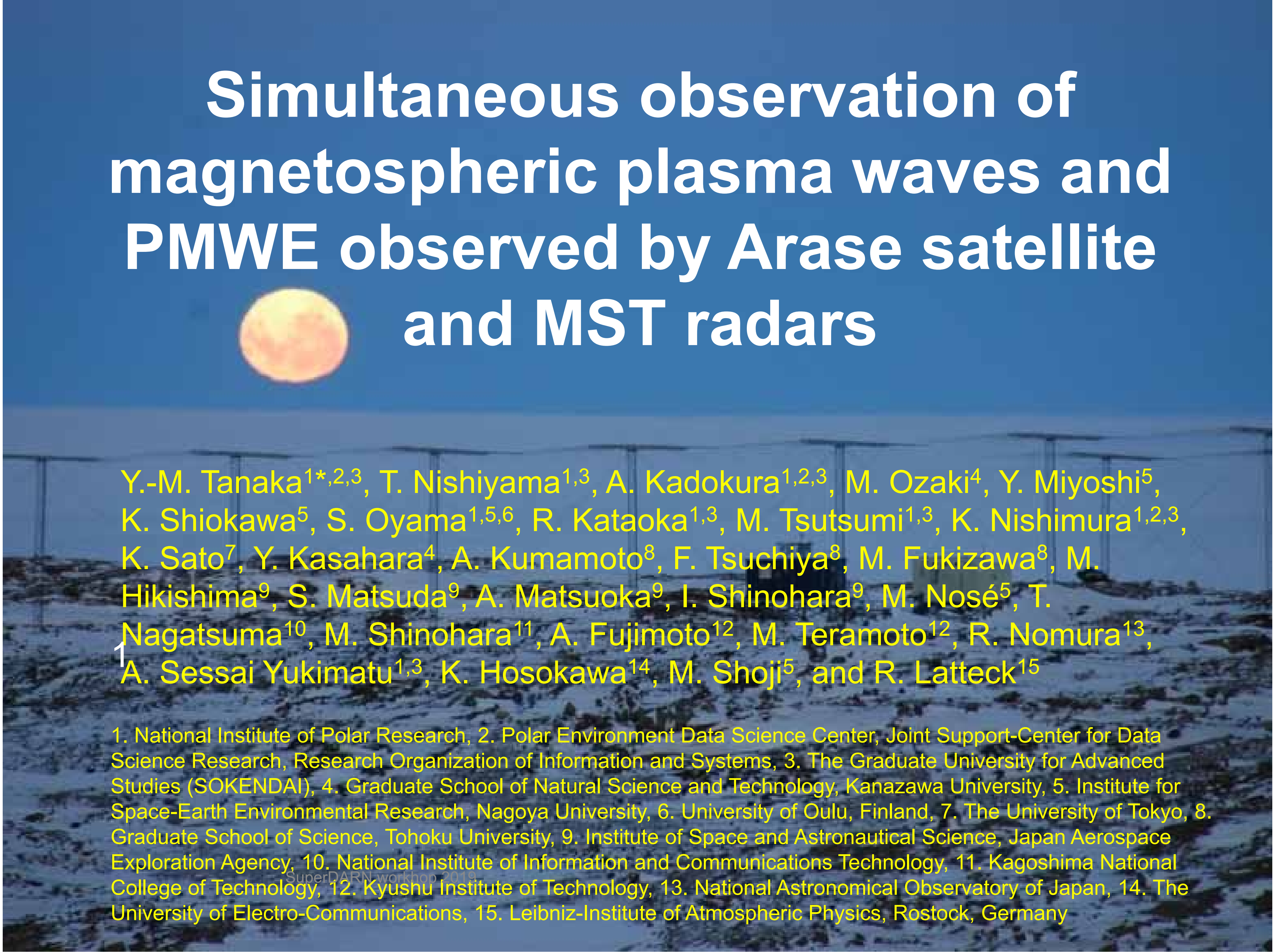


Simultaneous observation of magnetospheric plasma waves and PMWE observed by Arase satellite and MST radars

Y.-M. Tanaka[1*,2,3], T. Nishiyama[1,3], A. Kadokura[1,2,3], M. Ozaki[4], Y. Miyoshi[5], K. Shiokawa[5], S. Oyama[1,5,6], R. Kataoka[1,3], M. Tsutsumi[1,3], K. Nishimura[1,2,3], K. Sato[7], Y. Kasahara[4], A. Kumamoto[8], F. Tsuchiya[8], M. Fukizawa[8], M. Hikishima[9], S. Matsuda[9], A. Matsuoka[9], I. Shinohara[9], M. Nosé[5], T. Nagatsuma[10], M. Shinohara[11], A. Fujimoto[12], M. Teramoto[12], R. Nomura[13], A. Sessai Yukimatu[1,3], K. Hosokawa[14], M. Shoji[5], and R. Latteck[15]

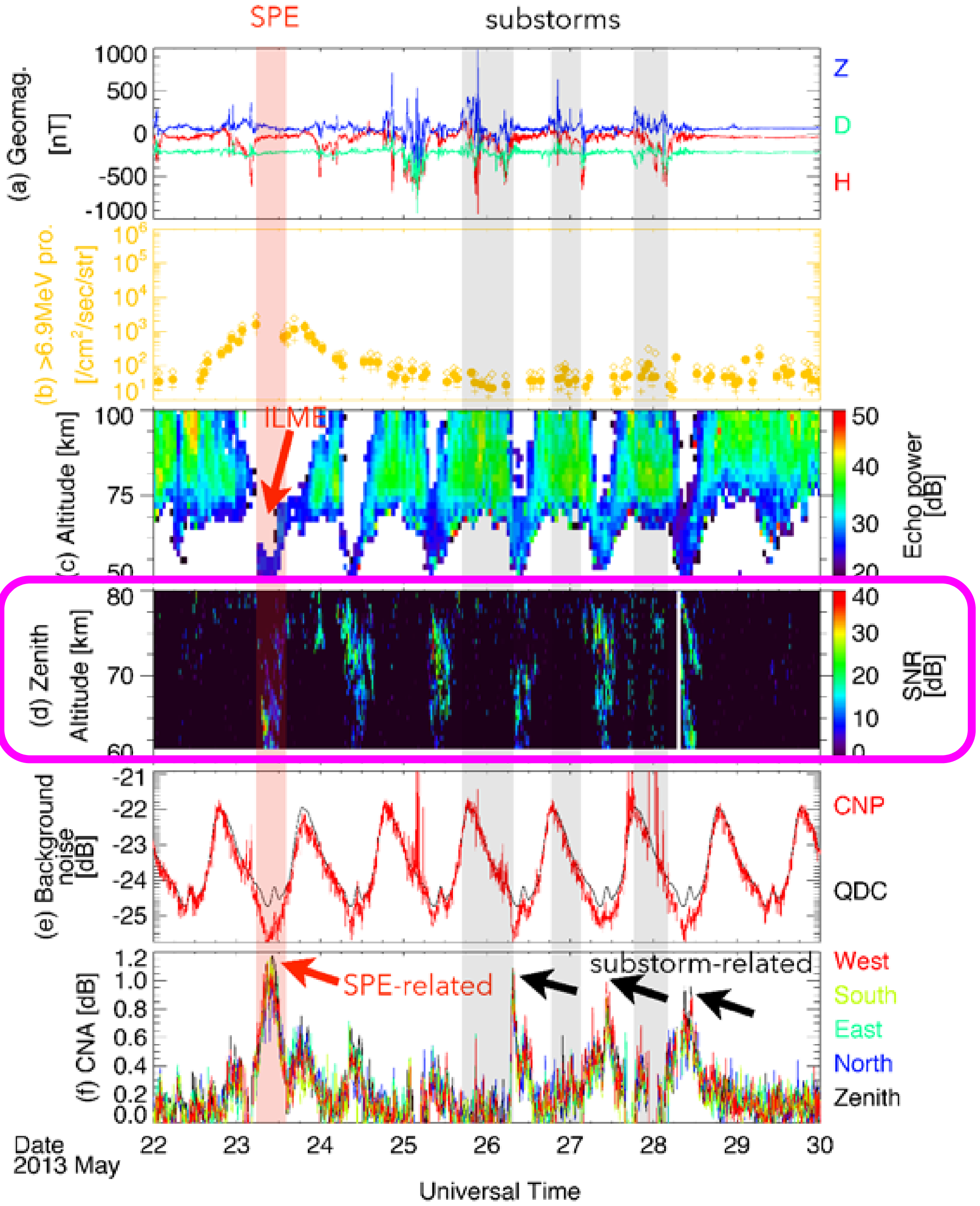
1. National Institute of Polar Research, 2. Polar Environment Data Science Center, Joint Support-Center for Data Science Research, Research Organization of Information and Systems, 3. The Graduate University for Advanced Studies (SOKENDAI), 4. Graduate School of Natural Science and Technology, Kanazawa University, 5. Institute for Space-Earth Environmental Research, Nagoya University, 6. University of Oulu, Finland, 7. The University of Tokyo, 8. Graduate School of Science, Tohoku University, 9. Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 10. National Institute of Information and Communications Technology, 11. Kagoshima National College of Technology, 12. Kyushu Institute of Technology, 13. National Astronomical Observatory of Japan, 14. The University of Electro-Communications, 15. Leibniz-Institute of Atmospheric Physics, Rostock, Germany

Introduction

- Energetic electron precipitation (EEP) during geomagnetic disturbances plays a key role in coupling between near-Earth space and the polar atmosphere.
- In particular, special attention has been paid to the precipitation of relativistic electrons with $E > 500$ keV, which can reach low altitude < 70 km.
- They increase concentrations of nitric oxides (NO_x) and hydrogen oxides (HO_x), which deplete the ozone in the mesosphere, and also even in the stratosphere through catalytic cycles directly or indirectly after downward transport during the polar winter.

Polar Mesosphere Winter Echoes (PMWE)

- Observed by VHF radars at high latitude during the winter months.
- Mainly observed in the daytime.
- One of the important factors causing the PMWE is neutral turbulence in the mesosphere, induced by wind shear or associated with breaking of atmospheric gravity waves (e.g., Czechowsky et al., 1989; Lübken et al., 2006).
- The other factor is the electron density enhancement in the mesosphere due to energetic proton precipitation during solar proton event (SPE; Kirkwood et al., 2002) or **energetic electron precipitation (EEP)** during substorms (Nishiyama et al., 2018).

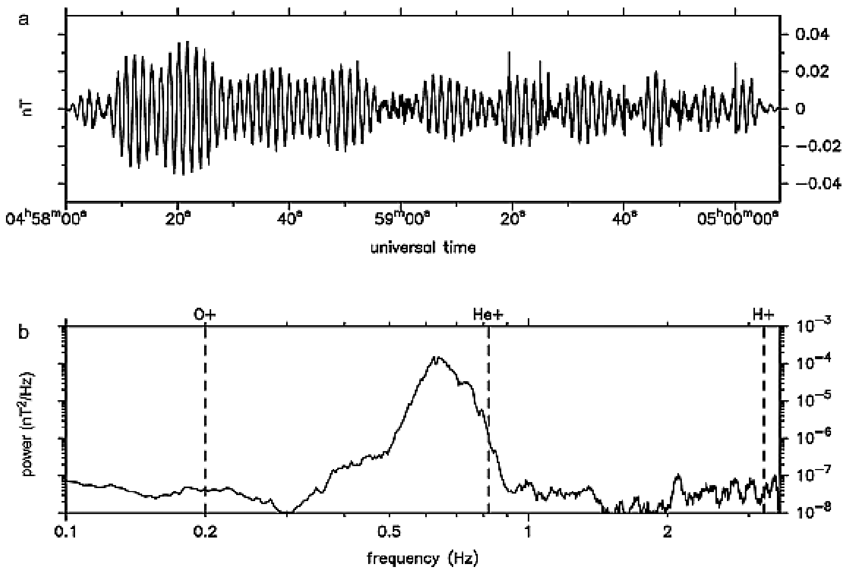


Nishiyama et al., *JGR*, 2018

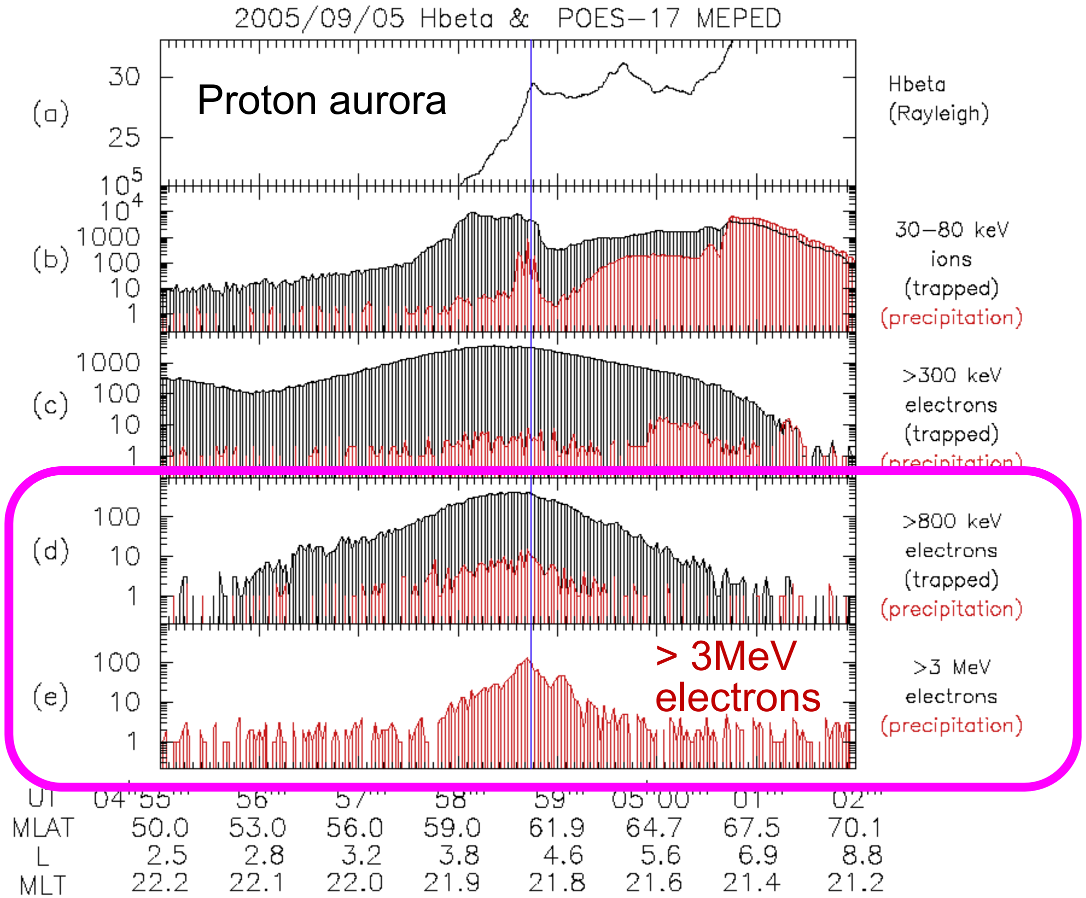
What causes EEP? (1)

- Electromagnetic ion cyclotron (EMIC) waves can resonate with not only ions with energies of tens of keV but also relativistic electrons (Thorne and Kennel, 1971).

EMIC waves



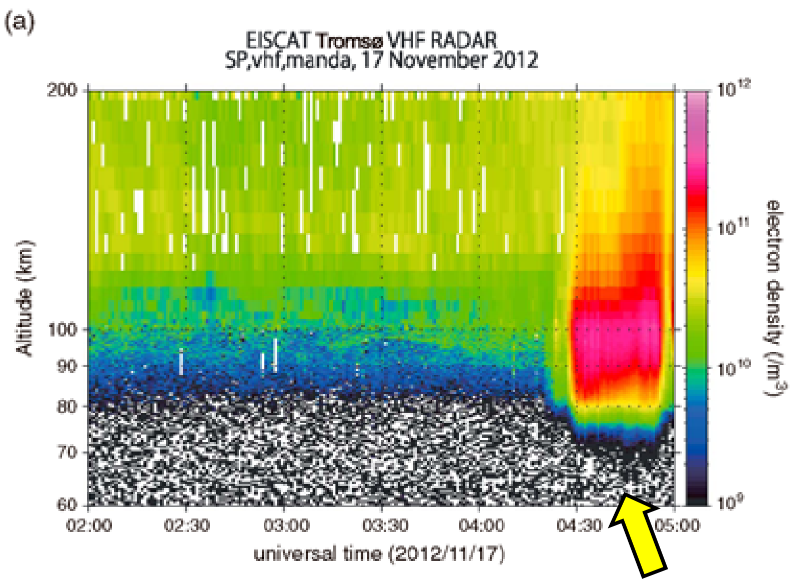
Misyoshi et al., *GRL*, 2008



This example shows that the sub-MeV and MeV electron precipitations coincided with the EMIC waves.

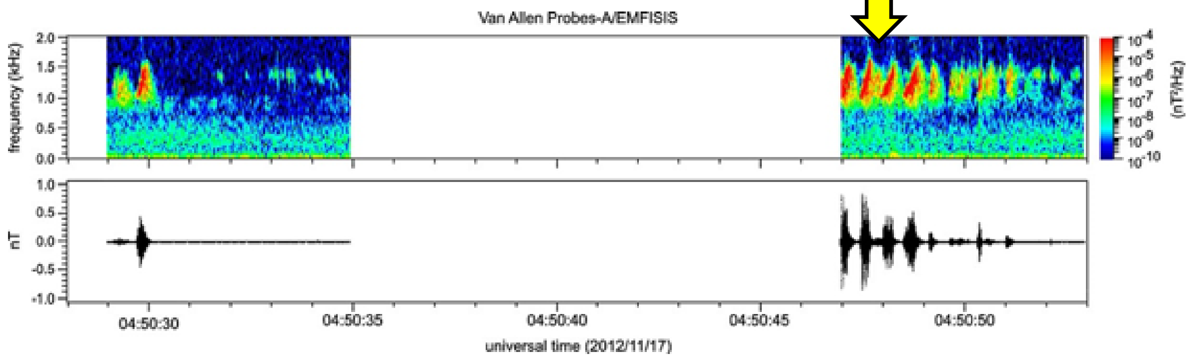
What causes EEP? (2)

- It has been believed that the whistler-mode chorus waves (e.g., Nishimura et al., 2010; Kasahara et al., 2018) and electron cyclotron harmonic (ECH) waves (e.g., Liang et al., 2010) are plausible drivers for the EEP associated with the pulsating auroras.
- Pulsating auroras (PsA) are caused by quasi-periodical precipitation of electrons with energies from a few keV to several tens of keV.



Ionization at an altitude of 68km (corresponding to the precipitation of electrons with E ~ 200keV)

Lower band chorus waves



Rising tone emissions of lower band chorus waves were simultaneously observed near the magnetic equator.

Miyoshi et al., *JGR*, 2015

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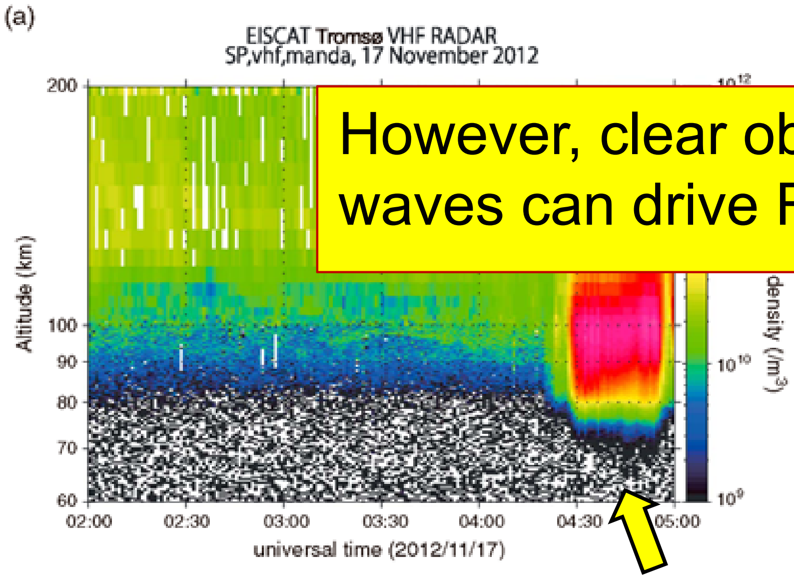
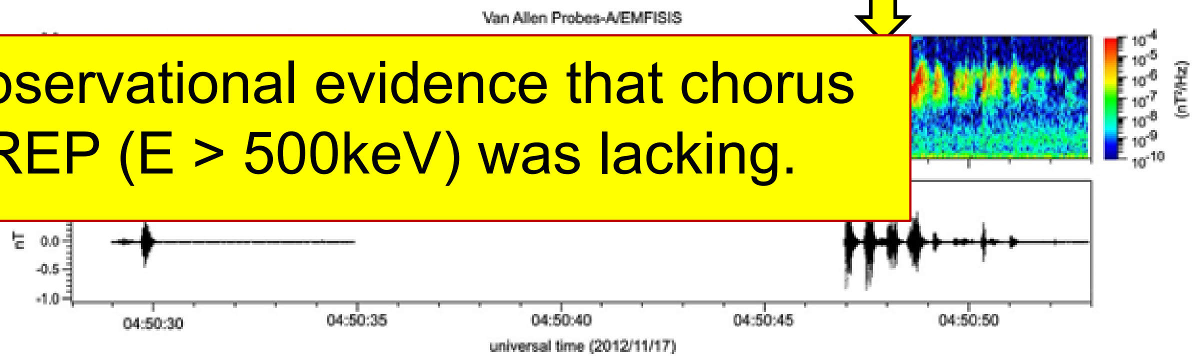
Lower band chorus waves





However, clear observational evidence that chorus waves can drive REP (E > 500keV) was lacking.

Ionization at an altitude of 68km (corresponding to the precipitation of electrons with E ~ 200keV)

Rising tone emissions of lower band chorus waves were simultaneously observed near the magnetic equator.

Miyoshi et al., *JGR*, 2015

Questions

- Are PMWE caused by EEP due to the interaction with plasma waves in the magnetosphere?
- Can whistler-mode chorus waves cause REP (E > 500keV) that leads to PMWE?

⇩

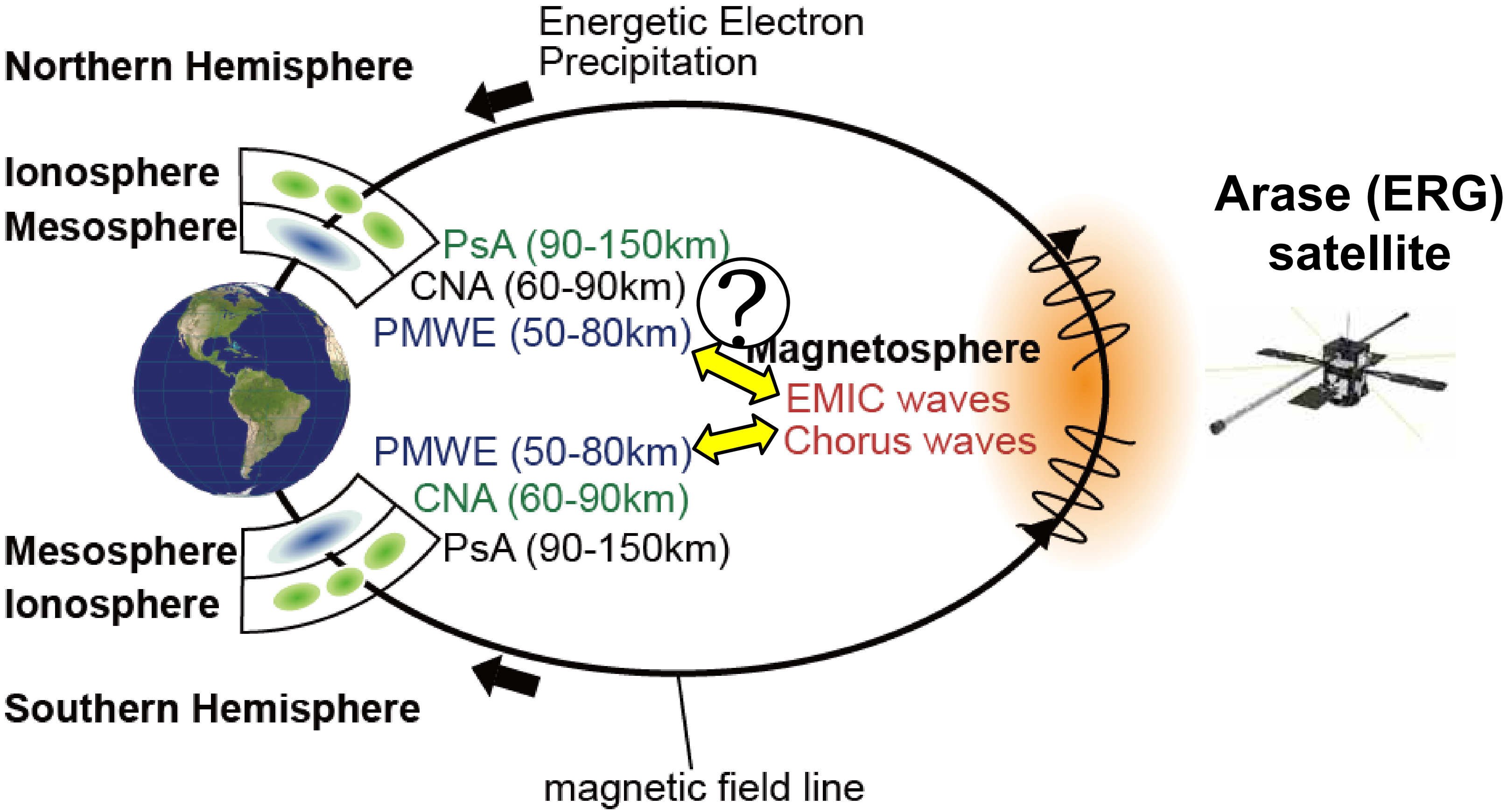
Yes for both questions in this study

Observation summary

03-07 UT on 21 March 2017

ASI@Husafell

PANSY@Syowa

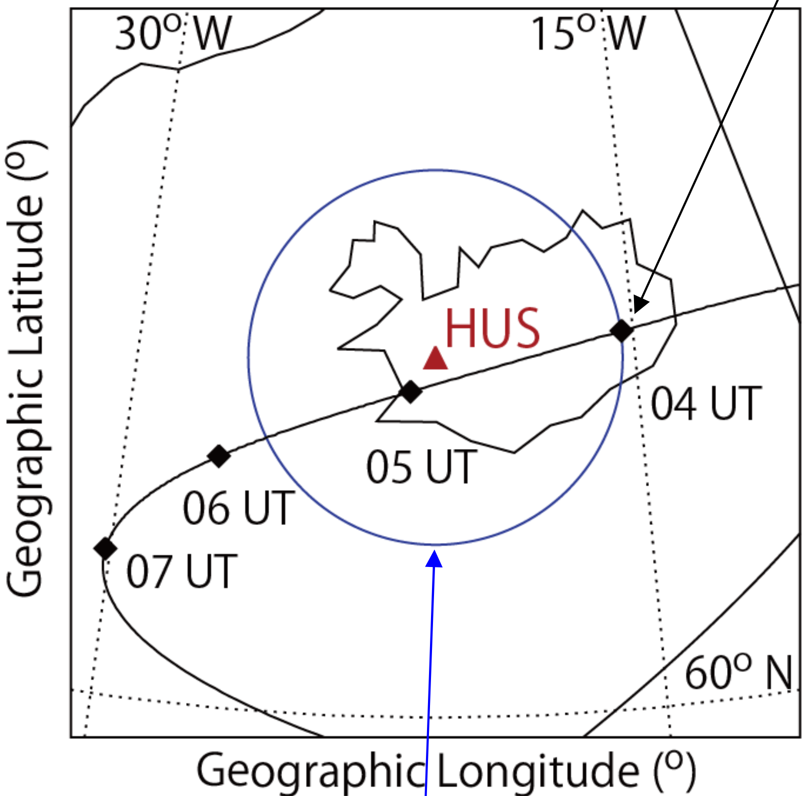


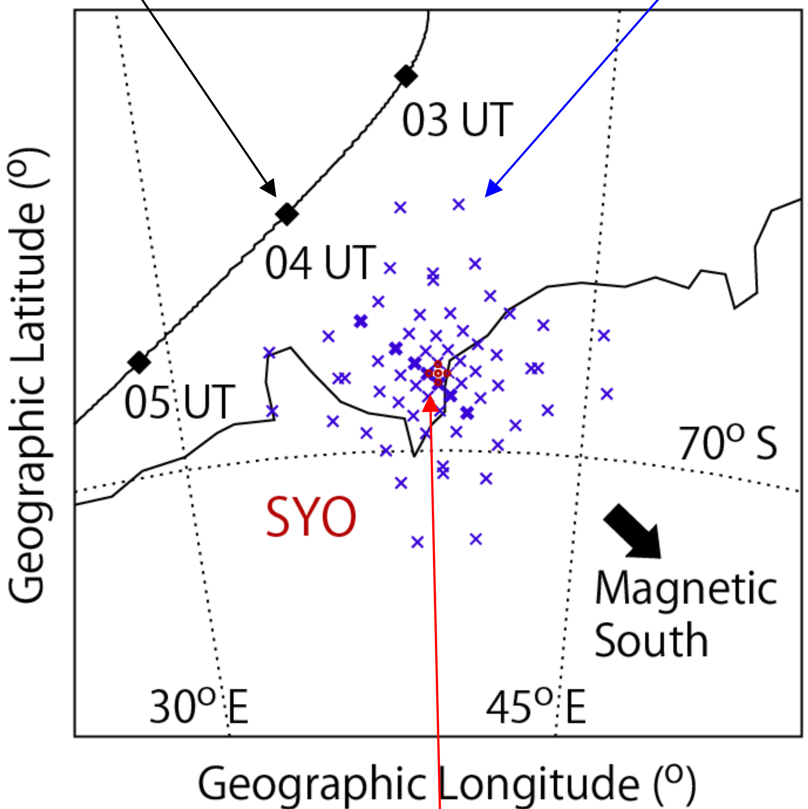
- During the first campaign of Arase (ERG) satellite and ground-based coordinated observations during 03-07 UT on 21 March 2017, several types of plasma waves were observed in the magnetosphere and pulsating auroras (PsA), cosmic noise absorption (CNA), PMWE, etc., on the ground in the northern and southern hemispheres.
- We made a direct comparison between the magnetospheric plasma waves and the ionospheric/mesospheric phenomena.

Conjugate observation by Arase and ground-based multiple instruments (03-07UT on 21 Mar. 2017)

Footprints of Arase at 100km altitude (by TS04 model)

Beam position of IRIO at SYO at 90km altitude

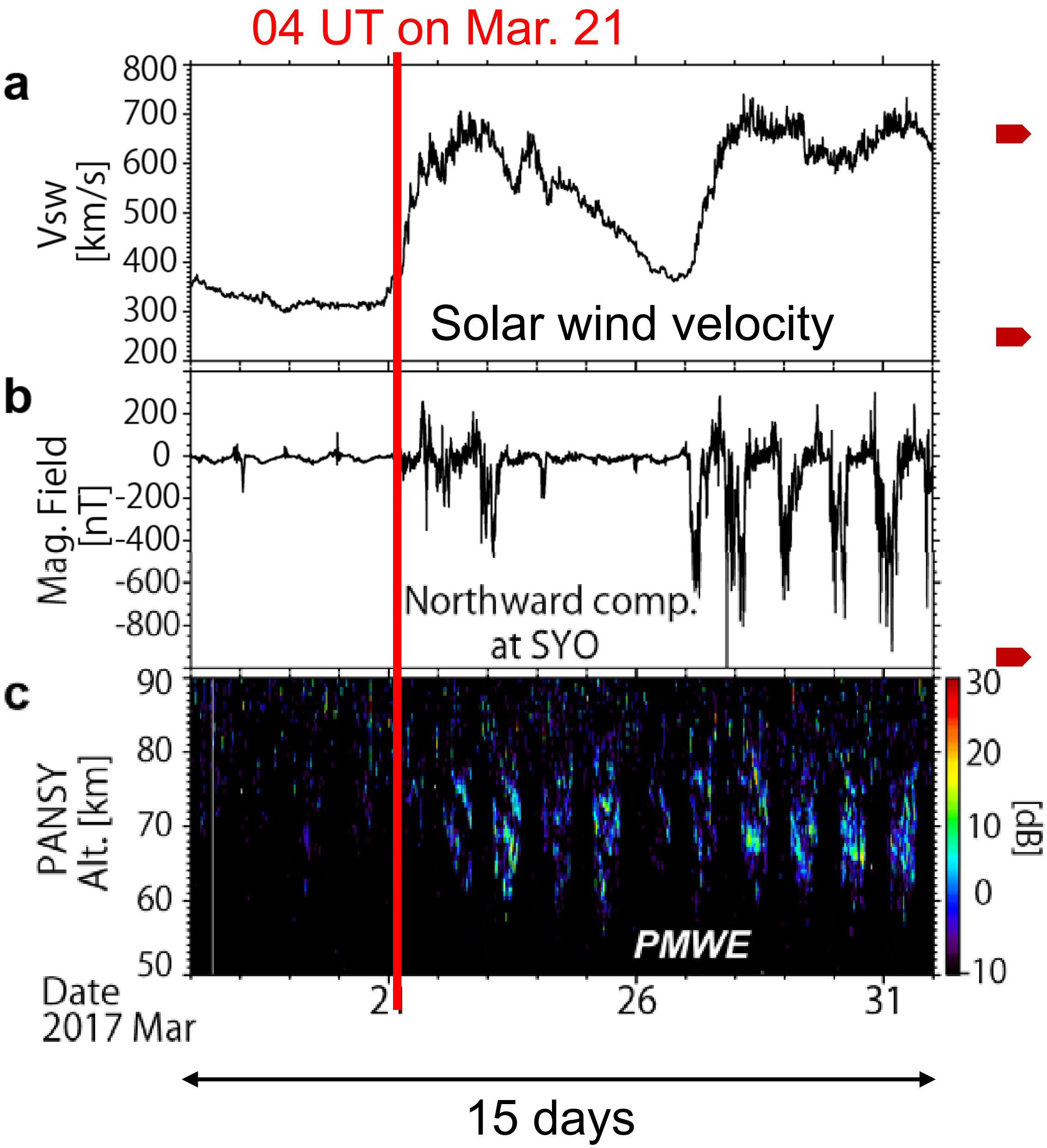




FOV of ASI at HUS, calculated assuming that 70 ° zenith angle and 105km altitude.

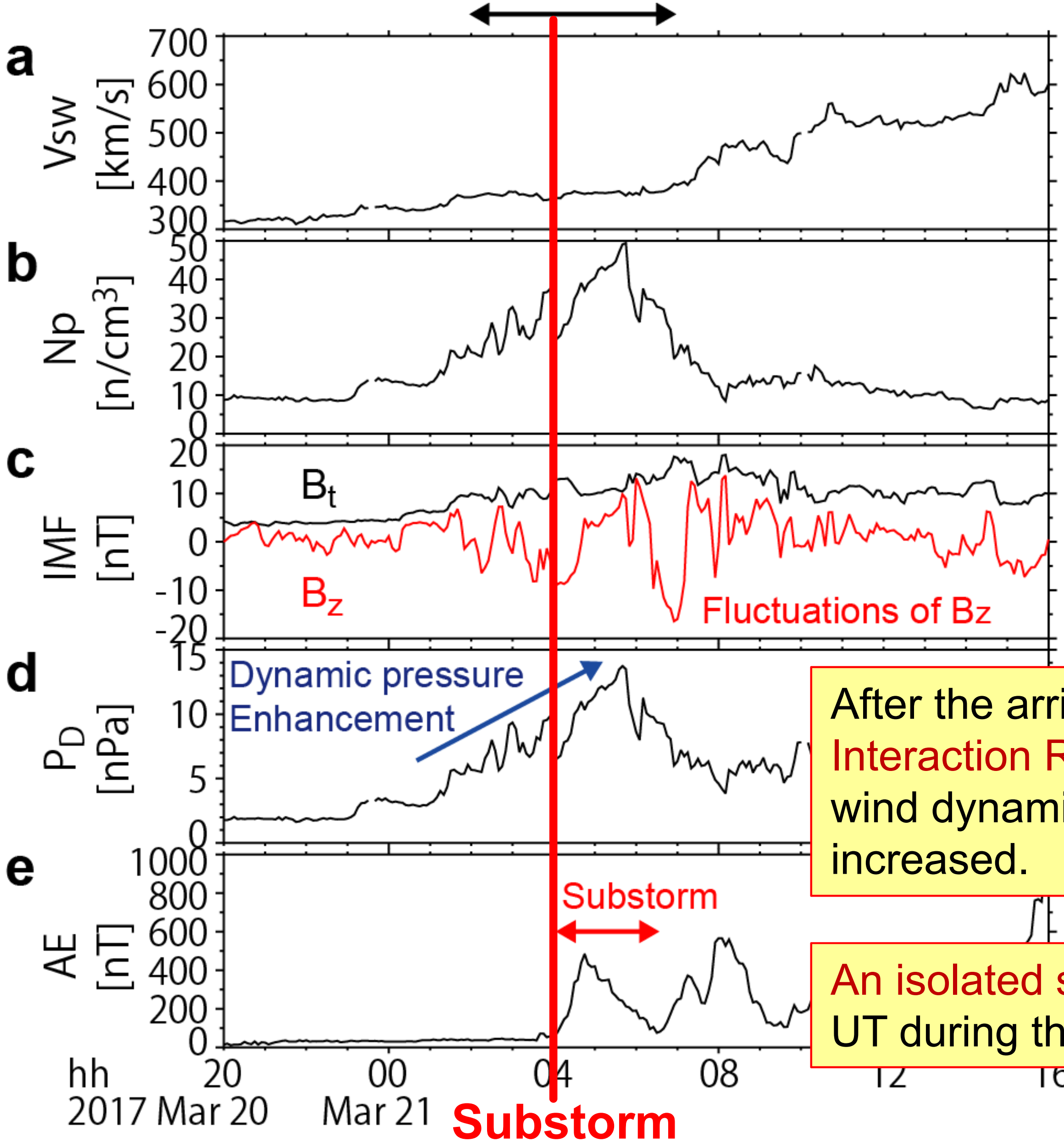
Beam position of the PANSY radar at 70km altitude

Relation between solar wind, geomagnetic activity and PMWE

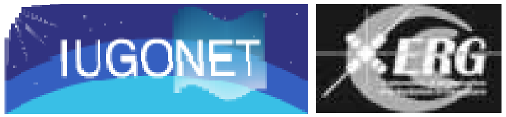


- This event occurred just after the arrival of high-speed solar wind stream (HSS).
- Before the arrival of HSS, the geomagnetic and PMWE activities were significantly quiet to make the relationship between them clear.
- The geomagnetic activity and PMWE power enhanced after the arrival of HSS.

Solar Wind Parameters (from OMNI)



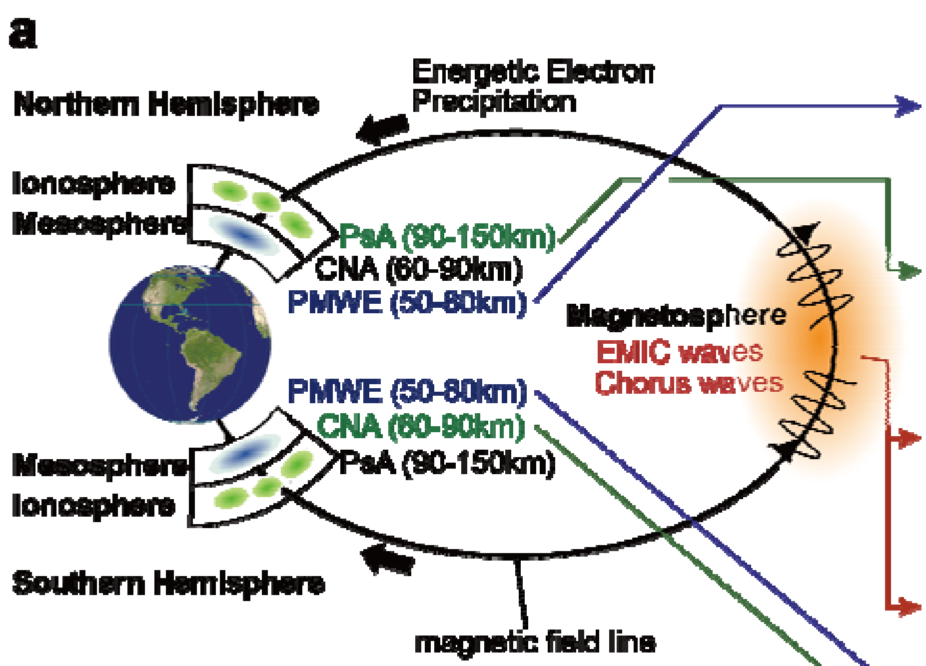
In this study, we analyzed data by using SPEDAS with the erg- and iugonet-plugins.

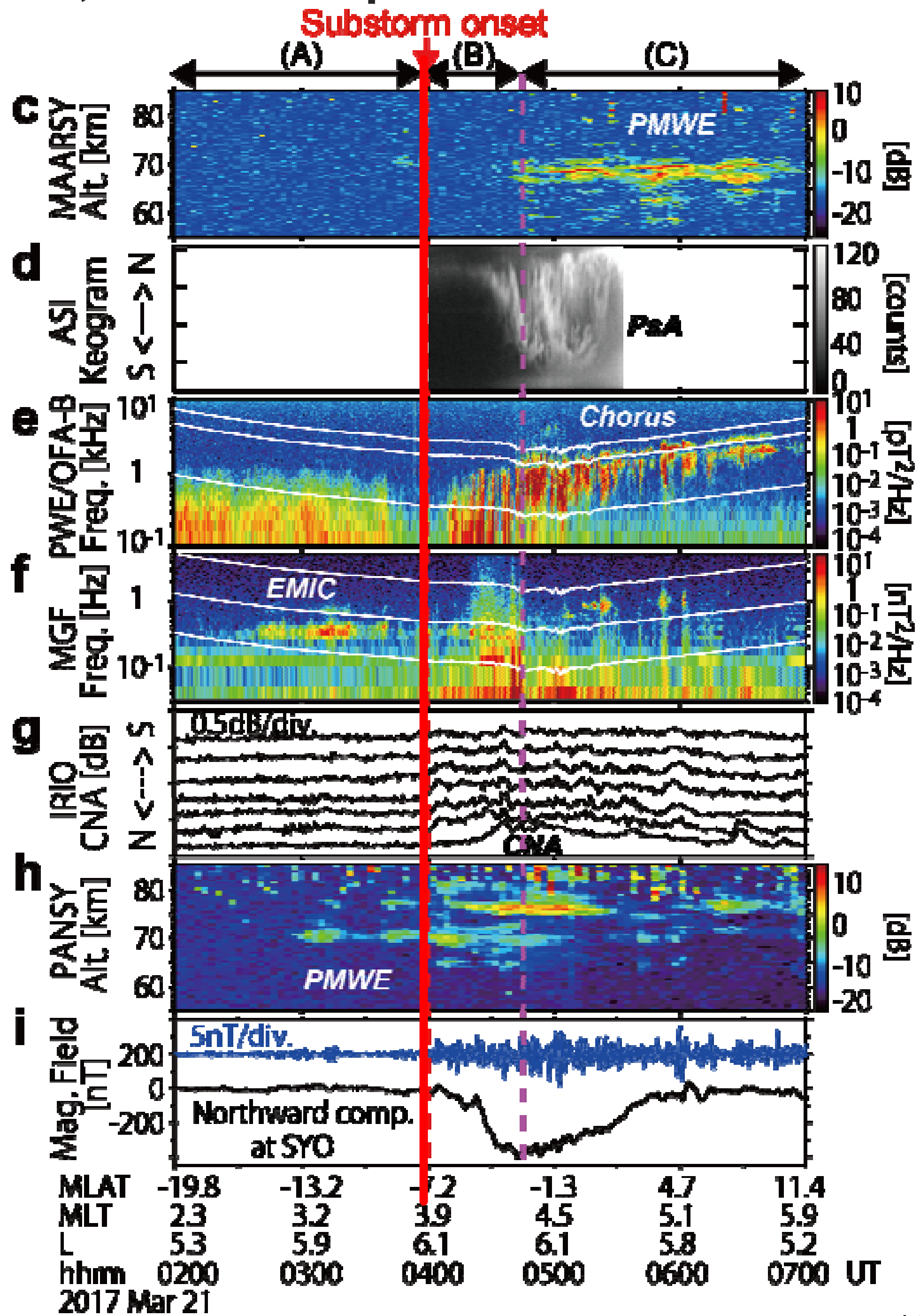


After the arrival of Corotating Interaction Region (CIR), the solar wind dynamic pressure gradually increased.

An isolated substorm occurred at 04 UT during the passage of the CIR.

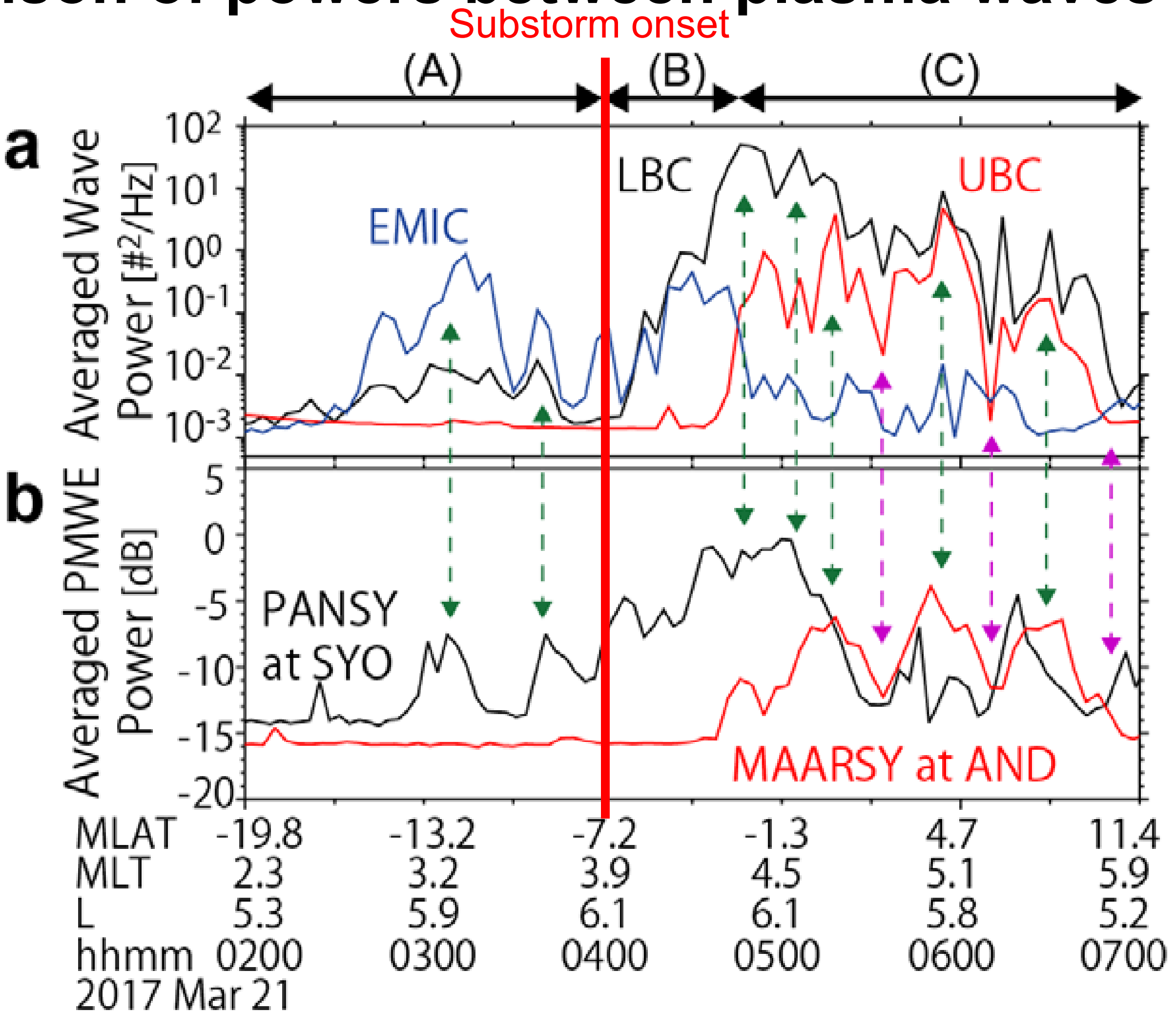
Magnetosphere, ionosphere, and mesosphere data





- EMIC waves and upper-band and lower-band chorus (UBC and LBC) waves were observed in the equatorial magnetosphere.
- CNA at SYO in the southern hemisphere occurred after the substorm onset.
- PsA at HUS in the northern hemisphere coincided with chorus waves.
- PMWE in both hemispheres were simultaneously observed with the EMIC and chorus waves.

Comparison of powers between plasma waves and PMWEs

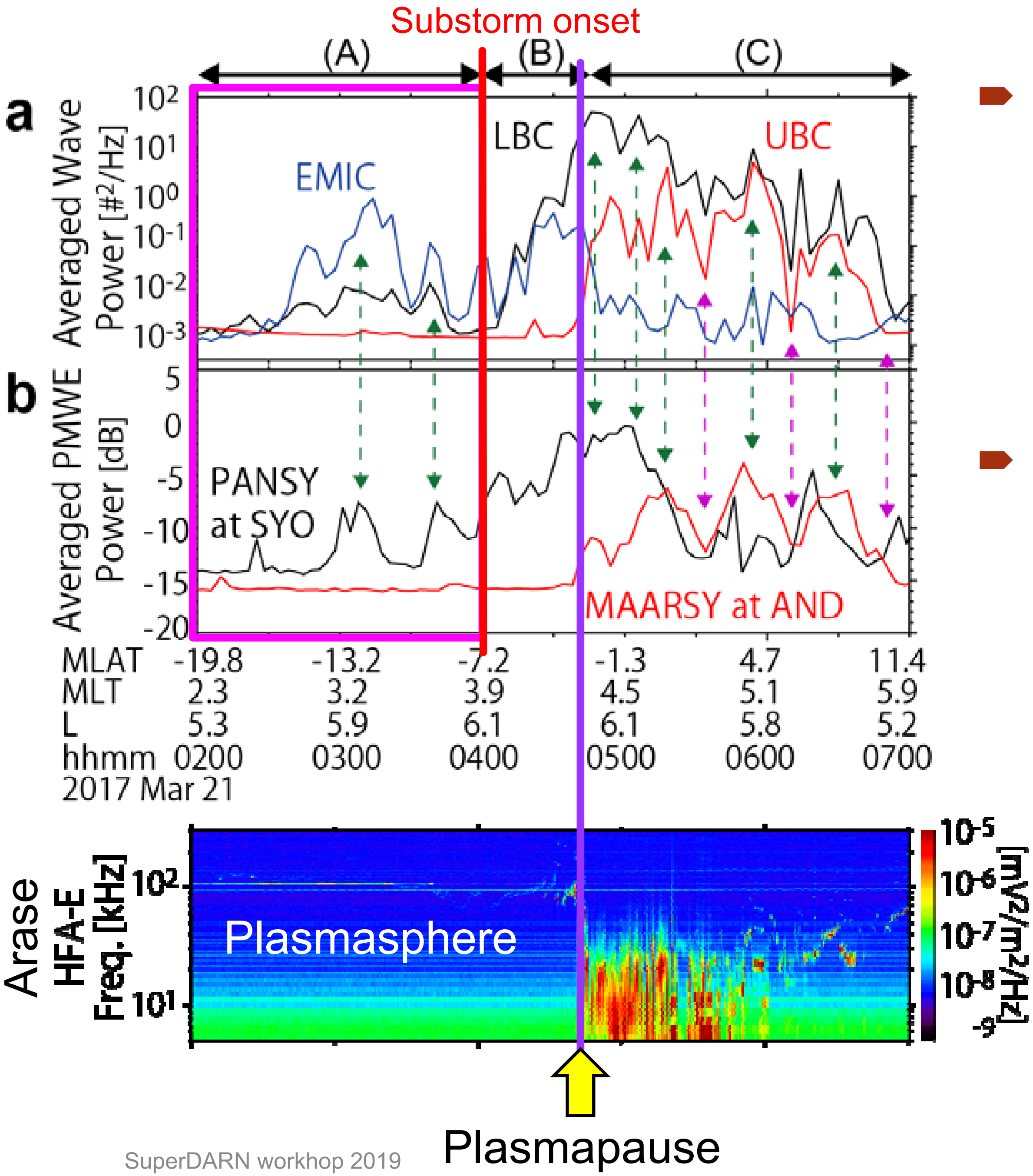


Chorus waves, EMIC waves @Arase

PMWE in both hemispheres

- The PMWE at SYO during the interval (A) appear to correspond to the EMIC waves.
- During the interval (C), the PMWE powers in both hemispheres show a quite similar trend to that of the chorus wave power.

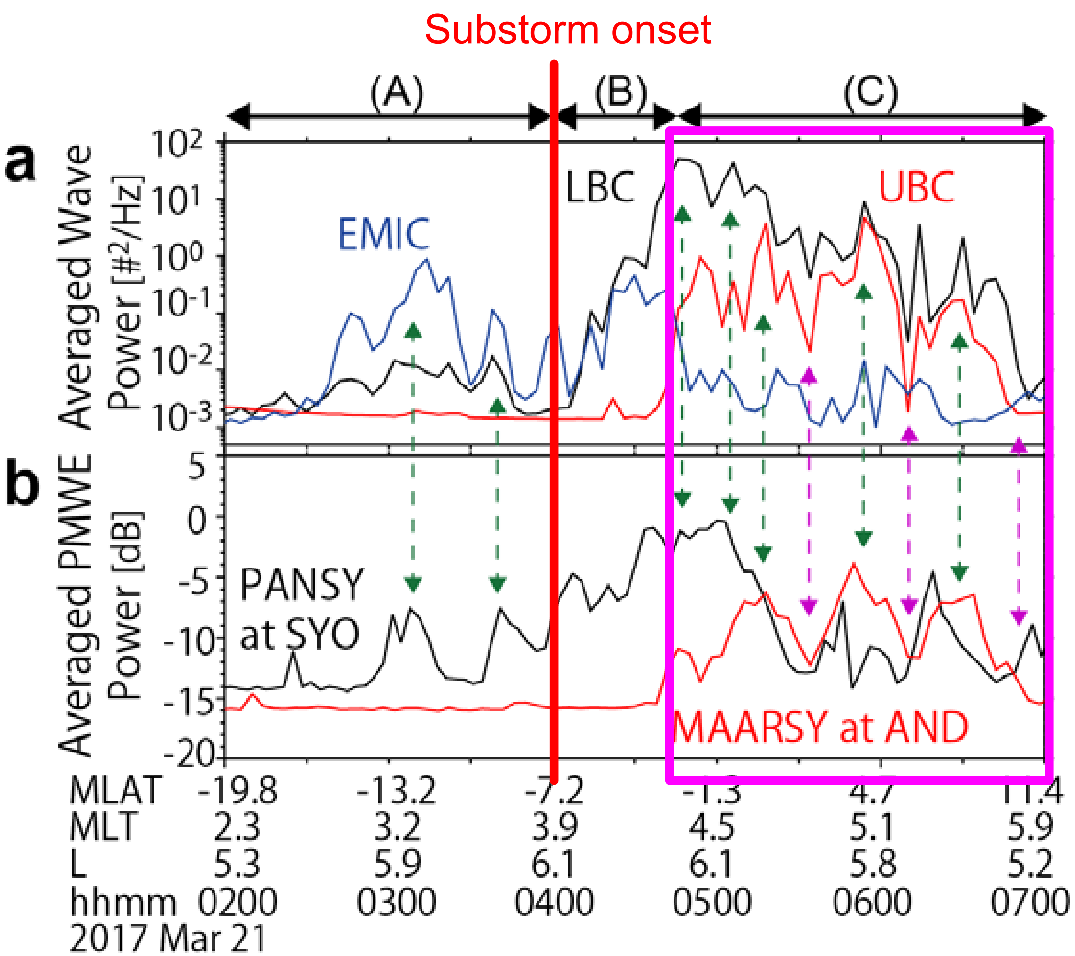
Cause of PMWE before the substorm onset



- Before the substorm onset (interval (A)), the PMWE observed at SYO can be related to the EEP due to the interaction with the EMIC waves, because there is no other candidate.

- It can be interpreted that the EMIC waves were generated inside the plasmasphere by ring-current hot ions with temperature anisotropy, which was developed by magnetospheric compression due to increasing solar wind dynamic pressure during 01:00-06:00 UT (Shiokawa et al., 2018).

Cause of PMWE during the recovery phase (1)



- During interval (C) after 04:45 UT, the PMWE in the both hemispheres may be caused by the EEP due to the interaction with the chorus waves.
- During this interval, the PMWE observed at 57 km correspond to the precipitation of relativistic electrons with $E \approx 1$ MeV.

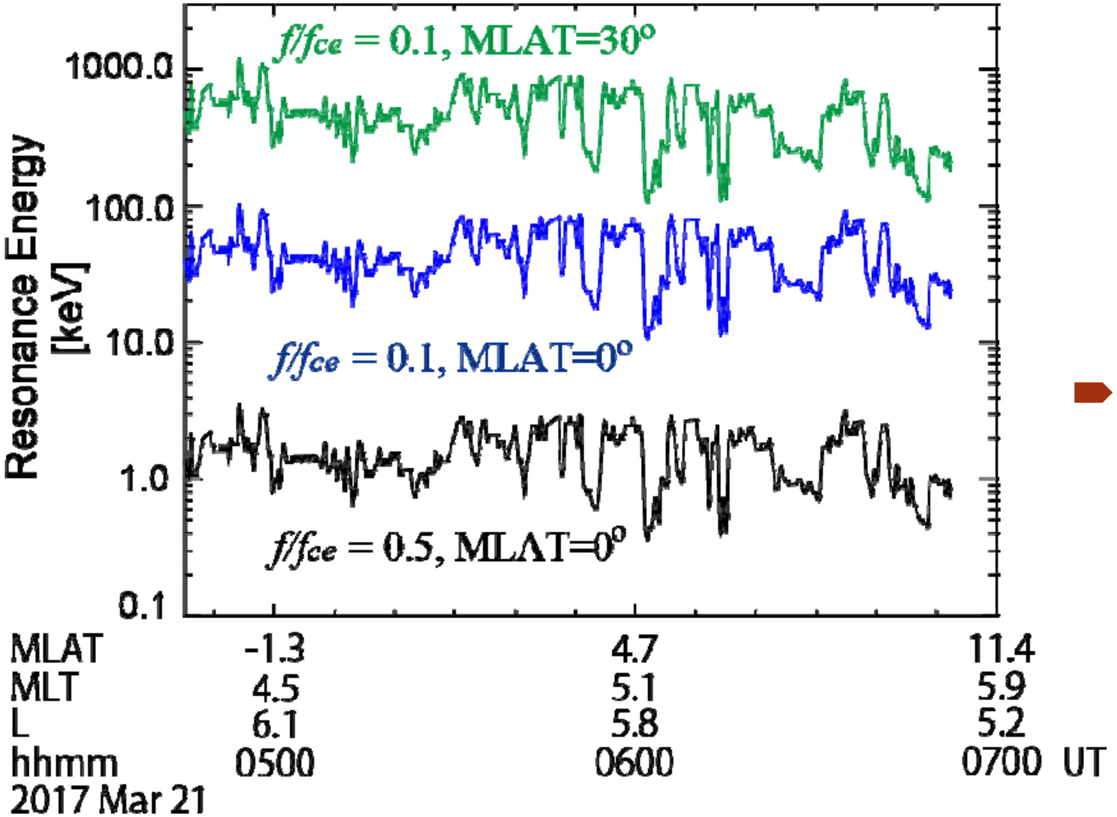
Cause of PMWE during the recovery phase (2)

- We estimated the resonance energy (E_{res}) of electrons interacting with the observed LBC waves near the magnetic equator by the following equation,

$$E_{res} = \frac{B^2}{2\mu_0 N_e} \frac{f_{ce}}{f} \left(1 - \frac{f}{f_{ce}}\right)^3$$

[Kennel and Petschek, 1966]

from HFA/PWE

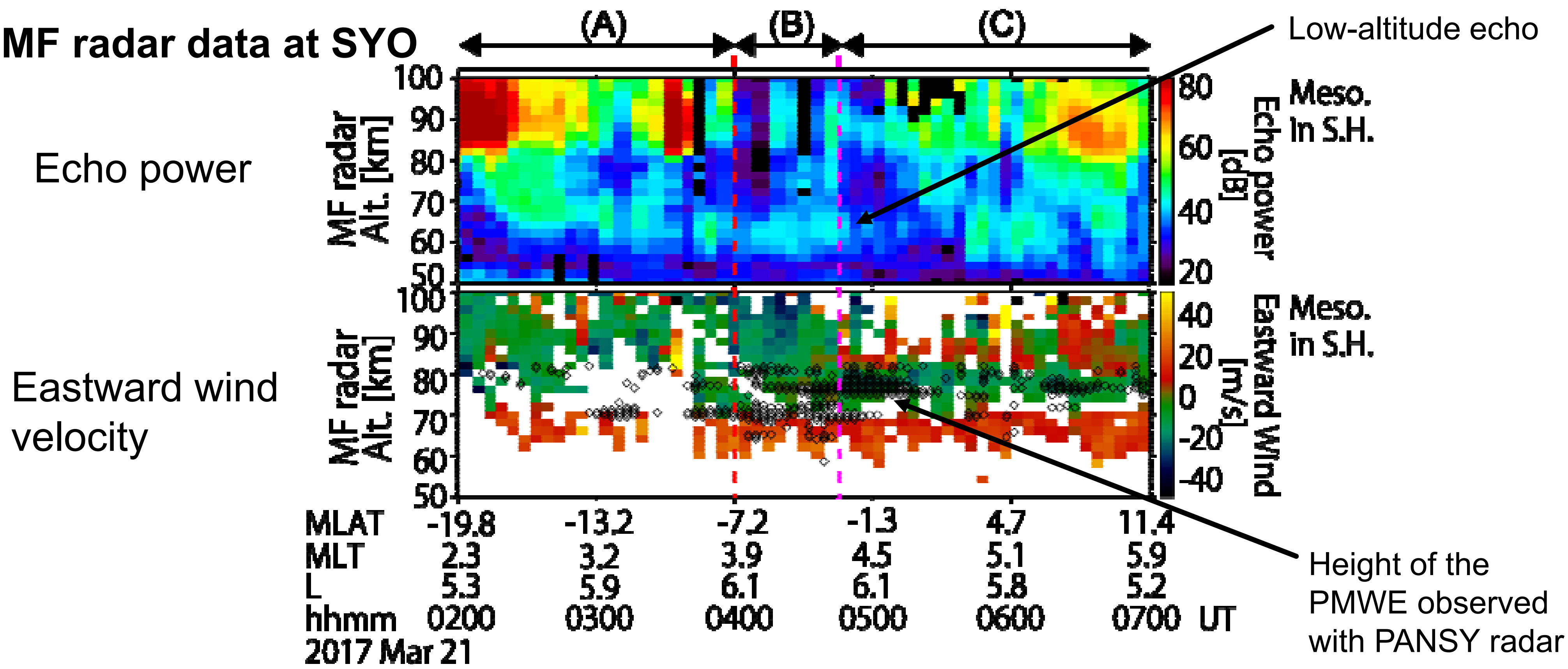


- If we assume that the wave-particle interaction happened at the equator, the estimated maximum energy was less than 100 keV at 04:45-07:00 UT, which can cause PsA and CNA. However, it is too small to cause the low-altitude PMWE.

- One possible explanation for the low-altitude PMWE is that the LBC waves propagated to higher latitudes and resonated with more energetic electrons there, because the E_{res} increases with increasing magnetic field intensity (Miyoshi et al., 2015).

What causes the non-perfect correlation between the PMWE and the magnetospheric plasma waves?

MF radar data at SYO



- Neutral turbulence in the mesosphere is another important factor for the PMWE enhancement and is often induced by wind shear (e.g., Belova et al., 2015)
- Large vertical shears in the horizontal wind velocity were observed at about 70 km and 80 km, which substantially agreed with the layered PMWE structure observed with the PANSY radar.

Conclusions

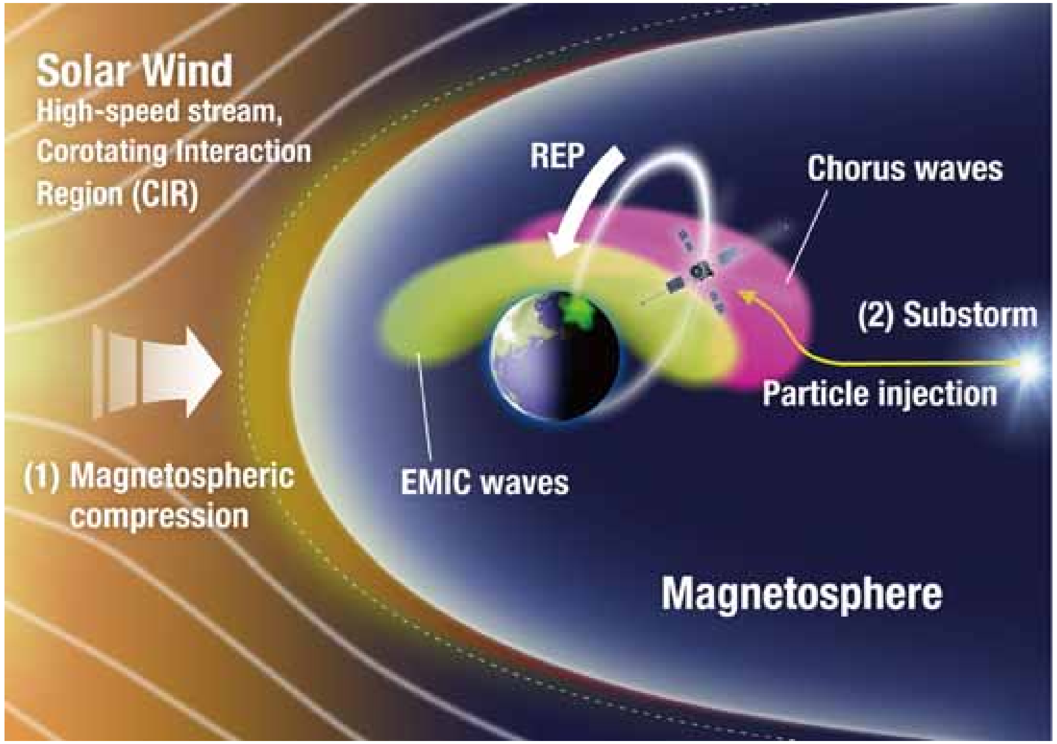
Possible scenario

⓪ Layered neutral turbulence due to the wind shear existed in the mesosphere over SYO (but, not enough electron density to detect PMWE).

① Magnetosphere was compressed after the arrival of CIR.

⑤ Chorus waves were generated in the morning-side magnetosphere.

⑥ The chorus waves propagated to higher latitudes along and across the field lines and precipitated energetic electrons, including relativistic electrons.



④ An isolated substorm and associated particle injection occurred at 04 UT.

② EMIC waves were generated inside the plasmasphere.

③ Energetic electrons were precipitated by the EMIC waves and caused the PMWE.

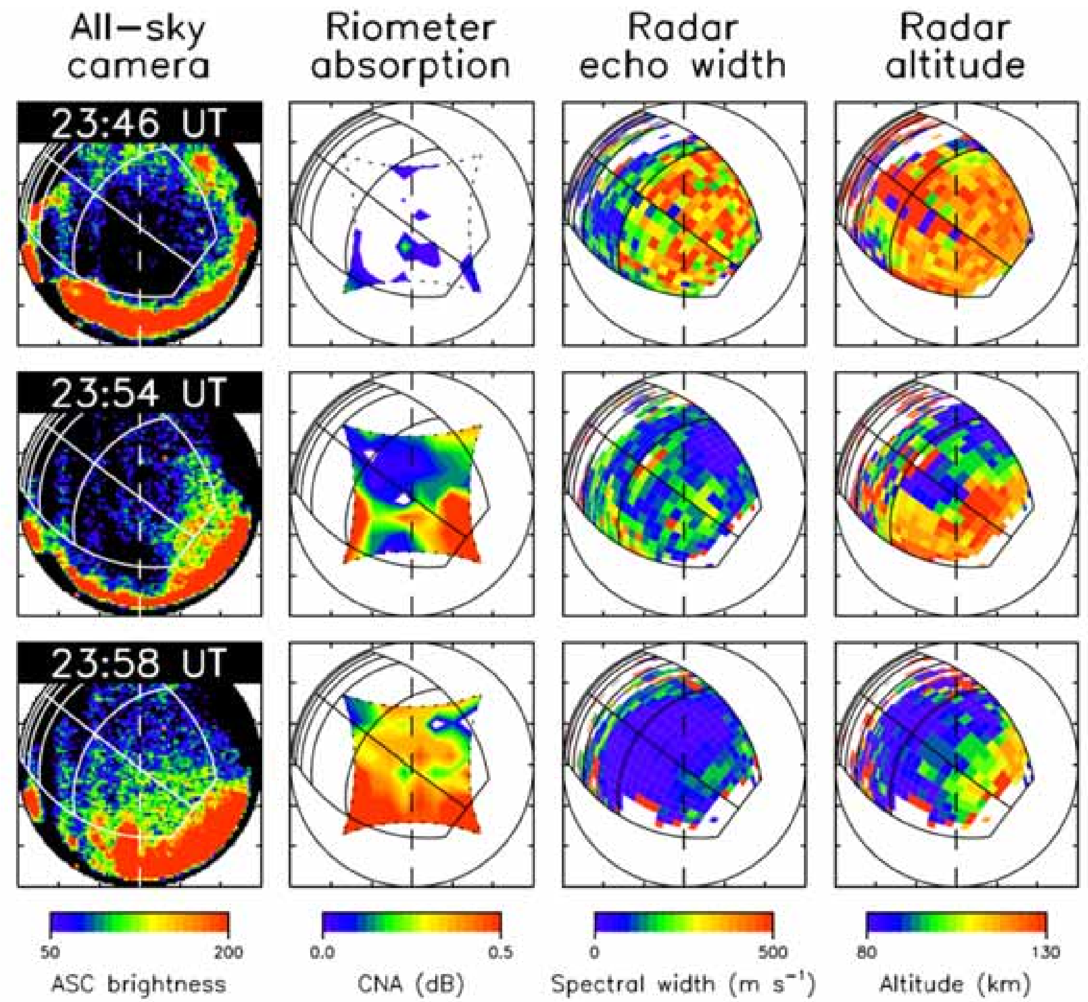
⑦ Pulsating auroras in the E-region ionosphere, CNA in the D-region ionosphere, and PMWE in the mesosphere were observed.

Future works

- Confirm statistically that the PMWE are caused by EEP due to the interaction with EMIC waves and chorus waves.

- Analyze SuperDARN radar data to investigate horizontal distribution of REP that causes the PMWE.

It has been reported that the ionospheric D-region echoes associated with EEP were observed with the SuperDARN radar during pulsating auroras.



Milan et al., *Ann. Geophys.*, 2008

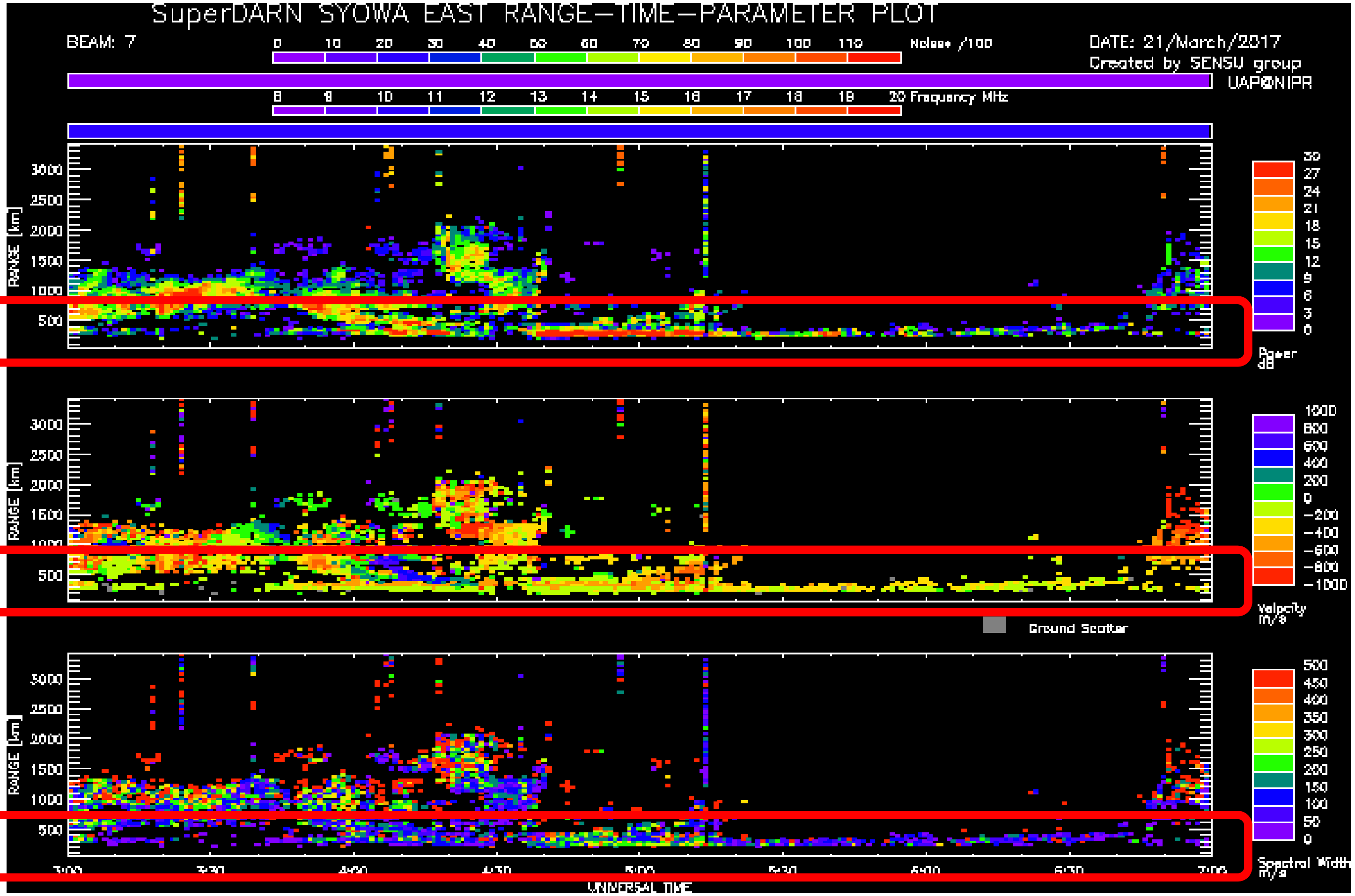
Future works

- During 03-07 UT on 21 March 2017, near-range echoes (associated with the D-region echoes) were also detected by the SuperDARN Syowa East radar.

Echo power

Doppler velocity

Spectral width



03 UT

07 UT