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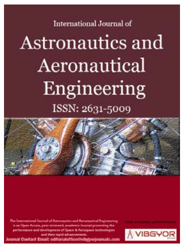

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HF-Induced Energetic Particle Precipitation Phenomena on Board Demeter

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Abstract

This paper is related to satellite observations on board DEMETER of energetic electrons scattering just over the SURA facility in Russia (L ≈ 2.6). Two kinds of perturbations occurred in energetic particles, one with increase of electron flux, and one with pitch angle modulation. The phenomena are due to the artificial HF wave heating, with wide frequency band electromagnetic emissions occurring simultaneously. Based on the analysis and observations in wave-particle interaction at different frequency bands, the lightning-like VLF emissions and enhanced VLF transmitter signals induced by HF heating may contribute to the increase of electron flux and the modulation of pitch angles around L ~ 2.6 over SURA heating region.

Keywords

Ionosphere, HF heating facility, Demeter

Introduction

The ionospheric heating experiments between DEMETER and HF (high frequency) heating facilities on the ground have been carried out a lot of times during its operation time in 2004-2010, in which artificial ducts were formed over the heating region and many perturbations in plasma parameters were detected in the topside ionosphere [1-4]. Besides that, the modulated ELF/VLF (extremely low frequency/very low frequency) electromagnetic waves and triggered emissions excited by HF heater were observed on satellite and ground stations [5-8]; which provides good opportunities for study of wave-particle interaction. However, as one of the major topic in ionospheric heating and magnetosphere physics, the real observations in energetic particle diffusion excited by HF heater have been rarely reported in previous studies.

In the present paper, we collect all the SURA-DEMETER heating events, and exhibit a few cases with energetic particle perturbations over heating region. We then investigate and discuss the interaction between electromagnetic waves and energetic particles.

Observations

Our data set consists of DEMETER observations with 29 experiments from SURA heater (56.15°N, 46.1°E, L ≈ 2.6), which were all took place in local night time. The passes were selected with clear HF bumping waves recorded at DEMETER to make sure that all the perturbations were directly related to HF heating. At the meantime, VLF spectrum from

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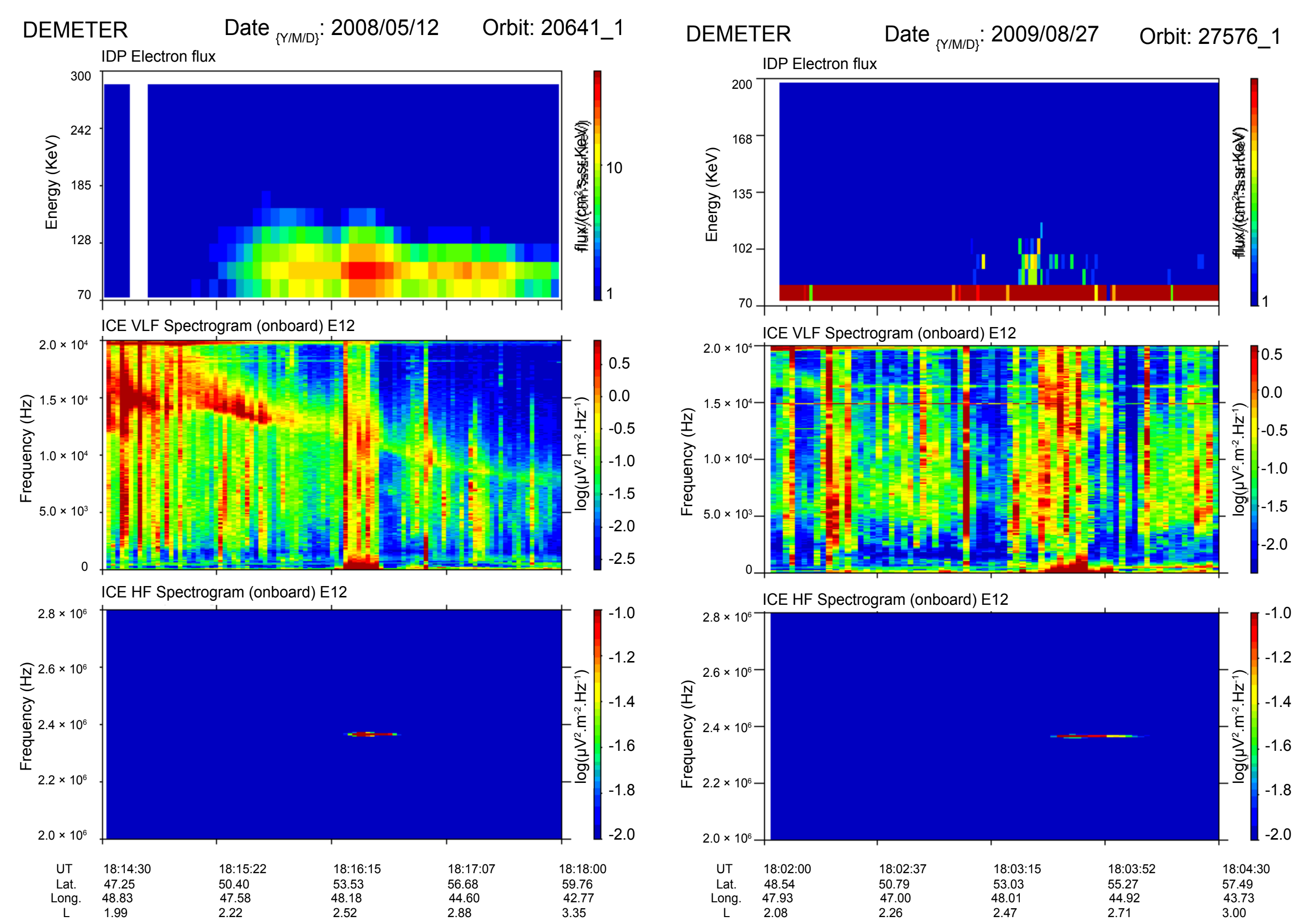

Figure 1: Observations above SURA on May 12, 2008 and August 27, 2009 (Top: Electron flux; Middle: VLF spectrogram of an E field component; Bottom: HF spectrogram of an E field component).

ICE [9] and high energy particle detection [10] from IDP were taken into account in this paper.

Energetic particle precipitation over heating region

Two typical events are identified with disturbances in high energy particles on May 12, 2008 and August 27, 2009 respectively during SURA heating experiments. In our previous study [4], there occurred intensive plasma perturbations simultaneously. It can be seen from Figure 1 that, the bumping waves from SURA were detected on HF spectrum at 2.36 MHz (due to the side-lobe effects of ICE as the difference between sampling frequency 6.66 MHz and SURA transmitted frequency 4.3 MHz). On May 12, 2008, the ionospheric heating took place during UT 18:16:27-18:16:39, while on August 27, 2009, it happened at UT 18:03:36-18:03:53. With the HF heating process, perturbations in electric field were presented in broad frequency bands from 19 Hz to 20 kHz, and the intensive disturbances occurred below 600 Hz in VLF spectrums in the middle panel of Figure 1. As for the energetic particles, they presented clear enhancement at energy band 70-100 keV. Relative to the HF wave intensity centres, perturbations in VLF and energetic particles exhibited a little drift to the south direction. Compared these two events, the electron precipitation was much more significant on May 12, 2008, and the electron flux on August 27, 2009 varied in a quite small scale within $2-3\ \mathrm{cm}^2.\mathrm{s.\ sr.\ KeV}$. The two events illustrated two facts: (1) The simultaneous electromagnetic emissions excited by HF heater; (2) Only lower energy band of electrons precipitating over the same heating region. It demonstrates the direct relationship between HF heating and energetic particle precipitation.

Pitch angle diffusion

In total 29 SURA-DEMETER experiments, only two passes observed the variations in pitch angle over SURA heater as shown in Figure 2. Along the orbit of 33262-1 on September 18, 2010, 2.36 MHz bumping waves were detected in HF spectrogram

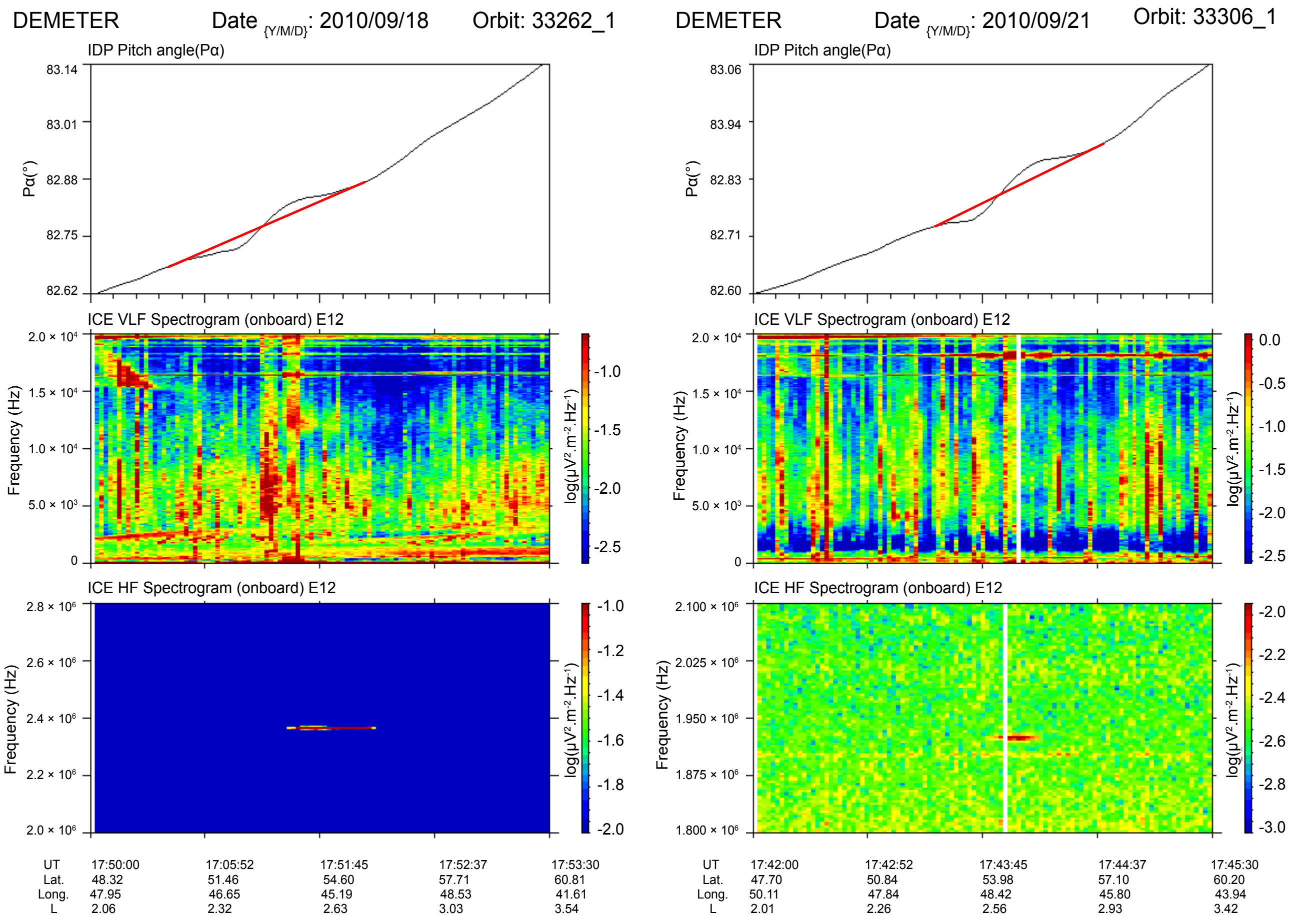

Figure 2: Observations above SURA on September 18, 2010 and 21, 2010 (Top: Electron pitch angle with red lines as a reference; Middle: VLF spectrogram of an E field component; Bottom: HF spectrogram of an E field component).

during UT 17:51:18-17:52:06 with intensity larger than $10-1\,\mu V^{2}.m^{-2}.\,Hz^{-1}$. VLF emissions distributed from 19 Hz to 20 kHz, with those transmitter signals enhanced and frequency broadened over 15 kHz. Over SURA heating region, the pitch angle of electrons decreased firstly, increased to reach a maximum, and then recovered to the normal ascending trend. The variation amplitude in pitch angle was about 0.03°. Three days later, along another orbit of 33306-1 on September 21 observed the similar phenomenon in pitch angle of electrons during the heating experiment. The bumping frequency at this time is 4740 kHz [11] shown as 1.926 MHz in HF spectrogram at UT 17:43:45-17:44:09. The transmitted power is 105 MW on this day, while on Sep. 18 being 50 MW. But the strength of electric field differed so largely between them, only about $10-2\,\mu V^{2}.m^{-2}.\,Hz^{-1}$ on Sep. 21, which illustrates great attenuation in lower ionosphere. In VLF spectrogram, there were almost no obvious perturbations detected, and only enhanced and frequency broadened VLF transmsitter signals could be distinguished, especially at 18.1 kHz. The pitch angle of electrons also showed modulation variations as on September 18, with amplitude about 0.03°. During both experiments, no *in-situ* plasma perturbations had been detected, and the electron fluxes did not exhibit corresponding variations over this region. Compared with the electron flux enhancement in Figure 1, the perturbations on ground-based VLF transmitters were much more intensive during both pitch angle diffusion events in Figure 2. The pitch angle variations over the heating region were too small, but they can be easily distinguished under their smoothing background curves. Additionally, they occurred just at the heating time period, so we need pay more attention on this kind of phenomenon in energetic particles.

Discussion

The analysis above demonstrated the existence of electron diffusion and precipitation induced by

HF heating, in which the electron flux increased one order of amplitude in the maximum at 70-100 keV and pitch angle modulated about 0.03°. Their same time periods and locations presented the close and direct relationships with HF heater. So how this electron diffusion happened, induced by HF bumping waves themselves, ELF emissions, or the VLF emissions? The VLF transmitter induced electron belts have been widely observed and studied on DEMETER [12-14]. The night time observations of energetic particle flux showed clear enhancement from NWC (L ~ 1.45) at higher L-shell around 1.67-1.9 [12,14], which illustrated the ducted propagation of VLF transmitters in the magnetosphere. Two years of experiments from NPM (L ~ 1.17) in Hawaii with 21.4 kHz to DEMETER presented a few cases of transmitter-induced electron precipitation around L ~ 1.9 [13]. From the observations of Figure 1 and Figure 2, the enhanced VLF transmitter signals were observed with the modulation of pitch angles (Figure 2), not the precipitation of low energy electrons. Parrot, et al. [15] reported the powerful VLF transmitter-induced ionospheric perturbations on DEMETER, and they found the precipitated electrons not located at the same position of plasma perturbations, but at a higher L value. So the enhanced VLF transmitter signals due to HF heating might contribute to the pitch angle diffusion of electrons over the heating region. Unfortunately we did not find the precipitated electrons at higher L-shell, but just over the same region with enhanced VLF transmitter signals, so there are some conflicts to explain the observations shown in Figure 1 by enhanced VLF transmitters.

Another enhanced EM waves were the lightning-like signals at kHz frequency band over SURA heater. The interaction between whistler-mode lightning events and trapped electrons can cause electron pitch-angle scattering, sometimes by as much as 1° [7,16] studied the lightning-induced electron precipitation detected by DEMETER satellite, and their results illustrated that 100-300 keV electron precipitation with electron flux increasing to half an order to 2 orders in amplitude, just over the localized lightning events or thunderstorms. It is consistent with the observations of particle precipitation from enhanced VLF-band whistler waves induced by HF heating as shown in Figure 1, which verifies the major contribution of VLF-band whistler waves in particle precipitation.

The strongest EM emissions from HF heating are at ELF/VLF frequency band, lower than 600 Hz. The three-component electromagnetic field data has been collected along the orbit of 27576 - 1 on 27 August, 2009 under burst mode during the heating time. Figure 3 shows the polarization analysis of ELF emissions during UT 18:03:30-18:04:00 over the heating region by using the SVD method [17]. It can be seen that, besides the enhanced signals within a wide frequency band above the cut-off frequency about 600 Hz, some whistler signals were also detected in magnetic field at 200-600 Hz, especially two signals with the electric field together over the heating region at UT 18:03-18:04 with polar angle near 90°, left hand polarization with ellipicity of - 0.8 and planarity near 0.8. But the emissions in magnetic field were not obvious below 200 Hz, which demonstrates that these emissions mainly were electrostatic waves at lower frequency band. In the analysis of HF-induced plasma perturbations [4] the ULF electric field disturbances were found due to the effects of $\vec{V} \times \vec{B}$ from upwards movement of ions in the artificial ducts. The relationship between these ULF/ELF electrostatic waves and energetic particles is rarely studied at middle or low latitude, so here we refer to other observational facts to discuss it. In VLF heating research [15] there occurred similar electrostatic waves at ULF/ELF frequency band due to the movement of ions in the VLF-induced artificial ducts over the heating region, but no simultaneous electron precipitation occurred at the same position, but at a higher L-shell (~ 1.9). Considering the similarity of the producing mechanism of these electrostatic waves induced by VLF and HF radio waves, the contribution of ULF/ELF electrostatic emissions on direct energetic particle precipitation over the same region still needs further investigations.

With the low orbiting satellite DEMETER which can measure wave and energetic particles and the multi times of experiments between SURA-DEMETER, it was possible to exhibit for the first time the *in-situ* electron precipitations and their pitch angle diffusion just over the heating region. Among different frequency band signals excited by HF heating process, the kHz whistler waves under the non-ducted propagation mode may be the major contributor to precipitated electrons, and the enhanced VLF transmitter signals play some roles in

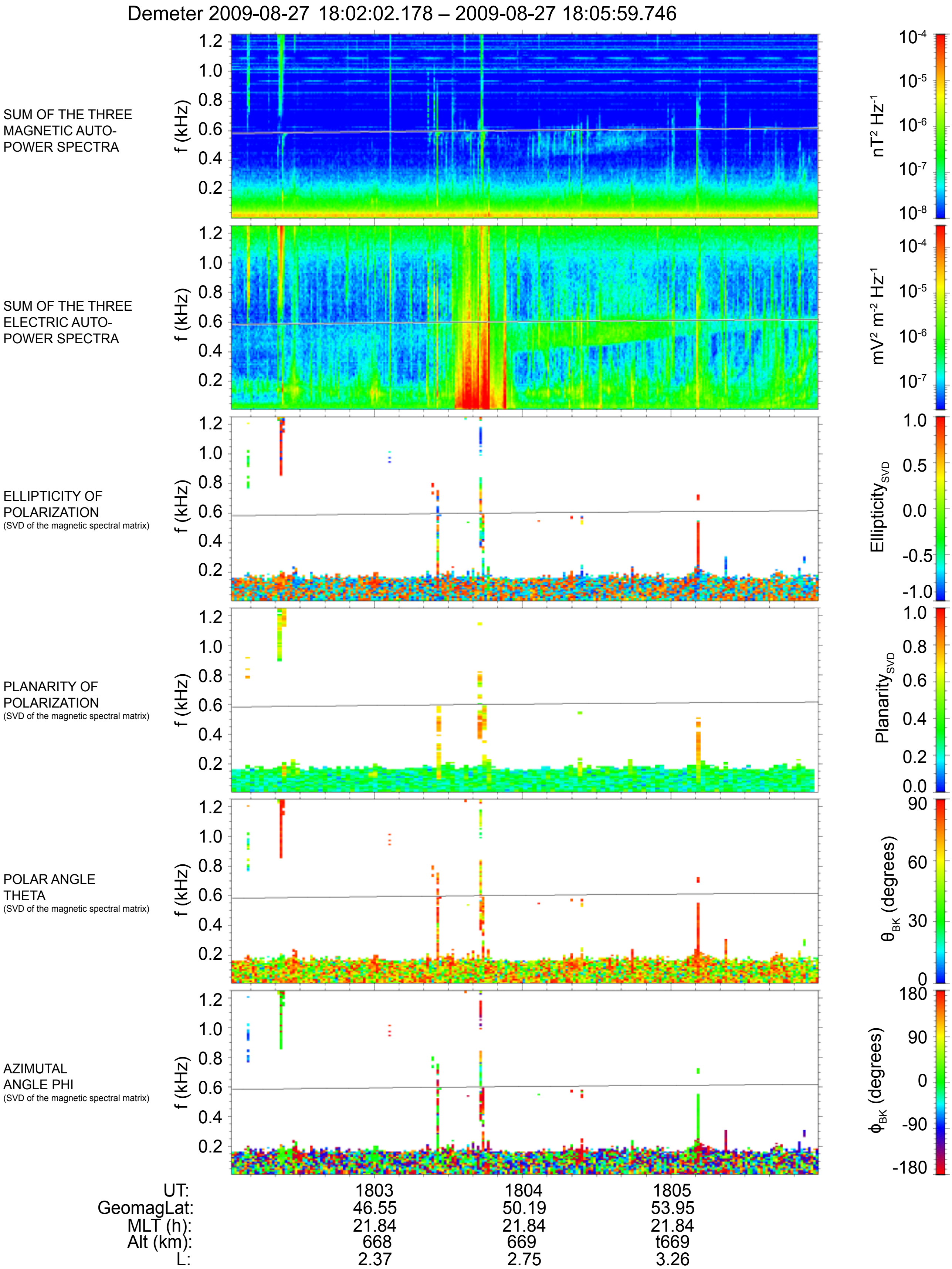

Figure 3: Wave analysis along the orbit of 27576-1 on August 27, 2009 (From the top to the bottom successively: Magnetic field spectra; Electric field spectra; Ellipticity; Planarity; Polar angle, Azimuthal angle).

pitch angle modulation, while ULF/ELF electrostatic waves for direct effects on energetic particle scattering needs further study.

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