Feb. 7, 2018

H^+ and O^+ ion heating by ELF waves in the dayside cusp region

昼側カスプ領域におけるELF帯プラズマ波動による水素・酸素イオン加熱

宇宙地球電磁気学分野
博士課程前期2年　石ケ谷 侑季

論文審査委員
熊本　篤志　准教授（指導教員・主査）
小原　隆博　教授
笠羽　康正　教授
笠原　禎也　教授（金沢大・総合メディア基盤センター）
加藤　雄人　准教授

Contents

1. Introduction

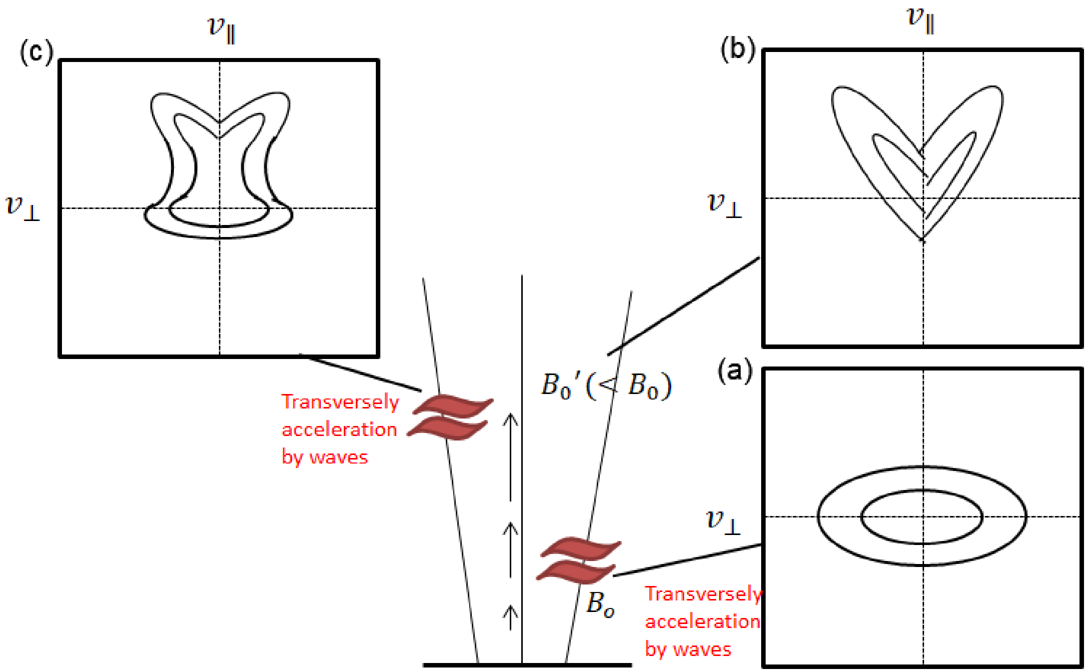
1.1 TAI and Ion Conics

Transversely Accelerated Ions –TAI

… Ions are heated transversely with respect to the geomagnetic field line by plasma waves

Ion conics

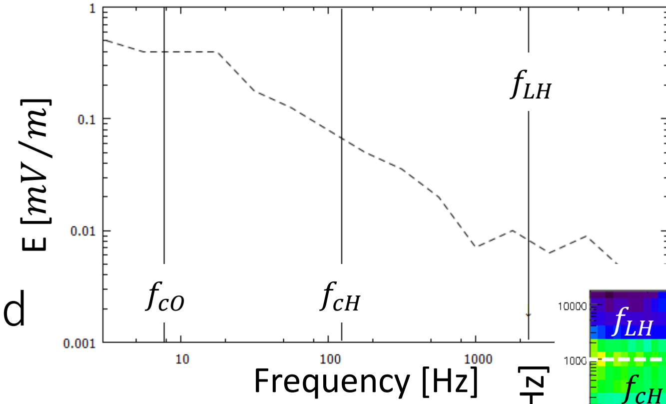
… Transverse energy of TAI converts into parallel energy due to the magnetic mirror force. As a result, conics distribution is formed.



$$\mu = \frac{W_\perp}{B} = \frac{mv_\perp^2}{2B}$$

$$W = W_\perp + W_\parallel$$

1.2 BBELF



Broadband ELF –BBELF

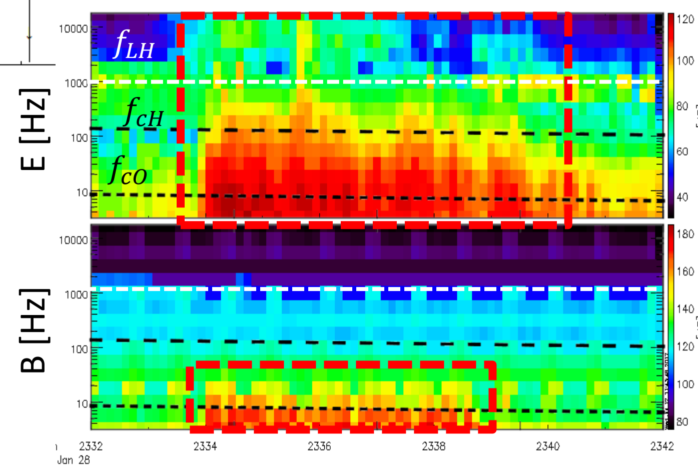
… Fluctuation of E field with a power law in frequency range from dc to f_{cH} or f_{LH}.

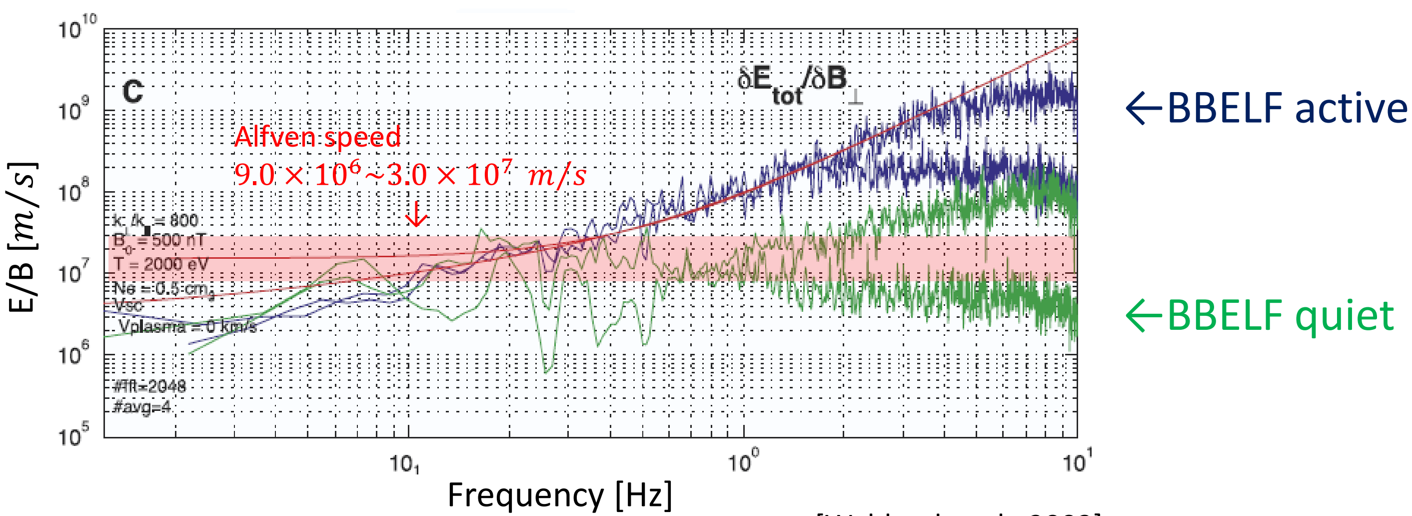
Electromagnetic components are also included in frequency range below f_{cO}.

-> Alfvenic components

satisfy $\delta E/\delta B \sim V_A$

[Wahlund et al., 2003; Chaston et al., 2004]





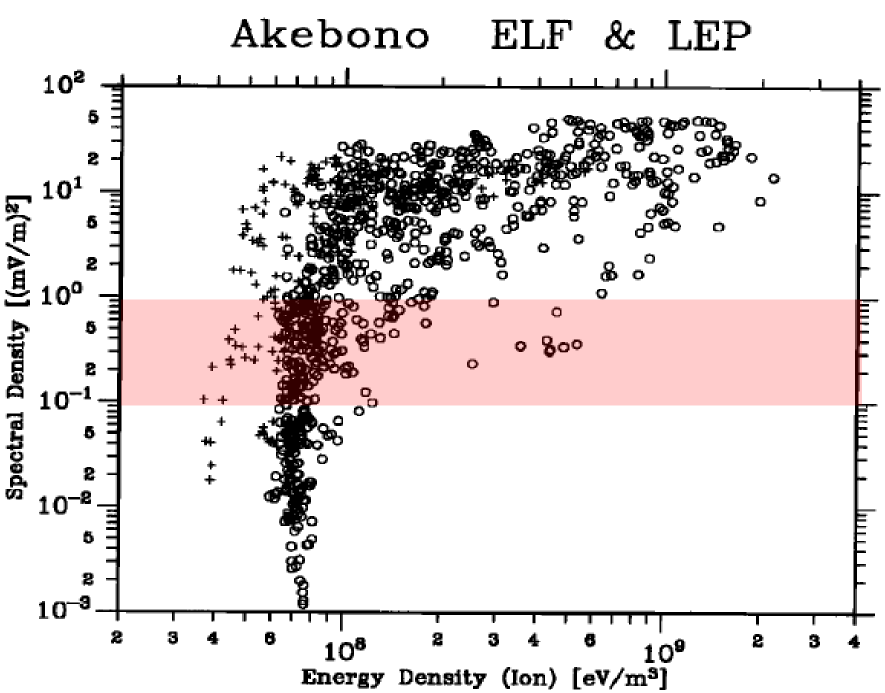
[Wahlund et al., 2003]

1.3 BBELF and Ion Heating

Kasahara et al., [2001]

◎Relation between E field spectral density of BBELF below 10 Hz and energy density of ions below 340 eV.

◎ Ions can be efficiently energized when wave spectral density is above a threshold level ($10^{-1} - 1(mV/m)^2$)



Singh et al., [2004; 2007]

2.5-D particle-in-cell simulations

Low frequency Alfvenic components

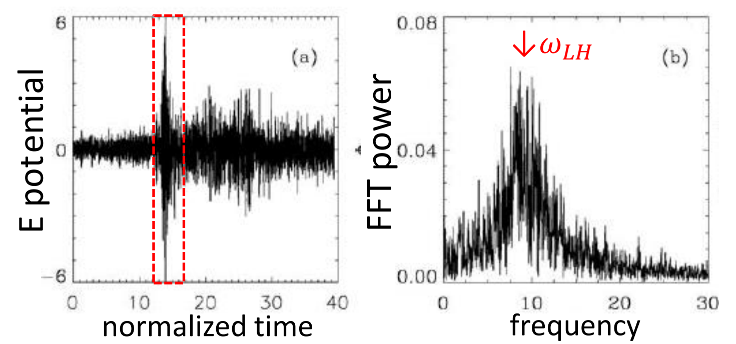
$$\downarrow v_y = \frac{\Omega_s^2}{\omega^2 - \Omega_s^2} \frac{E_x}{B_0} \sin(\omega t)$$

Polarization drift of ions

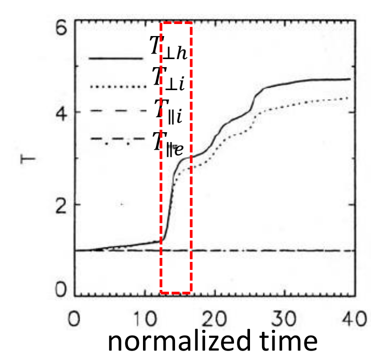
↓ Lower hybrid instability

Electrostatic wave enhancement

↓



Ion heating



1.4 Purpose of This Study

Motivation: **understanding ion heating processes by BBELF in the dayside cusp region**

◎**In statistical study**, we divided ion heating events into several groups by ion species, altitude and E/B ratio in a frequency range below f_{cO}.

◎**In event study**, we checked frequency spectra of E and B fields and E/B ratio, and we estimated polarization drift velocity.

Simulated by Singh et al., [2004; 2007]

Low frequency Alfvenic components below f_{cO}

↓

Ion drift

↓ **Instability**

Electrostatic wave enhancements
(lower hybrid mode near f_{LH},
ion cyclotron mode near f_{cH})

↓

Ion heating

correlation observed by Akebono satellite Kasahara et al., [2001]

2. Analysis Methods

2.1 Instruments

Akebono satellite

Operation period: February 1989 – April 2015

Apogee: 10500 km Perigee: 275 km

Inclination: 75 degree Orbital period: 211 minutes

-> We used data in period from January to June, 1990.

Instrument	data
ELF/VLF plasma wave [Kimura et al., 1990]	Plasma wave of ELF, VLF range (a few Hz - 17.8kHz)
Suprathermal Ion Mass Spectrometer (SMS) [Whalen et al., 1990]	Thermal (0~25.5eV) H^+ and O^+ ions at 4 energy steps (3.2, 5.4, 9.1, and 15.3V RPA energy) and at 16 spin angles.
Low Energy Particle (LEP) [Mukai et al., 1990]	13eV/q~20keV/q upward, downward and perpendicular ions
Plasma waves and Sounder experiments (PWS) [Oya et al., 1990]	Plasma wave of VLF-HF range (20 kHz -5.12MHz) electron number density estimated from upper hybrid frequency

N_s, T_s, v_{s0}, satellite potential: provided by Dr. Yamada [Watanabe et al., 1992]

2.2. Event criteria

We follow the following criteria and select data.

i. Dayside cusp region (10-14 MLT, ILAT 65-80 degree)
ii. The sum of ion counts of all channels of SMS enhance.
iii. Increase of E or B field intensity below oxygen gyrofrequency from about 1 hour average is more than 2 σ .
iv. Both ii and iii criteria of SMS and MCA are simultaneously satisfied.

	H^+	O^+
Event number	223	206

Classification of selected heating events

Altitude Above 7000 km ($H^+\cdots$83, $O^+\cdots$87)
below 7000 km ($H^+\cdots$140, $O^+\cdots$119)

E/B ratio in frequency range below f_{cO}

$E/B > V_A$ → ES type events
$E/B \leq V_A$ → EM type events

3. Statistical Study

3.1 Results

E field spectral density $\geq 1.0\ (mV/m)^2$

- Most ion heating events occur
- Some ions are not effectively heated

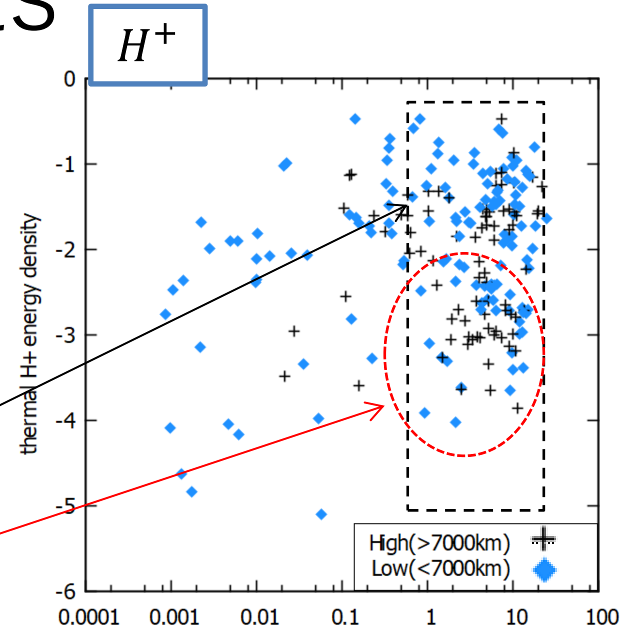
$H^+ < 10^{-2}\ eV/m^3$

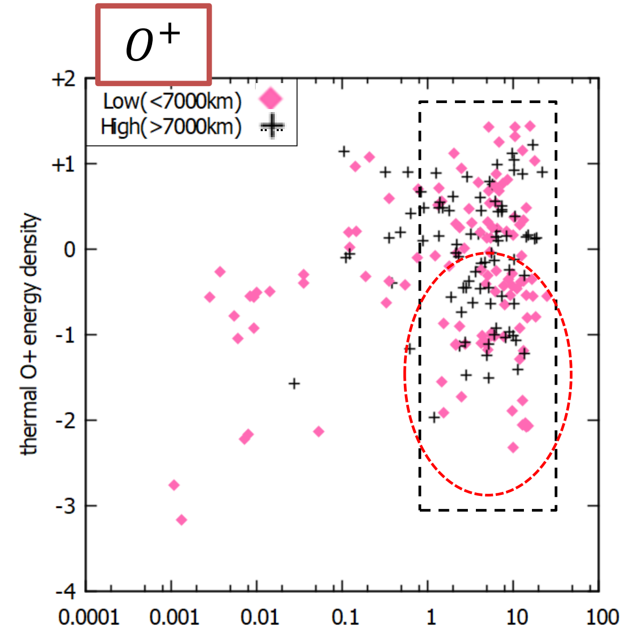
$O^+ < 1.0\ eV/m^3$

H^+ vs. O^+, EM vs. ES, >7000km vs. <7000km

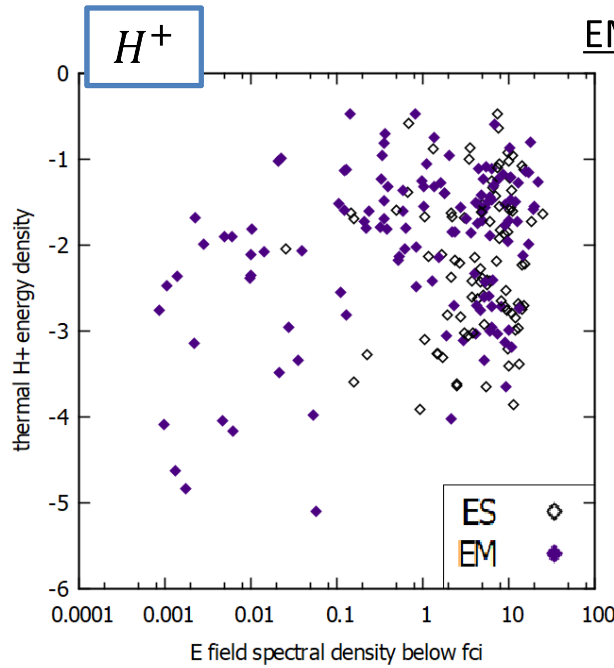
No clear difference

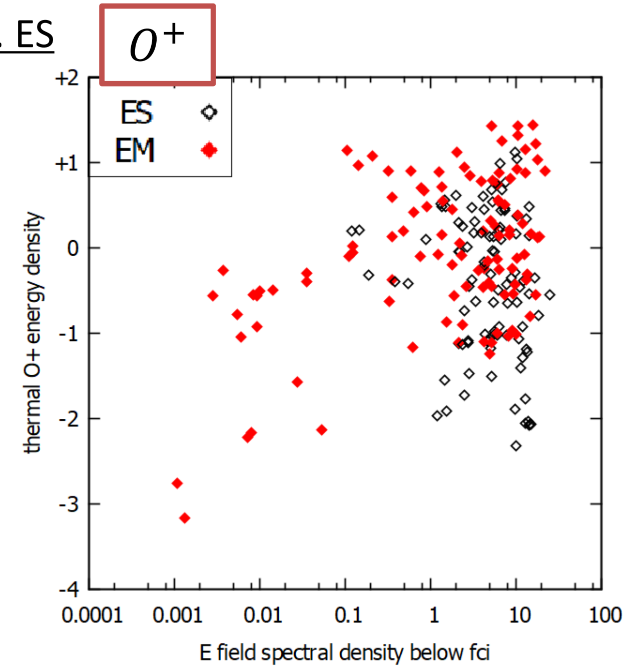
High altitude vs. low altitude





EM vs. ES





3.2 Summary and Discussion

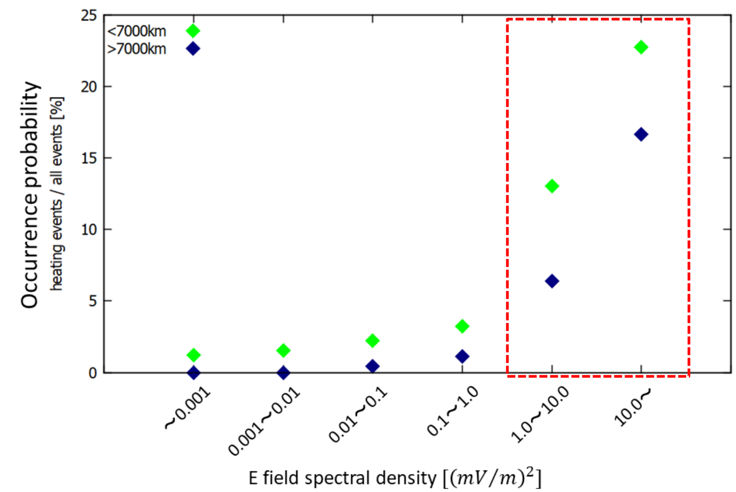
◎H^+ vs. O^+ / EM vs. ES

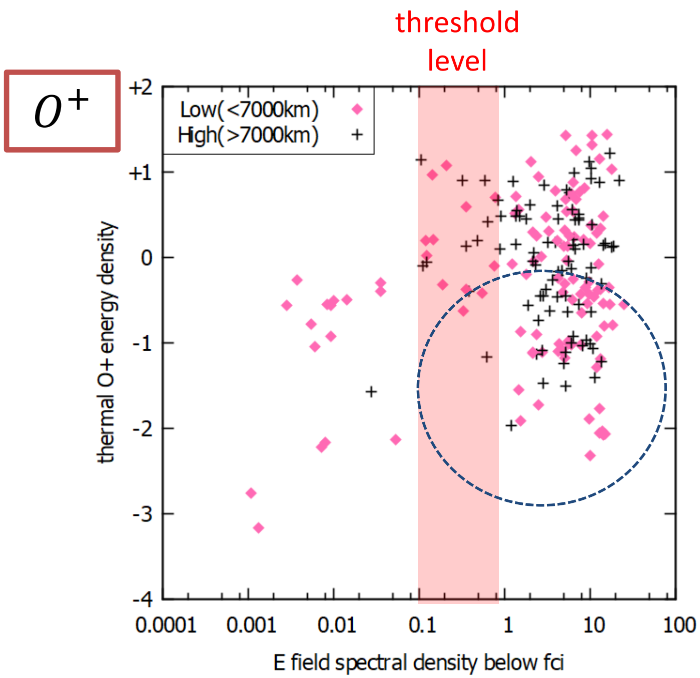
-> no clear difference

◎At high altitude (>7000 km), occurrence probability is low

ions are not effectively heated at high altitude

$$(Occurence\ probability) = \frac{(heating\ event\ number)}{(All\ event\ number)}$$





◎Most ion heating events occurred when E field spectral density was $\geq 1.0\ (mV/m)^2$

-> threshold level is $10^{-1} - 1\ (mV/m)^2$

consistent with Kasahara et al., [2001]

◎E field intensity was above threshold level but some ions are not effectively heated

-> What makes the threshold level?

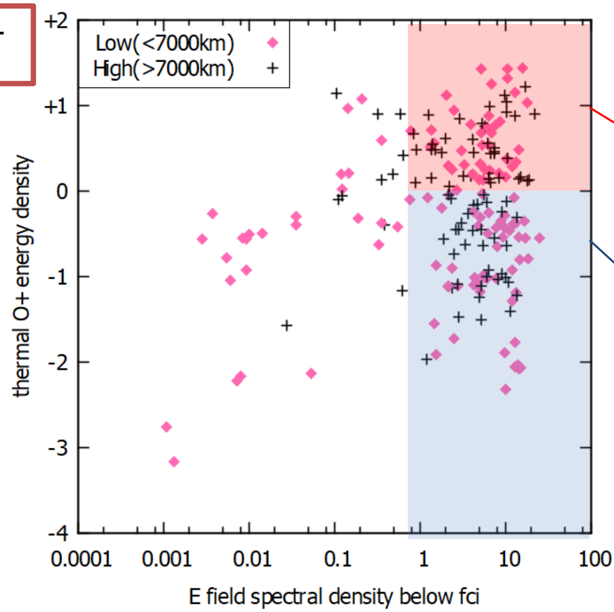
Why ions were not effectively heated?

event study

4. Event Study

4.1 Event study

O^+



six typical events in which E field spectral density below f_{cO} is $> 1.0\ (mV/m)^2$

Event 1, 2, 5
-> Strong heating events

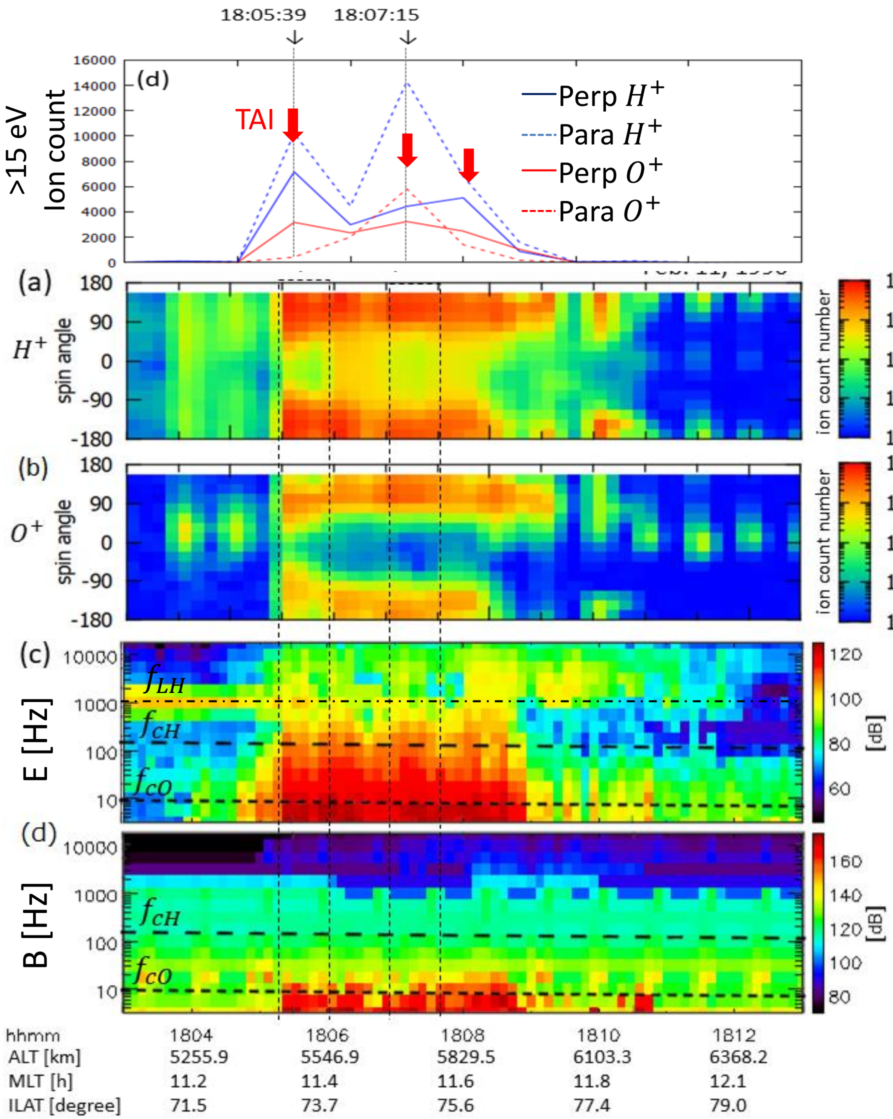
Event 3, 4, 6
-> Weak heating event

Event No	Max energy density $[eV/m^3]$	
	H^+	O^+
1	1.58×10^{-1}	10.6
2	6.96×10^{-2}	16.6
3	3.77×10^{-3}	8.06×10^{-1}
4	6.96×10^{-2}	5.71×10^{-1}
5	1.31×10^{-1}	5.75
6	1.60×10^{-3}	9.21×10^{-2}

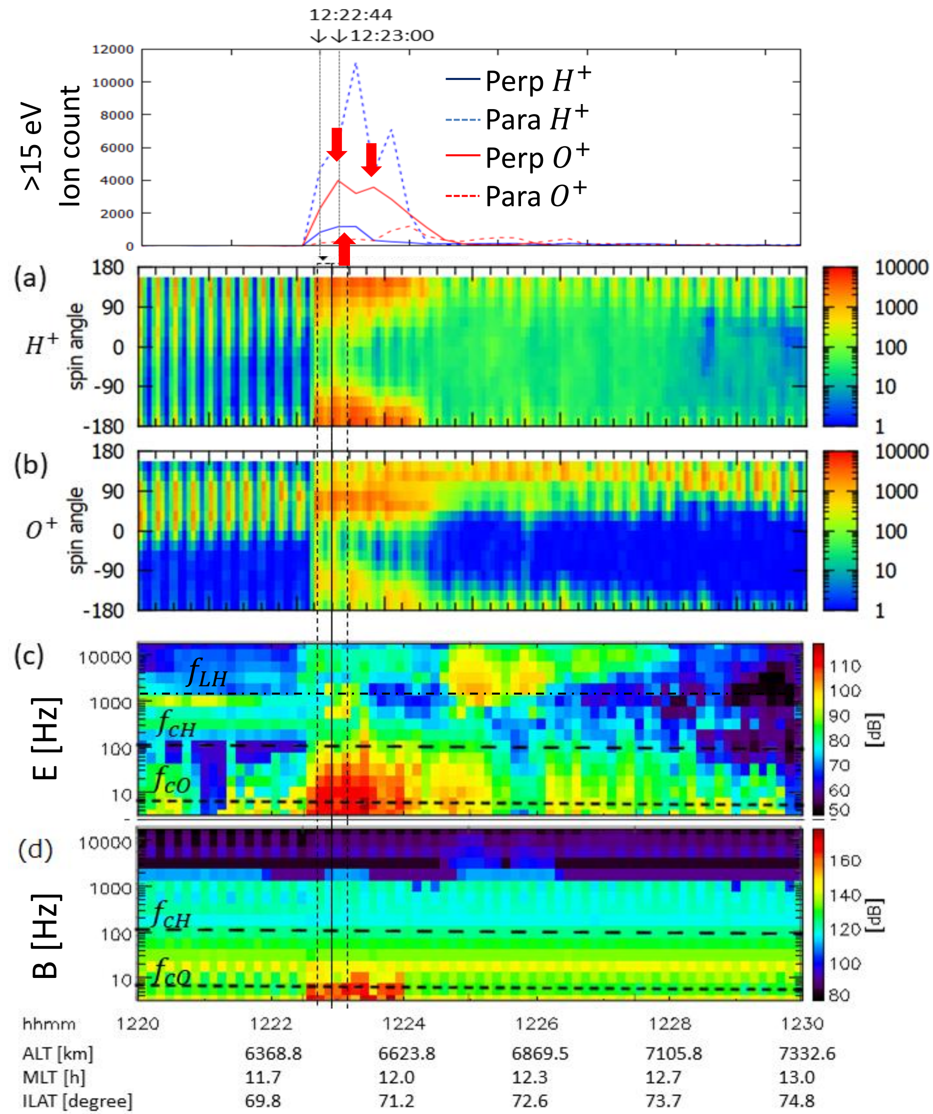
4.2 Result

Events selected in statistical study

Event 1 –Strong heating event

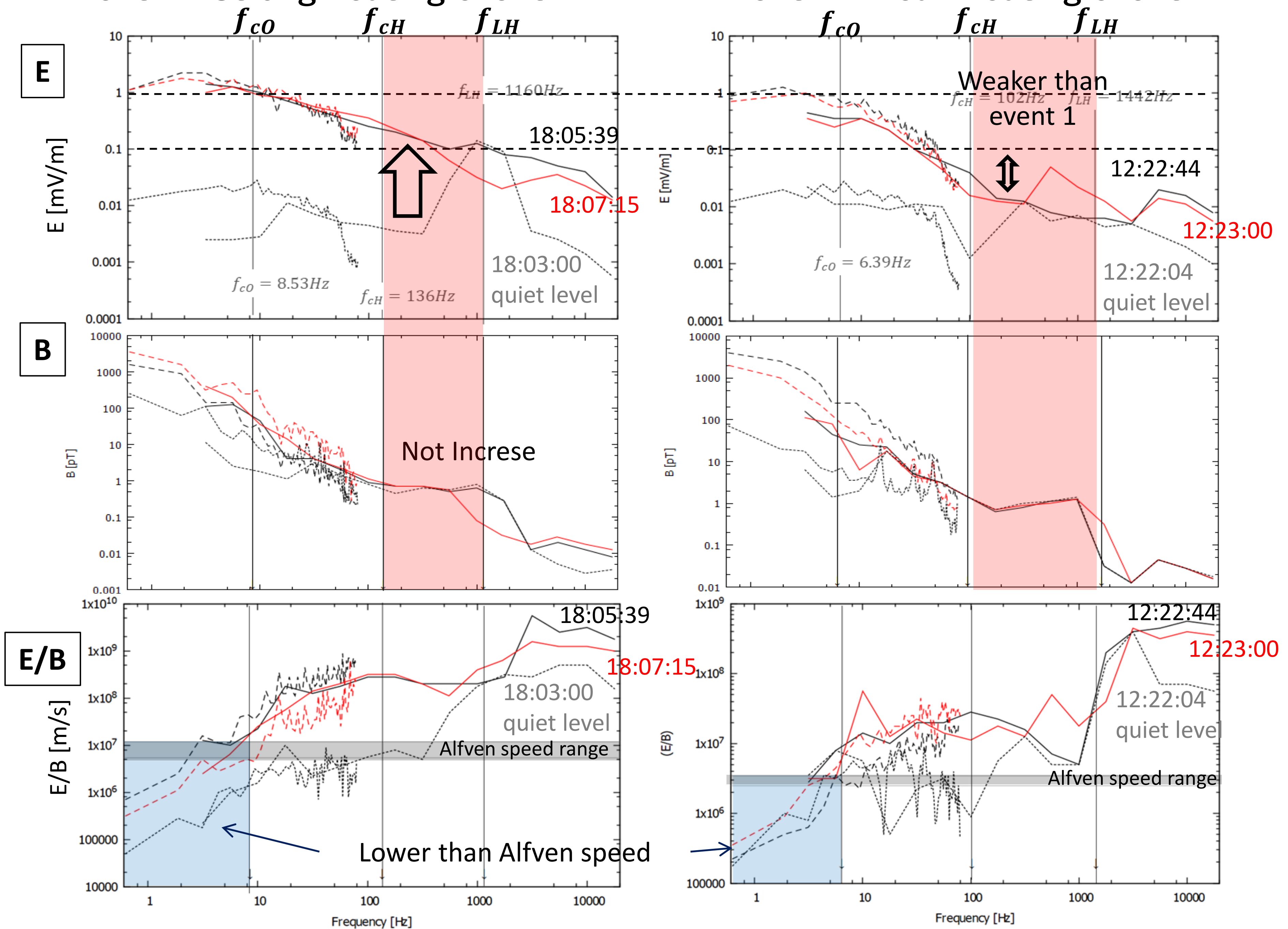


Event 4 –Weak heating event



Event 1 –Strong heating event

Event 4 –Weak heating event



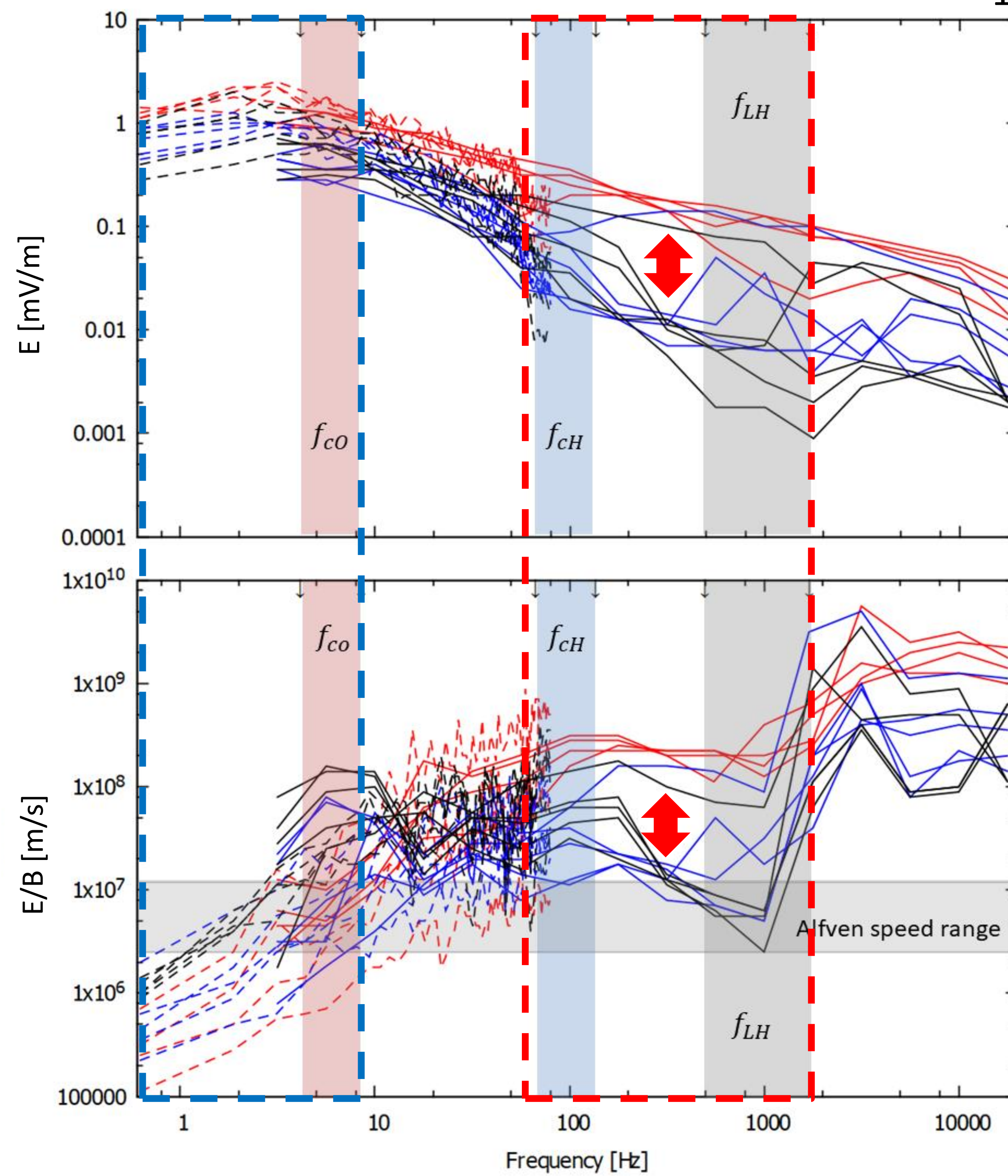
Event 1, Event 2

Event 3, Event 4

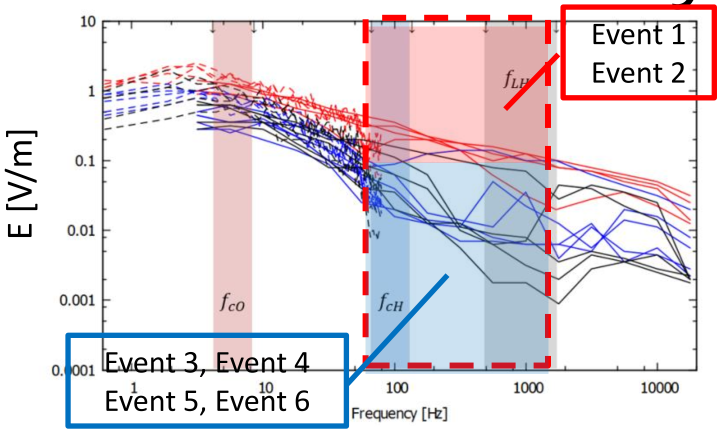
Event 5, Event 6

below f_{co}
No clear difference

from f_{cH} to f_{LH}
There is a gap between red curves and others.



4.3 Summary and Discussion



◎Frequency spectra of E field and E/B ratio are difference from f_{cH} to f_{LH} at all selected time

E field >0.1 mV/m

E/B ratio $> 10^8$ m/s

in frequency range from f_{cH} to f_{LH}

-> strong LH events (Event 1, Event 2)

◎Event 1, Event 2

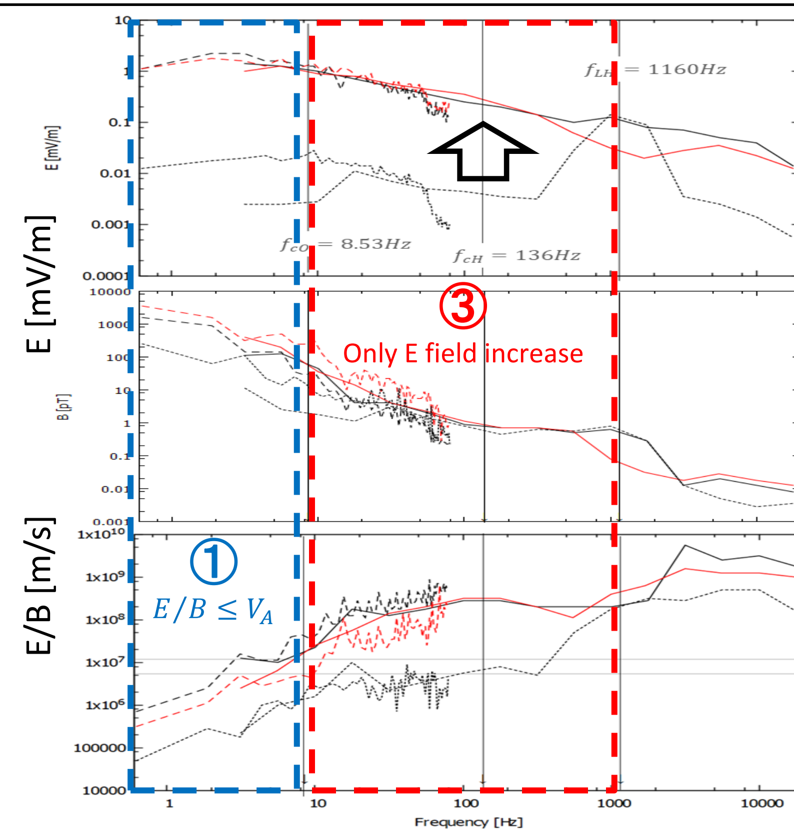
Low frequency Alfvenic components below f_{cO} ①

Ion drift — O^+ drift velocity is higher than O^+ thermal velocity

Electrostatic wave enhancements (lower hybrid mode near f_{LH}, ion cyclotron mode near f_{cH}) ③

Ion heating — Ion energy density is higher than other events

-> support Singh et al., [2004; 2007]



5. Conclusion

In order to understand ion heating processes by BBELF in the dayside cusp region, we performed and suggested following.

◎We divided ion heating events into several groups by ion species, altitude and E/B ratio in a frequency range below f_{cO} and statistical studies of ion energy density as a function of electric field spectral density below f_{cO} of BBELF were performed.

H^+ vs. O^+, EM vs. ES types -> no clear difference

>7000km vs. <7000km -> ions were effectively heated at low altitude.

a threshold level of effective ion heating -> 10^{-1} to $1\ (mV/m)^2$

consistent with Kasahara et al.,[2001]

◎We performed event study of six events in which E field spectral density of BBELF below f_{cO} was above $1.0\ (mV/m)^2$

frequency spectra of E field and E/B ratio

below f_{cO} -> no clear difference

from f_{cH} to f_{LH} -> divide into two types

We suggest that further statistical studies using the categorization based on E field intensity and E/B ratio in frequency range from f_{cH} to f_{LH} will be important to understand ion heating by ion cyclotron waves and LH waves.

Reference

- Kasahara Y., T. Hosoda, T. Mukai, S. Watanabe, I. Kimura, H. Kojima, and R. Niitsu, ELF/VLF waves correlated with transversely accelerated ions in the auroral region observed by Akebono, *J. Geophys. Res.,* Vol. 106, No. A10, 21, 123-21, 136, 2001.
- Khazanov G. V., E . N. Krivorutsk, T. E. Moore, M. W. Liemohn and J. L. subjected to ion cyclotron waves, *J. Geophys. Res.,* Vol. 102, No. A1, 175-184, 1997.
- Kimura, I., K. Hashimoto, I. Nagano, T. Okada, M. Yamamoto, T. Yoshino, H. Matsumoto, M. Ejiri, and K. Hayashi, VLF observations by the Akebono (EXOS-D) satellite, *J. Geomagn. Geoelectr.*, 42, 459-478, 1990.
- Mukai, T., N. Kaya, E. Sagawa, M. Hirahara, W. Miyake, T. Obara, H. Miyaoka, S. Machida, H. Yamagishi, M. Ejiri, H. Matsumoto, and T. Itoh, Low energy charged particle observations in the "Auroral" Magnetosphere: First results from the Akebono (EXOS-D) satellite, *J. Geomag. Geoelectr.*, 42, 479-496, 1990.
- Oya H. and K. Tsuruda, Introduction to the Akebono (EXOS-D) satellite observations, *J. Geomag. Geoelectr.,* 42, 367-370, 1990.
- Oya H., A. Morioka, K. Kobayashi, M. Iizima, T. Ono, H. Miyaoka, T. Okada and T. Obara, Plasma wave observation and sounder experiments (PWS) using Akebono (EXOS-D) satellite –Instrument and initial results including discovery of high altitude equatorial plasma turbulence, *J. Geomag. Geoelectr.*, 42, 411-442, 1990.
- Scales W. A. and P.M. Kintner, Artificial ion beam instabilities 1. Linear theory, *J. Geophys. Res.,* Vol. 95, No. A7, 10,623-10,641, 1990.
- Singh N. and G. Khazanov, Numerical simulation of waves driven by plasma currents generated by low-frequency Alfve ́n waves in a multi-ion plasma, *J. Geophys, Res.*, Vol. 109, A05210, doi:10.1029/2003JA010251, 2004.
- Singh N., G. Khazanov and A. Mulhter, Electrostatic wave generation and transverse ion acceleration by Alfvenic wave components of broadband extremely low frequency turbulence, *J. Geophys, Res.*, Vol. 112, A06210, doi:10.1029/2006JA011933, 2007.
- Wahlund J.-E., A. Yilmaz, M. Backrud, D. Sundkvist, A. Vaivads, D. Winningham, M. Andre, A. Balogh, J. Bonnell, S. Buchert, T. Carozzi, N. Cornilleau, M. Dunlop, A. I. Eriksson, A. Fazakerley, G. Gustafsson, M. Parrot, P. Robert, and A. Tjulin, Observations of auroral broadband emissions by CLUSTER, *Geophys. Res. Lett.,* Vol. 30, No. 11, 1563, soi:10.1029/2002GL016335, 2003.
- Watanabe S., B. A. Whalen, and A. W. Yau, Thermal Ion Observations of Depletion and Refilling in the Plasmaspheric Trough, *J. Geophys. Res.,* Vol. 97, No. A2, 1081-1096, 1992.
- Whalen, B. A., J. R. Burrows, A. W. Yau, E. E. Budzinski, A. M. Pilon, I. Iwamoto, K. Marubashi, S. Watanabe, H. Mori, and E. Sagawa, The Suprathermal Ion Mass Spectrometer (SMS) onboard the Akebono (EXOS-D) satellite, *J. Geomag. Geoelectr.*, 42, 511-536, 1990.

A1. Calculation

$$(\text{energy density}) = \sum_i^4 n_i E_i = \sum_i^4 n_i \sqrt{E_n + E_s} \quad (3)$$

We assumed a drifting Maxwell distribution f_s and estimated n_i

$$f_s(v) = N_s \left(\frac{1}{2\pi k_B T_s}\right)^{\frac{3}{2}} \exp\left(\frac{m_s (v - v_{s0})^2}{2 k_B T_s}\right) \quad (4)$$

$$n_i = \int_{v_i}^{v_{i+1}} f_s(v) dv \quad (5)$$

E_s: satellite potential, s: ion species, m_s: mass of a ion.

N_s, T_s, v_{s0}: density, temperature and bulk velocity of a ion

We used N_s, T_s, v_{s0} provided by Dr. Yamada [Watanabe et al., 1992].

The method of Watanabe et al., [1992] can be applied only drifting cold ions. Therefore, in some events selected in this study, we used A_i (Eq.) and satellite potential at the closest time to the time of selected events.

$$C_i = A_i n_i v_i = A_i n_i \sqrt{E_i} = A_i n_i \sqrt{E_n + E_s} \quad (6)$$

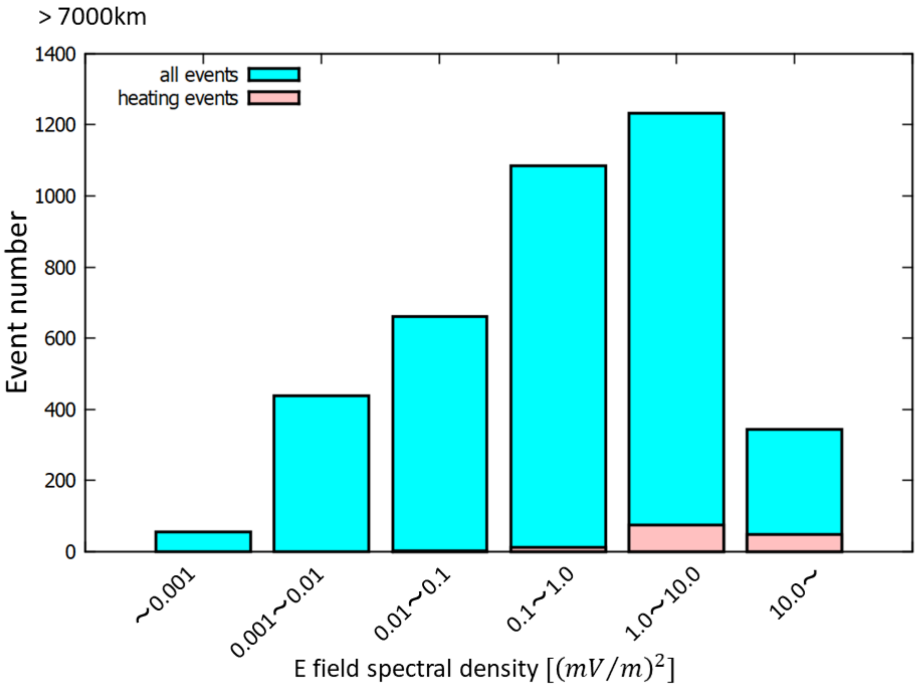
A2. Polarization Drift

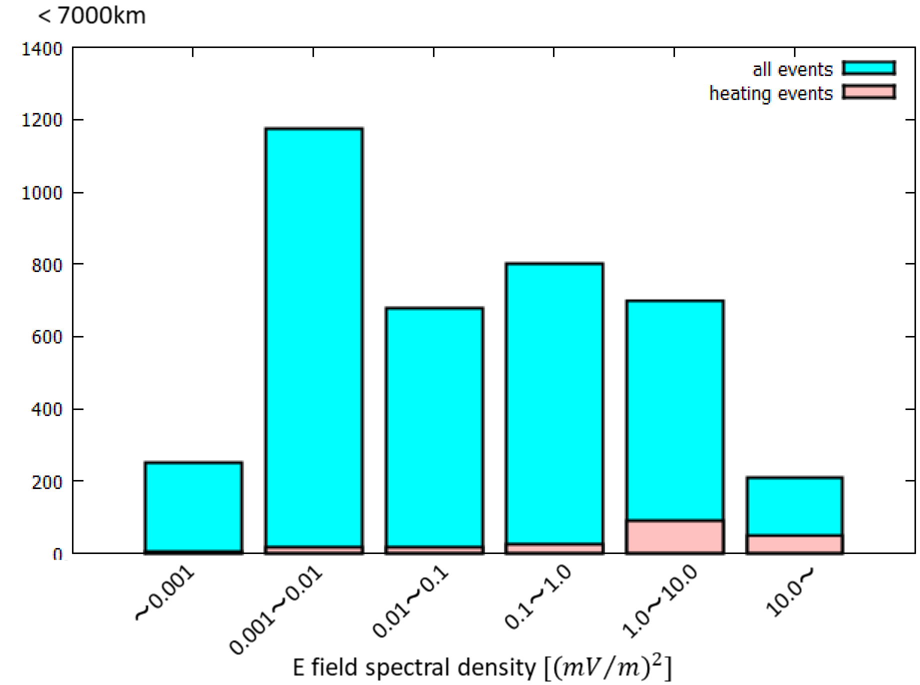
$$m_s \frac{d\boldsymbol{v}}{dt} = q\boldsymbol{E} + \mathrm{q}\boldsymbol{v} \times \boldsymbol{B_0}$$

$$\boldsymbol{B_0} = B_0 \boldsymbol{e_x}\,, \boldsymbol{E} = \sum_{\omega=0}^{\omega \leq \Omega_O} E_x \sin(\omega t)\, \boldsymbol{e_x}$$

$$Polarization\ drift\ velocity\!: \quad v_y = \sum_{\omega=0}^{\omega \leq \Omega_O} \frac{\Omega_s^2}{\omega^2 - \Omega_s^2} \frac{E_x}{B_0} \sin(\omega t)$$

Event number / Day	UT	polarization velocity [km/s]			Thermal velocity [km/s]		Bulk velocity [km/s]	
		H^+	O^+	relative	H^+	O^+	H^+	O^+
Feb.11 Event 1	18:05;39	0.049	2.93	2.88	29.4	6.09	15.4	6.26
	18:07:15	0.05	9.14	9.09				
Mar. 6 Event 2	14:06:20	0.069	13.7	13.6	33.9	7.33	18.6	9.13
	14:07:56	0.066	7.56	7.49				
Feb.17 Event 3	3:45:56	0.038	2.21	2.16	23.2	6.86	13.0	5.82
	3:47:48	0.043	2.22	2.2				
	3:48:52	0.022	1.02	1.0				
Feb. 25 Event 4	12:22:44	0.035	1.87	1.84	24.2	4.78	11.0	5.15
	12:23:00	0.029	1.45	1.42				
Event 5	15:49:32	0.05	2.62	2.57	30.3	7.07	21.4	2.27
	15:51:08	0.022	1.48	1.46				
	15:51:24	0.03	1.7	1.67				
Mar. 2 Event 6	14:54:04	0.024	2.56	2.54	57.7	14.1	12.5	4.44
	14:54:44	0.04	4.04	4.0				



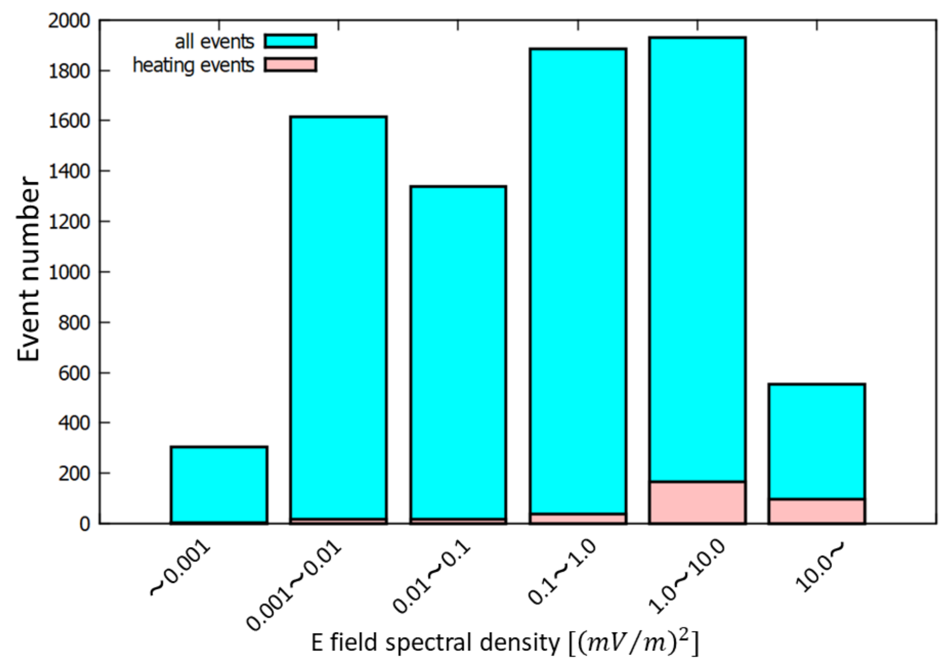


High altitude >7000 km

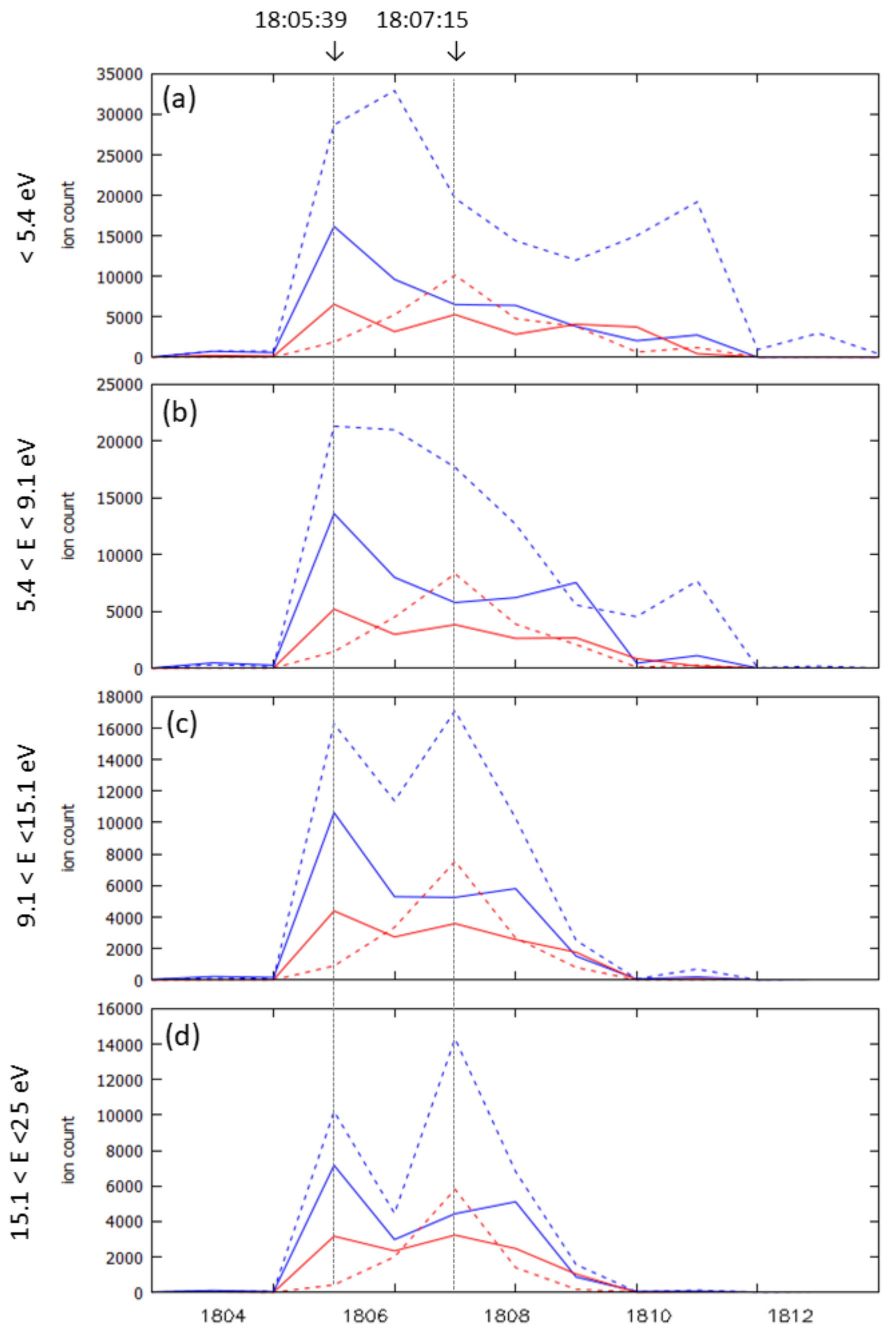
	~0.001	0.001 ~0.01	0.01 ~0.1	0.1 ~1.0	1.0 ~10.0	10.0~	total
All events	56	439	672	1084	1233	392	3876
Heating events	0	0	3	12	74	0	89

Low altitude <7000 km

	~0.001	0.001 ~0.01	0.01 ~0.1	0.1 ~1.0	1.0 ~10.0	10.0~	Total
All events	249	1176	678	802	697	211	3602
Heating events	3	18	15	26	91	48	201



Event 1 –Strong heating event



Event 4 –Weak heating event