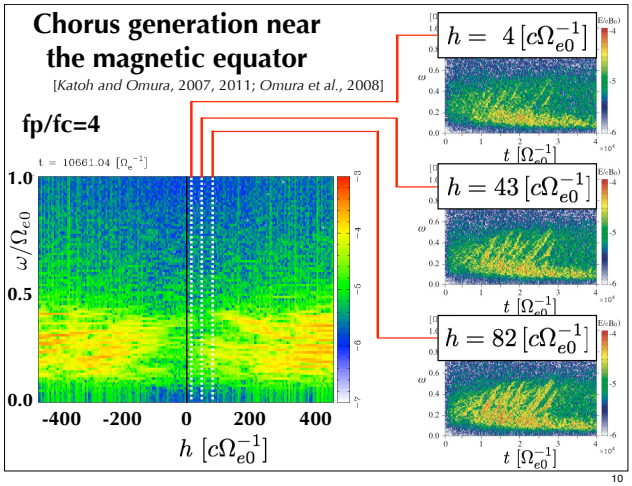


Fig: Chorus emissions observed by CLUSTER in the equatorial region of the inner magnetosphere
[*Santolik et al.*, 2004]

Chorus generation near the magnetic equator

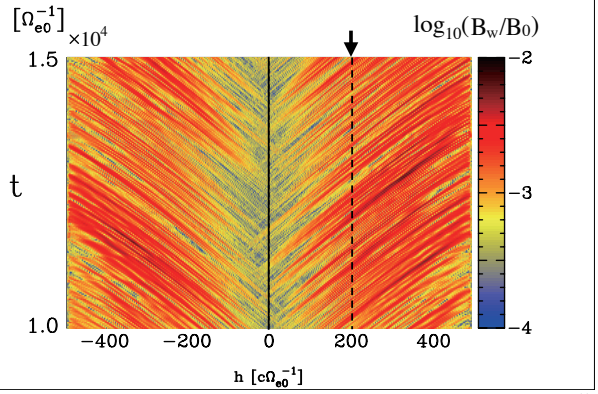
[*Katoh and Omura*, 2007, 2011; *Omura et al.*, 2008]

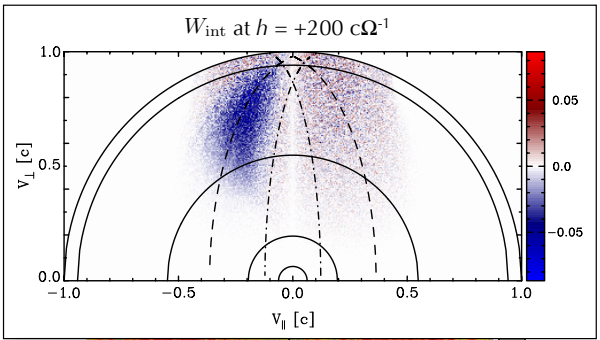
fp/fc=4



Pseudo-measurement of WPIA in the simulation results

[*Katoh et al.*, Ann. Geophys., 2013]

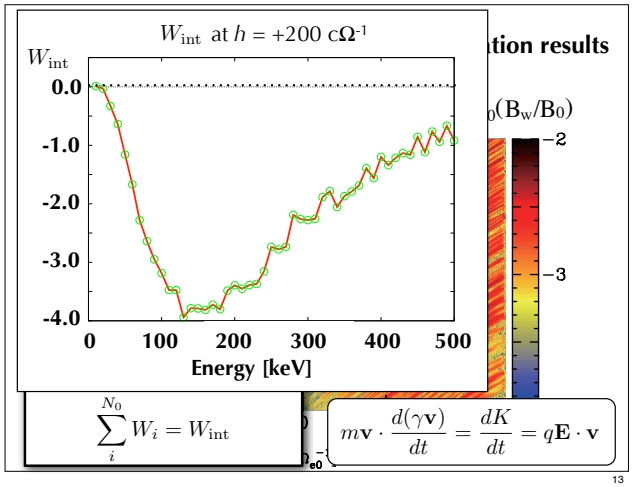




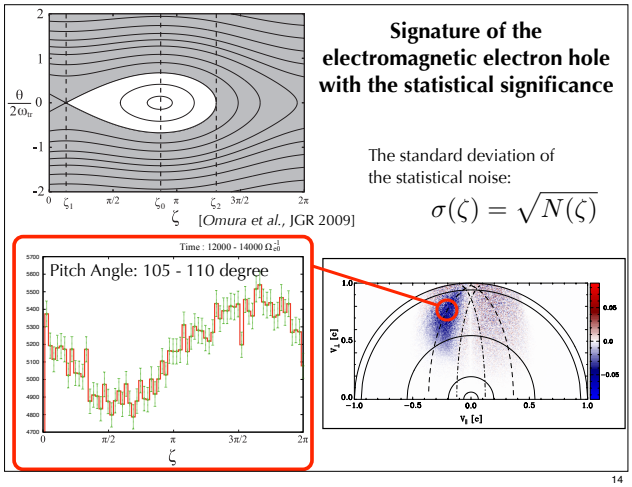
$$W(t) = q\mathbf{E}_W(t)\cdot\mathbf{v}(t)$$

$$\sum_i^{N_0} W_i = W_{\rm int}$$

$$m\mathbf{v}\cdot\frac{d(\gamma\mathbf{v})}{dt} = \frac{dK}{dt} = q\mathbf{E}\cdot\mathbf{v}$$



13



14

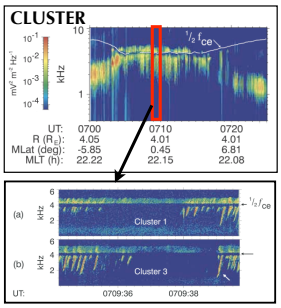
Science objectives of WPIA on JUICE

- Jovian chorus generation and relativistic electron acceleration
- Ion cyclotron waves around satellites: wave excitation and ion heating
- Interactions between Ion cyclotron waves and relativistic electrons

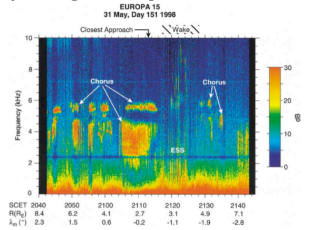
15

Objective 1: Chorus and relativistic electron acceleration

Chorus in planetary magnetospheres



Chorus emissions observed by CLUSTER in the equatorial region of the Earth's inner magnetosphere
[Santolik et al., GRL 2004]

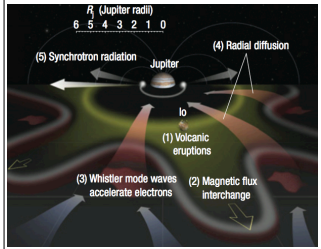


Chorus emissions observed by Galileo in the equatorial region of the Jovian inner magnetosphere
[Kurth et al., PSS 2001]

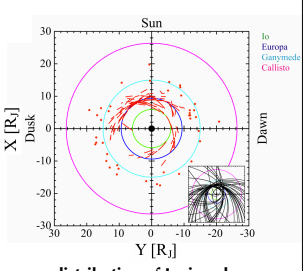
16

Objective 1: Chorus and relativistic electron acceleration

Acceleration of relativistic electrons by chorus in the Jovian inner magnetosphere



[Horne et al., Nature Phys. 2008]

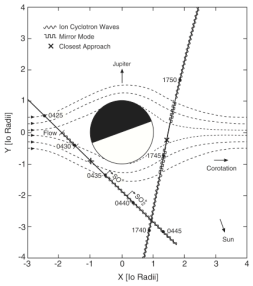


distribution of Jovian chorus
[Katoh et al., JGR 2011]

17

Objective 2: Ion cyclotron waves around satellites

Excitation of Ion cyclotron waves



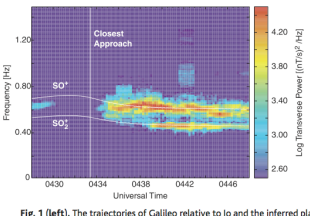
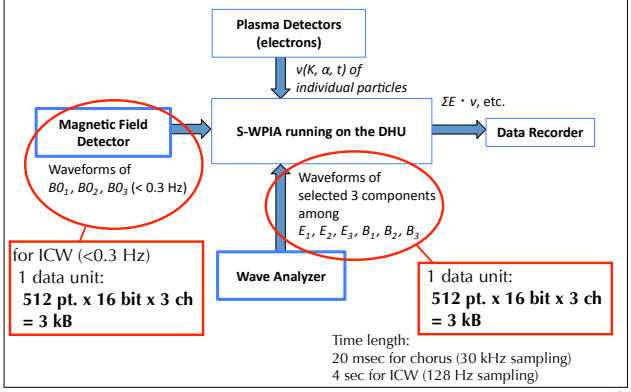


Fig. 1 (left). The trajectories of Galileo relative to Io and the inferred plasma flow on 7 December 1995 (labeled 1740 to 1750) and on 11 October 1999 (labeled 0425 to 0445). Sinusoids mark the presence of ion cyclotron waves, and square waves mark the presence of mirror mode waves (*14*). One Io radius is 1818 km. **Fig. 2 (right).** A dynamic spectrum showing the power spectral density of waves during the October 1999 Io flyby. Shown is the power in the derivative of the magnetic field in the direction transverse to the magnetic field. The analysis interval was 85.2 s in duration, and successive spectra are separated by 10.66 s. Spectral estimates have been averaged in bands of three frequencies to enhance statistical accuracy. The white lines are the gyrofrequencies of singly ionized SO and SO_2^+. The spectrum begins at the end of a 1-min data gap. There were no waves before this time.

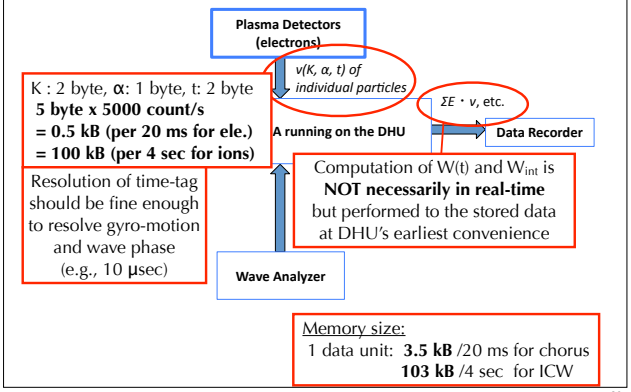
[Russell et al., Science 2000]

18

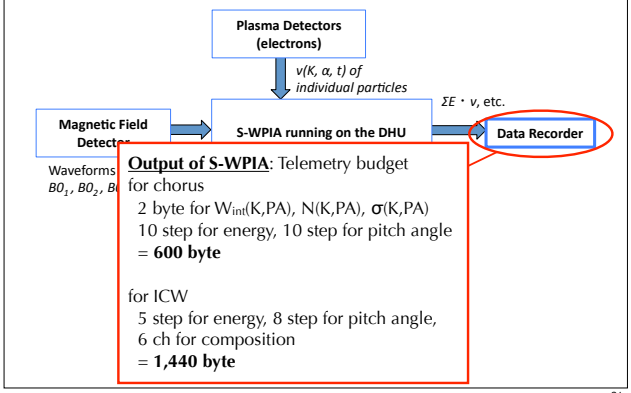
Necessary data interface of the S-WPIA on JUICE



Necessary data interface of the S-WPIA on JUICE



Necessary data interface of the S-WPIA on JUICE



Summary

- We studied the feasibility of the Wave-Particle Interaction Analyzer (WPIA) by using the simulation results reproducing chorus emissions
  - The present study clarified that the method of WPIA is useful to evaluate the energy exchange between waves and particles directly and quantitatively
  - Necessary time resolutions studied by the present study can be achieved by the state-of-the-art system of plasma instruments
- The WPIA measurements should be realized in the forthcoming missions (ERG, JUICE, ...).

References

- Fukuhara, H. *et al.*, *Earth Planets Space*, **61**, 765, 2009.
- Hospodarsky, G. B. *et al.*, *JGR*, **113**, A12206, doi:10.1029/2008JA013237, 2008.
- Horne, R. B. *et al.*, *Nature Phys.*, **4**, 301, doi:10.1038/nphys897, 2008.
- Katoh, Y. and Y. Omura, *GRL*, **34**, L03102, doi:10.1029/2006GL028594, 2007.
- Katoh, Y. and Y. Omura, *JGR*, **116**, A07201, doi:10.1029/2011JA016496, 2011.
- Katoh, Y. *et al.*, *JGR*, **116**, A02215, doi:10.1029/2010JA016183, 2011.
- Katoh, Y. *et al.*, *Ann. Geophys.*, **31**, 503, doi:10.5194/angeo-31-503-2013, 2013.
- Kurth, W. S. *et al.*, *Planet. Space Sci.*, 49, 345, 2001.
- Omura, Y. *et al.*, *JGR*, **113**, A04223, doi:10.1029/2007JA012622, 2008.
- Omura, Y. *et al.*, *JGR*, **114**, A07217, doi:10.1029/2009JA014206, 2009.
- Santolik, O. *et al.*, *GRL*, **31**, L02801, doi:10.1029/2003GL018757, 2004.
- Russell, C. T., and M. G. Kivelson, *Science*, **287**, 1998, 2000.