



## Origin of low proton-to-electron temperature ratio in the Earth's plasma sheet

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E. E. Grigorenko, E. A. Kronberg, P. W. Daly, N. Yu. Ganushkina, B. Lavraud, et al.. Origin of low proton-to-electron temperature ratio in the Earth's plasma sheet. *Journal of Geophysical Research Space Physics*, 2016, 121, pp.9985-10. <10.1002/2016JA022874>. <insu-03669418>

**HAL Id: insu-03669418**

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Submitted on 16 May 2022

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## RESEARCH ARTICLE

10.1002/2016JA022874

## Key Points:

- During dipolarizations, drops of  $T_p/T_e \leq 3.5$  often coincide with wave bursts in the frequency range  $f \sim f_{ce}$
- Generally, the decreases of  $T_p/T_e$  are due to some increase of  $T_e$  while  $T_p$  either decreases or remains unchanged
- Electron heating by ECH and EME with  $f \leq f_{ce}$  can be an additional mechanism affecting the  $T_p/T_e$  during dipolarizations

## Correspondence to:

E. E. Grigorenko,  
elenagrigorenko2003@yandex.ru

## Citation:

Grigorenko, E. E., E. A. Kronberg, P. W. Daly, N. Y. Ganushkina, B. Lavraud, J.-A. Sauvaud, and L. M. Zelenyi (2016), Origin of low proton-to-electron temperature ratio in the Earth's plasma sheet, *J. Geophys. Res. Space Physics*, 121, 9985–10,004, doi:10.1002/2016JA022874.

Received 28 APR 2016

Accepted 12 OCT 2016

Accepted article online 17 OCT 2016

Published online 31 OCT 2016

## Origin of low proton-to-electron temperature ratio in the Earth's plasma sheet

E. E. Grigorenko<sup>1</sup>, E. A. Kronberg<sup>2,3</sup>, P. W. Daly<sup>2</sup>, N. Yu. Ganushkina<sup>4,5</sup>, B. Lavraud<sup>6,7</sup>, J.-A. Sauvaud<sup>6,7</sup>, and L. M. Zelenyi<sup>1</sup>
<sup>1</sup>Space Research Institute of RAS, Moscow, Russia, <sup>2</sup>Max Planck Institute for Solar System Research, Göttingen, Germany, <sup>3</sup>Department of Earth and Environmental Sciences, Ludwig Maximilian University of Munich, Munich, Germany, <sup>4</sup>Finnish Meteorological Institute, Helsinki, Finland, <sup>5</sup>Department of Climate and Space Sciences and Engineering, College of Engineering, University of Michigan, Ann Arbor, Michigan, USA, <sup>6</sup>Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse (UPS), Toulouse, France, <sup>7</sup>Centre National de la Recherche Scientifique, Toulouse, France

**Abstract** We study the proton-to-electron temperature ratio ( $T_p/T_e$ ) in the plasma sheet (PS) of the Earth's magnetotail using 5 years of Cluster observations (2001–2005). The PS intervals are searched within a region defined with  $-19 < X \leq -7 R_E$  and  $|Y| < 15 R_E$  (GSM) under the condition  $|B_x| \leq 10$  nT. One hundred sixty PS crossings are identified. We find an average value of  $\langle T_p/T_e \rangle \sim 6.0$ . However, in many PS intervals  $T_p/T_e$  varies over a wide range from a few units to several tens of units. In 86 PS intervals the  $T_p/T_e$  decreases below 3.5. Generally, the decreases of  $T_p/T_e$  are due to some increase of  $T_e$  while  $T_p$  either decreases or remains unchanged. In the majority of these intervals the  $T_p/T_e$  drops are observed during magnetotail dipolarizations. A superposed epoch analysis applied to these events shows that the minimum value of  $T_p/T_e$  is observed after the dipolarization onset during the “turbulent phase” of dipolarization, when a number of transient  $B_z$  pulses are reduced, but the value of  $B_z$  is still large and an intensification of wave activity is observed. The  $T_p/T_e$  drops, and associated increases of  $T_e$  often coincide either with bursts of broadband electrostatic emissions, which may include electron cyclotron harmonics, or with broadband electromagnetic emission in a frequency range from proton plasma frequency ( $f_{pp}$ ) up to the electron gyrofrequency ( $f_{ce}$ ). These findings show that the wave activity developing in the current sheet after dipolarization onset may play a role in the additional electron heating and the associated  $T_p/T_e$  decrease.

## 1. Introduction

Thermal characteristics of the plasma sheet (PS) population reflect the energy dissipation processes operating either locally or at a remote location. The important parameter is the proton-to-electron temperature ratio  $T_p/T_e$ , which may influence the current sheet (CS) dynamics and stability. There are several mechanisms of plasma heating in the Earth's magnetotail, and they can operate in different ways for ions and electrons. Ions can be efficiently heated and accelerated in the course of their nonadiabatic interaction with a thin CS or in the vicinity of a magnetic reconnection X line [e.g., Ashour-Abdalla *et al.*, 1993, 1996, and references therein, Hoshino *et al.*, 1998], while electrons can be efficiently heated adiabatically in the course of gradient and curvature drifts in the reconnection pileup region and by surfatron acceleration at the boundary [e.g., Hoshino *et al.*, 2001; Hoshino, 2005; Imada *et al.*, 2007; Fu *et al.*, 2013a], in the contracting and/or coalescing magnetic islands [e.g., Drake *et al.*, 2006; Oka *et al.*, 2010], in dipolarization events [e.g., Birn *et al.*, 2013, and references therein], and in the course of their earthward convection by the convection electric field [Lyons, 1984].

The different efficiencies of the heating mechanisms affect the value of  $T_p/T_e$ . An important source of hot ion population in the near-Earth tail are bursty bulk flows (BBF), which transport the heated ion population from the distant acceleration sources to near Earth [e.g., Angelopoulos *et al.*, 1992; Sergeev *et al.*, 1996; Ohtani *et al.*, 2004; Sharma *et al.*, 2008]. During these periods electrons can experience adiabatic betatron and/or Fermi accelerations at the associated dipolarization fronts [e.g., Fu *et al.*, 2011; Birn *et al.*, 2013, 2014, and references therein]. These mechanisms are believed to be the major acceleration mechanisms for electrons. However, as it was shown in analytical simulations by Zelenyi *et al.* [1990] and in a recent MHD simulation of magnetotail reconnection, flow bursts and dipolarization by Birn *et al.* [2013] ions, although nonadiabatic, experience the similar acceleration as adiabatic electrons, at least, in the cases when the spatial scale of magnetic field gradient exceeds an ion gyroradius and full orbit integration can be applied. This comes from the fact that

in the presence of the magnetic field gradient and the dawn-dusk electric field the net energy gain of non-adiabatic ions is obtained at the last part of their orbits because of the difference between the duskward and dawnward parts of the ion trajectory. Since this is also the essence of betatron mechanism, the last generally should not affect the  $T_i/T_e$  ratio.

However, significant variations of  $T_i/T_e$  were reported in many studies using different instruments and different criteria for the plasma region selection. [e.g., Baumjohann *et al.*, 1989; Kaufmann *et al.*, 2005; Artemyev *et al.*, 2011; Wang *et al.*, 2012; Runov *et al.*, 2015]. Baumjohann *et al.* [1989], by using the Active Magnetospheric Particle Tracer Explorers/Ion Release Module data, reported that the value of  $T_i/T_e$  ranges between  $\sim 5$  and  $\sim 10$  with an average value  $\sim 7.0$ . Similar values of  $T_i/T_e$  were obtained by Kaufmann *et al.* [2005] using the Geotail data. For their analysis the authors used observations with  $T_e \leq 11$  MK that in some cases may cause an overestimation of  $T_i/T_e$ .

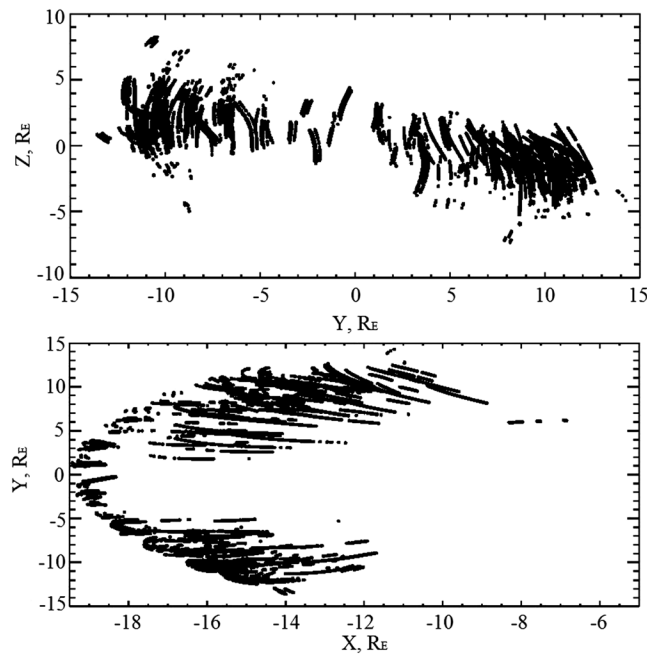
Wang *et al.* [2012] used Time History of Events and Macroscale Interactions during Substorms (THEMIS) observations to study statistically how  $T_i/T_e$  ratio changes spatially in the magnetosheath and in magnetotail and to identify the processes responsible for these changes. Authors showed that changes in  $T_i/T_e$  depend on the initial state of the PS, on the interplanetary magnetic field (IMF) direction, and on AE index. It was demonstrated that during the periods of cool PS  $T_i/T_e$  varies between  $\sim 6$  and 10. This value increases closer to the magnetotail flanks and during the periods of northward IMF. During the period of hot PS and high AE index  $T_i/T_e$  decreases and becomes  $\sim 2$ –5. Authors suggested that the lower values of  $T_i/T_e$  can be produced by nonadiabatic heating of electrons. For the near-Earth tail region ( $X > -10 R_E$ ) authors reported a strong dawn-dusk asymmetry with very high  $T_i/T_e$  ( $\sim 15$ –100) observed near the dusk flank and very low  $T_i/T_e$  ( $\sim 1$ ) registered near the dawn flank. Authors explained this feature by gradient drift of hot ions toward the dusk flank and of hot electrons toward the dawn flank.

Runov *et al.* [2015] used THEMIS data to study average thermodynamic properties of the plasma in and around dipolarizing flux bundles (DFB) in the magnetotail at radial distances  $5 < R < 25 R_E$ . To select the PS region, authors used samples collected within  $|B_X| < 15$  nT for  $R < 12 R_E$  and  $|B_X| < 10$  nT for  $R > 12 R_E$ . They reported that for relatively cold ion populations ( $T_i < 10$  keV) the average value of  $T_i/T_e$  is  $\sim 7$ , while for the hotter ion population and closer to the Earth (at  $R < 12 R_E$ )  $T_i/T_e$  decreases down to  $\sim 1.0$ . The analysis of nine events with  $T_i/T_e \sim 1$  showed that seven of them were detected near the dawn side of DFB. Authors explained the drop of  $T_i/T_e$  by the gradient drifts of ions and electrons in opposite directions, so that hotter electrons appear near the dawnward edge of DFB, while hot ions drift duskward.

Sergeev *et al.* [2015] using data from six tail seasons of THEMIS observations showed statistically that proton and electron temperature and pressure depend in a different ways on solar wind conditions and substorms. While the proton parameters are well correlated with the solar wind density, velocity, and temperature, the behavior of electron temperature and pressure in the PS is mostly controlled by the substorm-related processes. Authors showed that during the periods of BBFs electrons experience a stronger heating than protons, so that  $T_i/T_e$  can occasionally drop down to  $\sim 1$ .

Strong variations of proton-to-electron temperature were reported in a statistical study by Artemyev *et al.* [2011] based on 4 years of Cluster observations in the near-Earth magnetotail. Authors reported that the average value of  $T_p/T_e \sim 3.5$ , and it can occasionally decrease below 2.0. Authors used proton moments obtained by the Composition and Distribution Function Analyzer (CODIF) [Réme *et al.*, 2001], which measures proton population in energy range below 40 keV. They found statistically that the dependence of  $T_p$  on  $T_e$  can be approximated by the power law function and showed that the higher values of  $T_e$  are observed during intervals of larger values of the ion and electron bulk velocities.

Summarizing the previous results, one can conclude that the transient processes in the PS associated with the substorm-related phenomena (magnetic dipolarizations, bursty bulk flows, and so on) may affect electron population in much significant way than the ion one and cause the decrease of  $T_p/T_e$ . In the present paper we study in detail the PS dynamics observed during the periods of low  $T_p/T_e$  ( $\leq 3.5$ , the average value reported by Artemyev *et al.* [2011]) in order to identify the additional nonadiabatic mechanisms which may affect electron and/or proton temperature and cause  $T_p/T_e$  decrease. For this purpose we study 5 years of Cluster observations in the PS of the near-Earth tail ( $-19 < X \leq -7 R_E$ ) using the  $|B_X| \leq 10$  nT as the PS selection criterion. To determine proton temperature, we used both CODIF data and the observations provided by the “Research



**Figure 1.** The scatterplots of the PS samples used in our studies in the (YZ) and (XY) planes.

from our database, in which  $T_p/T_e \leq 3.5$  is observed and describe phenomena associated with the  $T_p/T_e$  decreases.

## 2. Data Selection and Statistical Distribution of $\langle T_p/T_e \rangle$

We have analyzed 5 years of Cluster observations in the near-Earth magnetotail in 2001–2005. The PS intervals were selected as the samples when  $|B_x| \leq 10$  nT within the region with  $-19 < X \leq -7 R_E$  and  $|Y| < 15 R_E$ . The magnetic field data are obtained by the fluxgate magnetometer (FGM) [Balogh *et al.*, 2001]. The electron moments are obtained by the Plasma Electron and Current Experiment (PEACE) [Johnstone *et al.*, 1997].

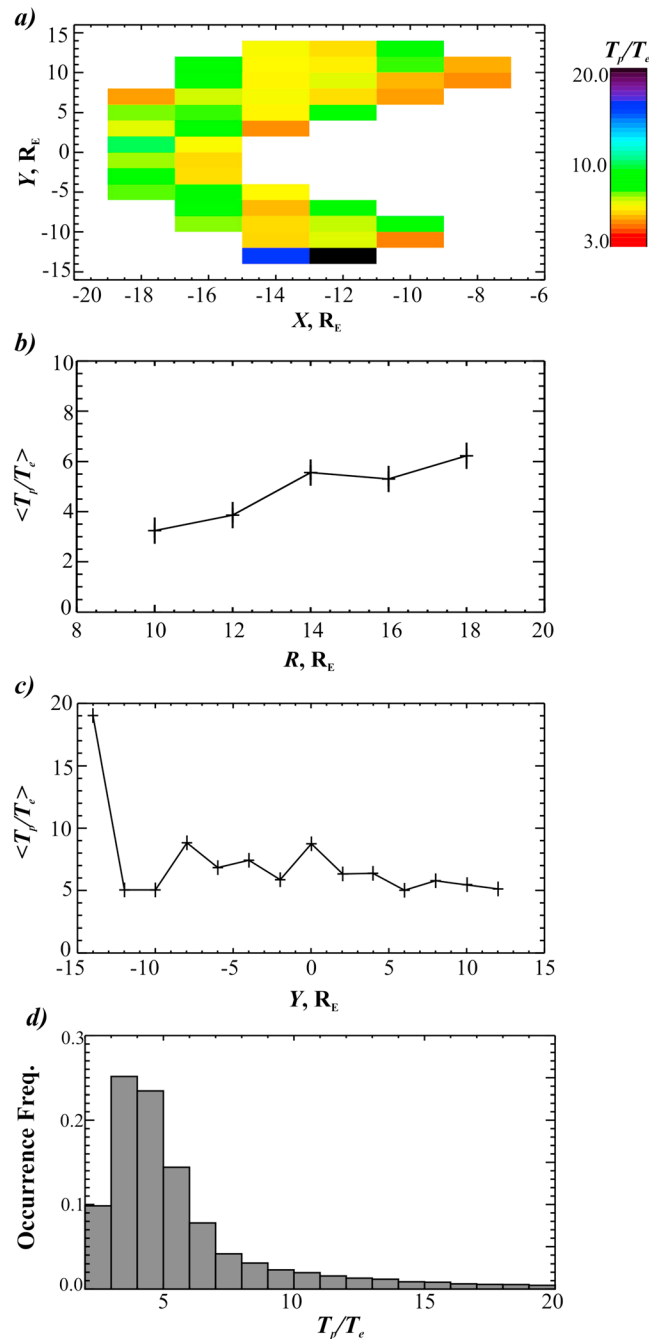
We used observations from Cluster 1 and Cluster 3 spacecraft (hereafter CI-1 and CI-3) and found in total 731,961 PS samples (4 s bins) observed in 160 intervals. The GSM coordinate system was used for orbit and magnetic field data. In Figure 1 we display the scatterplots of the selected PS samples in the (YZ) and (XY) planes.

For each PS sample the values of the proton and electron moments were obtained from the Cluster Science Archive and interpolated (a linear interpolation was used) to the magnetic field data. It is worth noting that during periods of strong ion heating the proton temperature and  $T_p/T_e$  value can be underestimated, because the ion energy approaches the upper energy threshold of the CODIF instrument, and, hence, only the low energy part of the high-energy ion population is actually measured. Indeed, in our database in approximately 30% of the PS crossings the energy corresponding to the peak of proton flux exceeded 20 keV. To avoid such bias, we performed a visual analysis of the intervals with low values of  $T_p/T_e$  ( $\leq 4.0$ ). For those PS intervals in which proton energy corresponding to the peak particle flux becomes  $\geq 20$  keV ( $\sim$ half of the value of the CODIF upper energy threshold), we calculate  $T_p$  using both CODIF and RAPID observations according to the method described by Daly and Kronberg [2015] and Kronberg *et al.* [2015]. By combining observations from the two Cluster instruments (CODIF and RAPID) we have found that the minimum trusted value of  $T_p/T_e$  is  $\sim 2.0$ .

A possible other bias could come from the entry of low  $T_p/T_e$  plasma populations (of solar wind origin) from the flanks during low solar wind Mach number [Lavraud *et al.*, 2009] or northward IMF  $B_z$  period [Fu *et al.*, 2012a]. In such instances a low  $T_p/T_e$  is observed in the magnetosheath from overall lower particle heating, and of protons in particular, at the low Mach number bow shock. Subsequent entry of this low  $T_p/T_e$  through the magnetopause was observed [Lavraud *et al.*, 2009]. However, this does not appear to be a possible bias for the low  $T_p/T_e$  events from our database, since they statistically correspond to more central PS intervals with typical high temperatures, so that the plasma seems heated by local magnetotail processes.

with Adaptive Particle Imaging Detectors" (RAPID) [Wilken *et al.*, 2001] to avoid a possible underestimation of proton temperature and  $T_p/T_e$  value during hot PS periods.

The structure of the paper is as follows. In the next section we describe the data selection for the statistical analysis and present the statistical distribution of the average  $\langle T_p/T_e \rangle$  value in the PS. In section 3 we show one example from our database in which a  $T_p/T_e \sim 2.0$  was observed and discuss the associated PS dynamics. In section 4 we present the statistical analysis to reveal at which phase of the PS dynamics the minimum of  $T_p/T_e$  is observed. In the last section we summarize our results and discuss the possible mechanisms responsible for the decrease of  $T_p/T_e$  in the near-Earth tail. In Appendix A we present the list of the PS intervals



**Figure 2.** (a) The statistical distribution of the average values of  $\langle T_p/T_e \rangle$  in the (XY) plane. The  $\langle T_p/T_e \rangle$  were averaged over  $2 R_E \times 2 R_E$  bin. The colored scale in the right part of the figure displays the values of  $\langle T_p/T_e \rangle$ . (b) The  $\langle T_p/T_e \rangle$  (R) profile integrated over all Y locations for a given R bin. (c) The  $\langle T_p/T_e \rangle$  (Y) profile integrated over all R locations for a given Y bin. (d) A histogram of the occurrence frequency distribution of the  $T_p/T_e$  observed in the PS samples from our database.

dawn-dusk asymmetry in the  $T_i/T_e$  distribution with the smallest values of  $T_i/T_e$  detected at the dawn flank. This discrepancy can be explained by different radial distances between our observations and those of Wang et al. The asymmetry reported by Wang et al. was observed closer to the Earth at  $X > -6 R_E$ . The authors suggested that the decrease of the  $T_i/T_e$  in the dawn flank and its increase in the dusk flank are

Figure 2a presents the statistical 2D distribution of the average values of  $\langle T_p/T_e \rangle$  in the (XY) plane within the region of interest. The  $\langle T_p/T_e \rangle$  were averaged within each  $2 R_E \times 2 R_E$  bin. To construct this distribution, we use only those (XY) bins in which the number of data samples exceeded 10. The bins in which the number of data samples  $\leq 10$  are colored white. The majority of the other colored bins contain  $> 100$  data samples per bin.

The value of  $\langle T_p/T_e \rangle$  averaged over the whole region of study is  $\sim 6.0$ . The median value of the observed  $T_p/T_e$  is 4.5. Figure 2b displays the  $\langle T_p/T_e \rangle$  (R) profile integrated over all Y locations for a given R bin. One can see that the  $\langle T_p/T_e \rangle$  decreases toward the Earth from  $\sim 6.0$  at  $R \sim 18 R_E$  to  $\langle T_p/T_e \rangle \sim 3.0$  at  $R \sim 10 R_E$ , which is consistent with the previous results of  $T_i/T_e$  spatial behavior obtained by THEMIS observations [Wang et al., 2012; Runov et al., 2015]. Unfortunately, magnetotail segments of Cluster orbits during the time period studied do not allow the detailed study of the radial distribution of the  $T_p/T_e$  in the PS within the midnight sector ( $|Y| \leq 5 R_E$ ).

Figure 2c shows the  $\langle T_p/T_e \rangle$  (Y) profile integrated over all R locations for a given Y bin. Within the  $R \sim 10$  to  $18 R_E$  no evident dawn-dusk asymmetry in the  $\langle T_p/T_e \rangle$  distribution is observed. There is an increase of  $T_p/T_e \sim 20.0$  at  $Y \sim -14 R_E$ . Although there are many data samples ( $\sim 1500$ ) within the corresponding Y bin, this was only a single PS crossing when very hot proton population was observed.

The absence of dawn-dusk asymmetry in the  $\langle T_p/T_e \rangle$  distribution obtained from our observations is opposite to the results by Wang et al. [2012], which reported a

associated with the gradient drifts of hot ions and electrons toward the dusk and dawn flanks, respectively. Near the Earth this effect dominates. However, further downtail other mechanisms can smear out this asymmetry. In the following sections we discuss another possible mechanism which can contribute to the decrease of  $T_p/T_e$  in the PS.

Figure 2d presents a histogram of the occurrence frequency distribution of the  $T_p/T_e$  observed in the PS samples from our database. It is seen that a wide range of the  $T_p/T_e$  is detected in the PS. The most frequently observed values are  $3.0 \leq T_p/T_e < 5.0$ . The lower and upper quartiles are 4.0 and 5.5, respectively. There is also some fraction of the PS samples in which the  $T_p/T_e < 3.0$  is observed. An example of such observations is presented in the next section.

### 3. Variations of the $T_p/T_e$ and Associated PS Dynamics

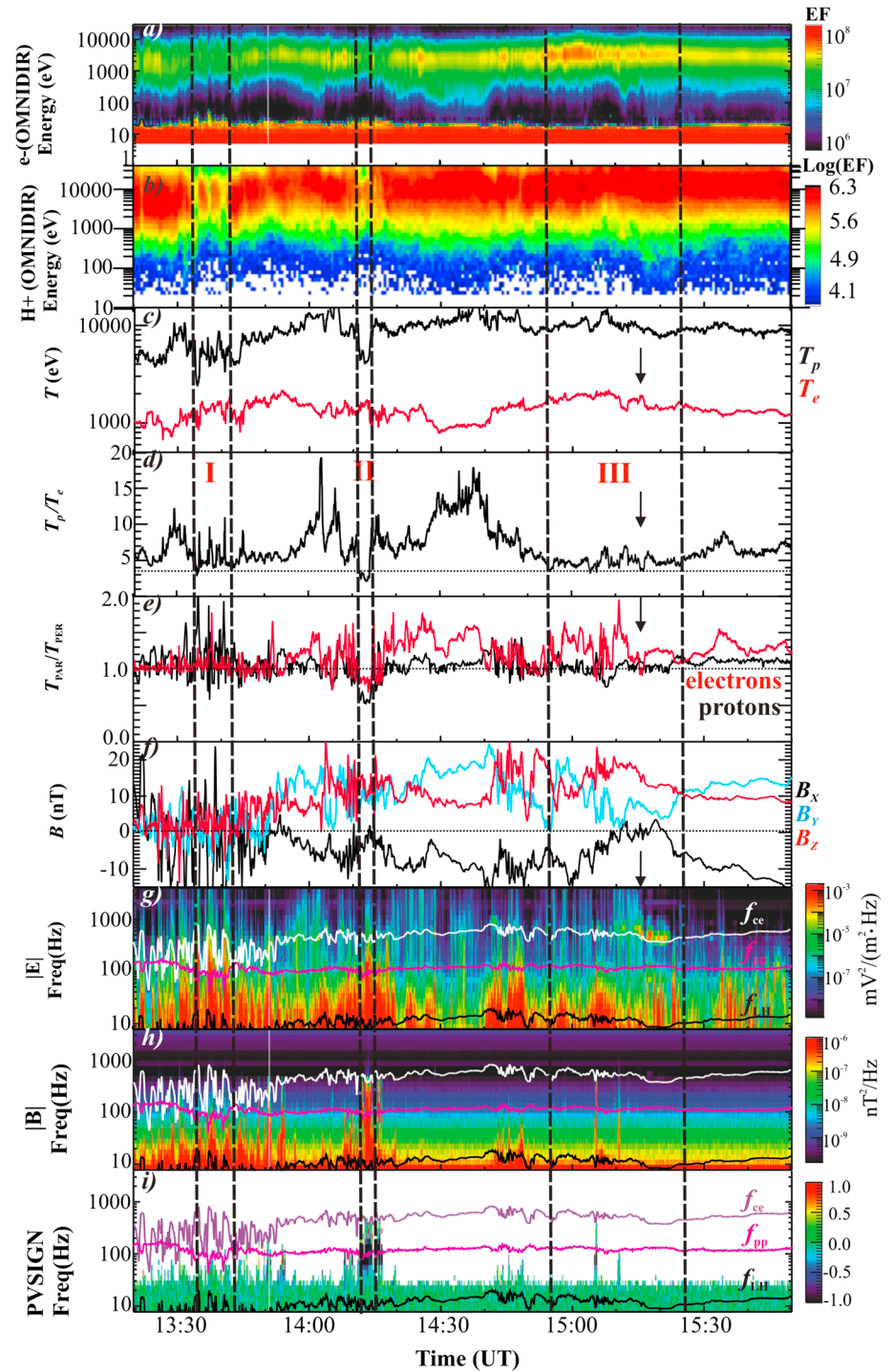
It was mentioned above that the  $T_p/T_e$  value varies significantly in the PS and can occasionally drop down to  $\sim 2.0$ . Figure 3 shows an example of the PS crossing by Cl-1, in which such a phenomenon was observed. On 8 October 2001 between 13:20 and 15:50 UT Cluster was located in the magnetotail PS at  $[-15.7, 9.7, -0.2] R_E$ . During the interval of interest the energy corresponding to the peak electron flux is well below the upper energy threshold of the PEACE instrument (see electron energy-time spectrogram in Figure 3a). However, for protons the energy corresponding to the peak flux approaches to the upper energy threshold of the CODIF instrument (see energy-time spectrogram of protons in Figure 3b). Thus, to calculate  $T_p$ , we used both CODIF and RAPID data.

From the time profiles of the  $T_p$  and  $T_e$  shown in Figure 3c it is seen that during this event there are periods when the temperatures of both species change in a similar way, so that  $T_p/T_e$  is roughly constant. Such changes of particle temperature without affecting the  $T_p/T_e$  value are most likely caused by the adiabatic mechanisms operating during magnetic dipolarizations and discussed before by, e.g., Zelenyi *et al.* [1990], Fu *et al.* [2011], Birn *et al.* [2013], and Runov *et al.* [2015]. However, there are also periods when either the  $T_p$  and  $T_e$  change in an opposite way or their increase (or decrease) occurs with different speeds. This leads to the observed significant variations in  $T_p/T_e$  between  $\sim 20.0$  and  $2.0$  (see Figure 3d). Such strong variations may indicate the importance of additional, possible, nonadiabatic mass-dependent mechanisms of particle heating. We may roughly select three periods when  $T_p/T_e$  becomes  $\leq 3.5$ , which are marked as “I,” “II,” and “III” and by vertical dashed lines in Figure 3.

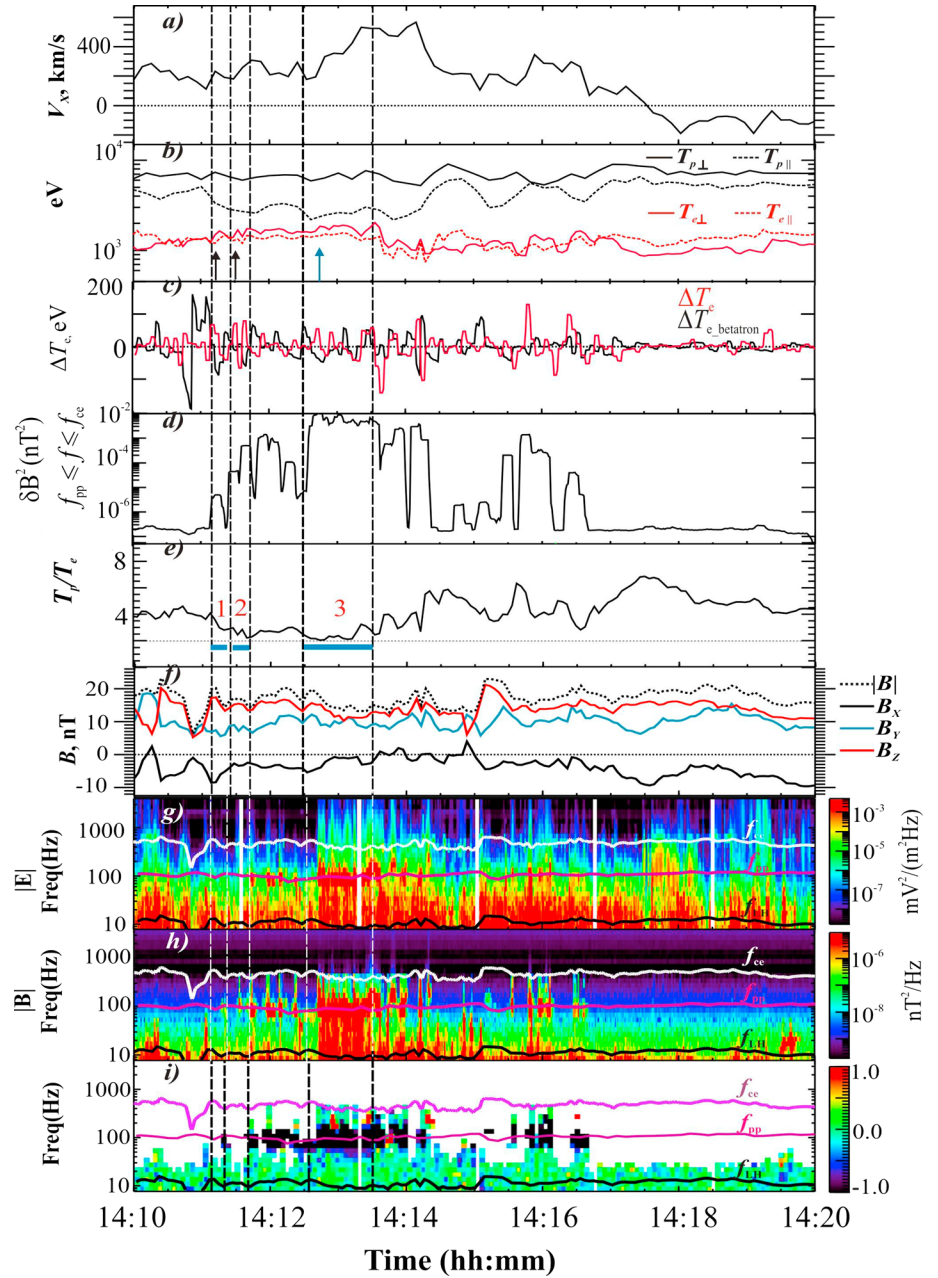
Between 13:20 and 15:50 UT several periods of magnetic dipolarization are observed. The first strong dipolarization starts around 14:03 UT with the positive jump  $\Delta B_z \sim 23$  nT (see Figure 3f). After the onset the  $B_z$  field remains larger than it was before the onset and fluctuating during  $\sim 0.5$  h. Five transient pulses of the  $B_z$  field with the amplitudes 8–16 nT were observed within  $\sim 8$  min after the onset. At the later phase of the dipolarization event (between 14:11 and 14:19 UT) only one pulse of the  $B_z$  field was observed (at  $\sim 14:15$  UT). During this later phase, which we will call below as the “turbulent” phase of dipolarization, the  $B_z$  field remains still large and experiences low-amplitude fluctuations along with the enhancement of wave activity in the frequency range up to electron gyrofrequency ( $f_{ce}$ ) (see Figures 3g and 3h).

The first drop of  $T_p/T_e$  (period I) precedes the onset of dipolarization. During this period strong PS flapping is observed: the  $B_x$  field experiences fast variations between  $-15$  nT and  $+20$  nT, so that the Cluster periodically exits to the outer PS. Bursts of wave activity are observed in the electric and magnetic field wave spectra measured from 8 Hz to 4096 Hz by the Spatio-Temporal Analysis of Field Fluctuations (STAFF) experiment [Cornilleau-Wehrlin *et al.*, 2003] and shown in Figures 3g and 3h. The time profiles of  $f_{ce}$ , proton plasma frequency ( $f_{pp}$ ) and the lower hybrid frequency  $f_{LH} = (f_{ce} \cdot f_{ci})^{1/2}$  are shown by white, magenta, and black lines, respectively. The values of proton and electron temperatures experience variations and  $T_p/T_e$  ranges between  $\sim 10$  and  $\sim 3.0$ . We do not discuss the period I in detail, since because of the fast PS flapping it is difficult to link the  $T_p/T_e$  variations with specific processes in the central PS. We just mention briefly that during this period the broadband electromagnetic emissions (EMEs) from 0.25 Hz to several tens of hertz ( $\leq f_{pp}$ ) are observed. At higher frequencies (up to  $f_{ce}$ ) the electrostatic emission is detected. The power of this emission increases in the outer part of the PS (in the region with  $|B_x| > 10$  nT) and decreases in the central PS region (not shown). These fluctuations may represent the broadband electrostatic noise (BEN), which is often observed in the plasma sheet boundary layer and in the outer PS in the course of propagation of field-aligned





**Figure 3.** An example of the PS crossing by CI-1 On 8 October 2001, in which the decreases of  $T_p/T_e$  below 3.5 were observed. The energy-time spectrograms of omnidirectional (a) electrons (PEACE data) and (b) protons (CODIF data); (c) the time profiles of the  $T_p$  (black line) and  $T_e$  (red line); (d)  $T_p/T_e$ ; (e)  $T_{PAR}/T_{PER}$  for protons (black line) and electrons (red line); (f) the three components of the magnetic field; the frequency spectra of the (g) electric |E| and (h) magnetic |B| field fluctuations in frequency range 8–4096 Hz; and (i) the time-frequency distribution of the value of angle between the Poynting flux of electromagnetic fluctuations and the ambient magnetic field obtained by STAFF experiment. The time profiles of  $f_{ce}$ ,  $f_{pp}$ , and  $f_{LH}$  are shown by the white, magenta, and black lines, respectively, in Figures 3g and 3h and by the purple, magenta, and black lines, respectively, in Figure 3i.



**Figure 4.** The zoom of the interval “II,” in which the minimum of  $T_p/T_e$  was observed (see Figure 3). Time profiles (a) of  $X$  component of proton bulk velocity and (b) of proton (in black) and of electron (in red)  $T_{\parallel}$  and  $T_{\perp}$ ; (c) the variations of electron temperature  $\Delta T_e$  observed by PEACE instrument (in red) and the variations of electron temperature expected from the betatron heating  $\Delta T_{e, \text{betatron}}$  (in black); (d) the time profile of the magnetic fluctuations power  $\delta B^2$  integrated in  $[f_{pp}, f_{ce}]$  frequency range; (e) the time profile of  $T_p/T_e$ ; and (f) three components of the magnetic field and (g–i) STAFF observations in the same format as in Figure 3.

beams [e.g., Gurnett et al., 1976; Matsumoto et al., 1994]. The study of these phenomena is beyond the scope of the present paper.

After the dipolarization onset, during period II, the strongest variations of  $T_p/T_e$  between 19.0 and 2.0 are observed. During this period Cluster was mainly located in the central PS ( $|B_X| \leq 5$  nT). A zoom of CI-1 observations during period II is shown in Figure 4. The absolute minimum of  $T_p/T_e \sim 2.0$  was observed at 14:12:44 UT, i.e., after the observation of multiple  $B_Z$  pulses (see Figure 4e). Figure 4b shows the time profiles of parallel and perpendicular temperatures of protons (black line) and electrons (red lines). Since during this period



the energy corresponding to the peak proton flux was well below the upper energy threshold of the CODIF instrument (see proton energy-time spectrogram in Figure 3b), we used the parallel and perpendicular proton temperatures calculated from the CODIF data.

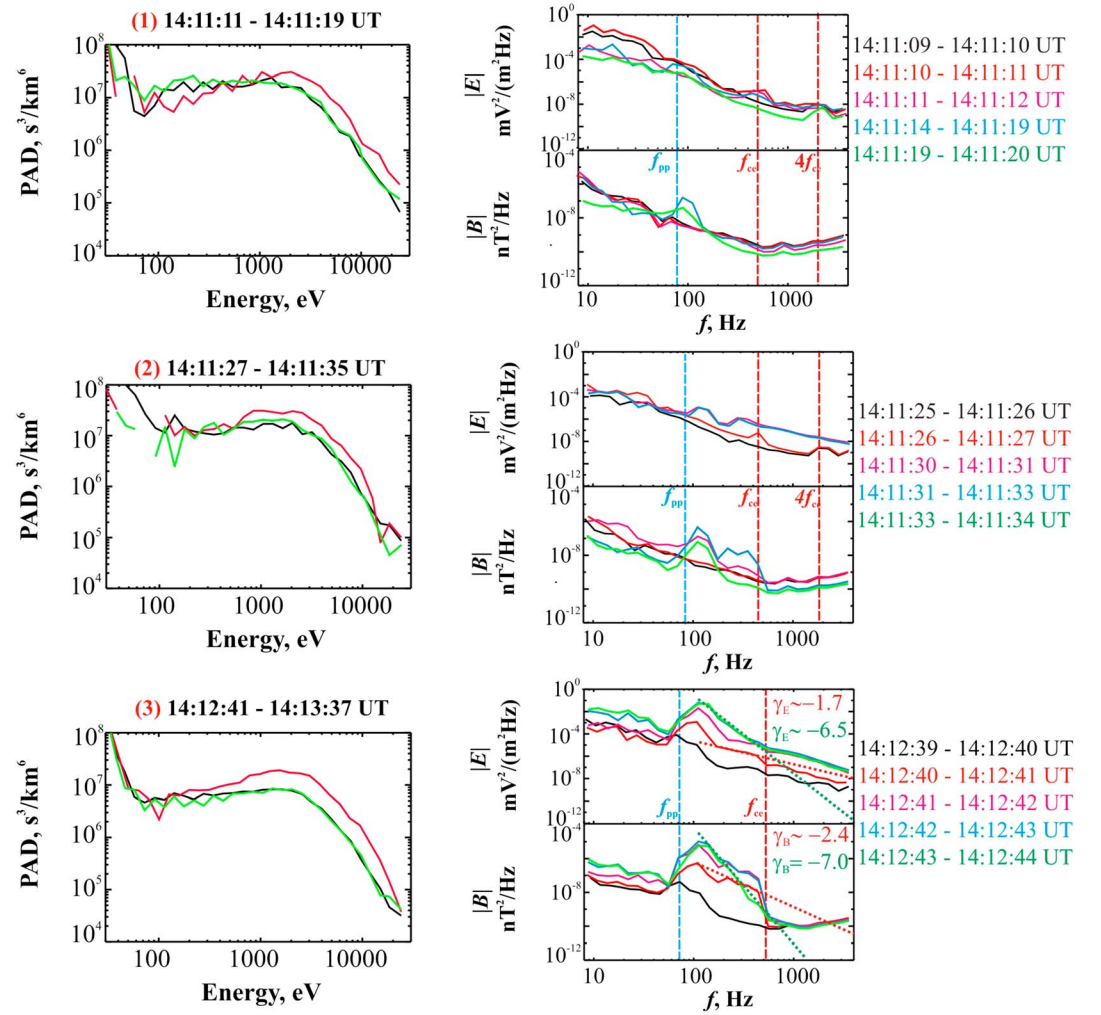
In the beginning of the interval, between 14:10 and 14:10:45 UT,  $T_p/T_e$  experiences small variations around  $\sim 4.0$  (see Figure 4e). From 14:10:45 UT  $T_p/T_e$  starts to decrease. Between 14:10:45 and 14:11:11:45 UT the decrease of  $T_p/T_e$  was due to the significant decrease of  $T_p$  and the increase of  $T_e$ . The decrease of  $T_p$  while electrons are being heated is a puzzling feature. Zelenyi *et al.* [1990] and Birn *et al.* [2013] showed that the betatron mechanism of electron heating and nonadiabatic ion interaction with the CS in the presence of magnetic field gradient provide the similar energy gain for both plasma components. This condition can be broken if the characteristic spatial scale of magnetic field gradient becomes less than an ion gyroradius  $\rho$ . The observed anticorrelation between  $\Delta T_p$  and  $\Delta T_e$  may indicate the existence of the small-scale ( $\leq \rho_p$ ) magnetic gradients. In such case one can observe only that part of a proton orbit at which particle moves in the direction opposite to the electric field and loses its energy. Another possibility of the  $T_p$  decrease is the dissipation of their energy due to the interaction with low-frequency waves. Also, the observed decrease of  $T_p$  can be due to the crossing of different plasma tubes populated by plasma coming from different sources. This puzzling feature deserves further investigation.

Electrons are heated mainly by betatron mechanism [e.g., Fu *et al.*, 2011; Birn *et al.*, 2013, 2014]. But sometimes additional mechanisms may contribute to the observed variations of  $T_e$ . In Figure 4c we present the time profile of electron perpendicular temperature gain measured by PEACE instrument at the  $i$ th time moment:  $\Delta T_{e\perp}(i) = T_{e\perp}(i) - T_{e\perp}(i-1)$  (it is shown by the red line) and the time profile of electron temperature gain expected from the betatron heating:  $\Delta T_{e\text{-betatron}} = T_{e\perp}(i-1) \cdot \frac{B(i)}{B(i-1)} - T_{e\perp}(i-1)$  (shown by the black line). One can see that there are time moments when  $\Delta T_{e\perp}$  and  $\Delta T_{e\text{-betatron}}$  have opposite signs. At such moments additional mechanisms may contribute to the observed changes of  $\Delta T_{e\perp}$ .

In Figure 4d we show a power  $\delta B^2$  of the magnetic field fluctuations integrated over the  $[f_{pp}, f_{ce}]$  frequency range. It is seen that the positive  $\Delta T_{e\perp}$  are often observed at the moments of the  $\delta B^2$  increase. The correlation coefficient between  $\delta B^2(t)$  and  $\Delta T_{e\perp}(t)$   $CC \sim 0.62$ . As it was discussed by Fu *et al.* [2011, 2012a, 2014], the betatron heating of electrons increases their perpendicular anisotropy, which, in turn, can be a source for the whistler wave generation. For a few short intervals corresponding to the period of  $T_p/T_e$  decrease we tried to define a link between the changes in electron anisotropy and in the wave spectra. These intervals are marked as "1," "2," and "3" in Figure 4.

Before the start of interval "1" at 14:11:11 UT the electron distribution was almost isotropic (see Figure 4b). At 14:11:11 UT the perpendicular anisotropy increases. The moment of  $\Delta T_{e\perp}$  increase is marked in Figure 4b by the black arrow. Around this moment  $\Delta T_{e\perp}$  and  $\Delta T_{e\text{-betatron}}$  variations have the opposite signs (Figure 4c). Thus, the betatron mechanism cannot be responsible for the observed increase of electron perpendicular temperature. In Figure 5 we show the energy distribution of  $0^\circ$ ,  $90^\circ$ , and  $180^\circ$  electrons measured at 14:11:11–14:11:19 UT along with the time series of 1 s averaged spectra of the electric and magnetic field fluctuations observed by STAFF instrument just before and during the two-spin period. One can see that just 1 s before the appearance of the perpendicular anisotropy the increase of electric field power localized near  $f_{ce}$  is detected. The electron cyclotron harmonics (ECH) was observed during  $\sim 2$  s and then disappeared. Note that the observation of ECH after dipolarization onset was previously reported by Zhou *et al.* [2009] and Zhang and Angelopoulos [2014]. They demonstrated that these fluctuations can energize resonant electrons. The generation of the ECH can be due to the positive slope in  $90^\circ$  electron distribution observed in the energy range 0.2–1 keV at 14:11:03–14:11:11 UT (not shown) [e.g., Zhou *et al.*, 2009]. We can assume that the ECH can contribute to the perpendicular electron heating and the increase of the perpendicular anisotropy.

Approximately 4 s after the increase of  $T_{e\perp}$  a bulge near  $f_{pp}$  appears both in the electric field and magnetic field power spectra. Figure 4i shows the direction of the Poynting flux of EME relative to the ambient magnetic field. It is seen that the broadband EME consists of oblique wave modes in the low-frequency range ( $f \leq f_{pp}/2$ ), which may represent Alfvén waves. The waves with  $f \sim f_{pp}$  have their Poynting flux directed almost parallel to the ambient magnetic field. During this time Cl-1 was located mainly in the southern part of the central PS (see the time profile of  $B_x$  field in Figure 4h), so that the wave modes with  $f \sim f_{pp}$  propagated outward from the neutral sheet. Such behavior is typical for whistler modes, which are often observed during



**Figure 5.** Pitch angle distributions (PAD) of electrons and the spectra of electric  $|E|$  and magnetic  $|B|$  field fluctuations observed in three time periods (“1–3”) marked by the blue horizontal lines in Figure 4.

magnetic dipolarizations and near a reconnection region [e.g., Petkaki et al., 2006; Le Contel et al., 2009; Viberg et al., 2014; Fu et al., 2014]. Thus, we may assume that the generation of ECH before the start of interval “1” caused the perpendicular heating of electrons in a finite energy range and the increase of perpendicular anisotropy. The last, in turn, can be a source for the whistler wave generation with  $f \sim f_{pp}$ .

After 14:11:19 UT the perpendicular anisotropy in electron distribution decreases. By this time the ECH disappeared and the magnetic field power corresponding to the bulge near  $f_{pp}$  reduced also. The next increase of  $T_{e\perp}$  is observed during interval “2” at  $\sim 14:11:30$  UT (this moment is marked by the second black arrow in Figure 4b). Similarly to interval “1” the variations of  $\Delta T_{e\perp}(t)$  and  $\Delta T_{e\text{-betatron}}(t)$  observed during this interval do not correlate. Again, the increase of  $T_{e\perp}$  is preceded by the observation of ECH at 14:11:25–14:11:30 UT (see the corresponding spectra in Figure 5). At 14:11:30 UT a bulge near  $f_{pp}$  appears in the magnetic and electric field power spectra. This bulge then spreads to the higher frequency range up to  $f_{ce}$  denoting the generation of the broadband whistler EME. This emission disappears rapidly (compare 1 s averaged spectra at 14:11:31 and at 14:11:33 UT in Figure 5). Comparing the electron distributions measured during the periods “1” and “2,” one can see that in the last period the increase of phase space density of  $90^\circ$  electrons expanded to the lower energy range. Similarly to the previous interval, we may assume that the ECH contribute to the perpendicular heating of electrons and to the increase of perpendicular anisotropy. The last can be a source for generation of whistler waves. Possibly, the process of electron interaction with the waves had nonlinear

character, which manifests in expansion of the EME in higher frequency range up to  $f_{ce}$  and its fast damping due to the absorption of wave energy by resonant electrons.

The absolute minimum of  $T_p/T_e \sim 2.0$  was observed during interval “3” at 14:12:44 UT (this moment marked by the blue arrow in Figure 4b). Around this moment both  $T_p$  and  $T_e$  increased but  $T_e$  experienced the faster increase. The minimum of  $T_p/T_e$  coincides with the positive variation of  $T_{e\perp}$ , while the corresponding variation of  $\Delta T_{e\text{-betatron}}$  is negative. Again, we may assume that other additional mechanism contributed to the electron heating.

During interval “3” the most intense wave emissions were detected. A bulge near  $f_{pp}$  in the spectra of the magnetic and electric field fluctuations was observed permanently from  $\sim 14:12:20$  UT to  $14:12:40$  UT. This bulge can be produced by whistler waves propagating almost along the magnetic field and outward the neutral sheet (see Figures 4f and 4i). These waves can be generated due to the presence of electron perpendicular anisotropy (Figure 4b). Another possible source for the waves can be related to plasma density and magnetic field gradients [e.g., *Le Contel et al.*, 2009], which can be observed near the leading edge of a high-speed bulk flow. Indeed, the  $X$  component of proton velocity started to increase in the beginning of interval “3” and reached its maximum value  $V_X \sim 500$  km/s by the end of this interval (at 14:13:30 UT, see Figure 4a).

In Figure 5 we show the electron distribution measured around the  $T_p/T_e$  minimum at 14:12:44–14:13:40 UT and 1 s averaged wave spectra observed during 5 s interval preceding the detection of this distribution. In comparison to the previous intervals the increase of phase space density was observed for  $90^\circ$  electrons in the wider energy range: from a few hundreds of eV and up to 20 keV. In the STAFF spectra the wave power in the  $[f_{pp}, f_{ce}]$  range increased at 14:12:40 UT and it was observed until 14:12:43 UT (see the corresponding spectra in Figure 5). As in the previous periods the EME most likely represents the broadband whistler EME and consists of wave modes with  $f \sim f_{pp}$  propagating almost along the magnetic field outward the CS and the oblique waves with  $f_{pp} < f \leq f_{ce}$ . It is worth noting that the integral energy density of the EME was of the order of the observed  $\Delta n k T_e$  (not shown). Thus, we may assume that the EME can contribute to the electron heating observed during the first half of interval “3” when  $\Delta T_{e\perp}$  and  $\Delta T_{e\text{-betatron}}$  were anticorrelated.

The wave energy dissipation just 1 s before the minimum of  $T_p/T_e$  is confirmed by the significant change in the spectral slopes of the electric and magnetic field fluctuations. Indeed, the spectral indexes  $\gamma$  calculated for the electric and magnetic field power in the frequency range between the frequency of the bulge ( $\sim f_{pp}$ ) and  $f_{ce}$  changes from  $\gamma_E \sim -1.7$  and  $\gamma_B \sim -2.4$  in the beginning of interval “3” to  $\gamma_E \sim -6.5$  and  $\gamma_B \sim -7.0$  just before the  $T_p/T_e$  minimum observation. We may suggest that the changes in spectra near  $f_{ce}$  can be caused by the absorption of the wave energy by resonant electrons leading to their perpendicular heating.

In the remaining part of interval “3” the periodic increases and damping of the broadband whistler EME were repeated. At the end of interval “3,” when the maximum of the plasma bulk flow was observed a good correlation between  $\Delta T_{e\perp}$  and  $\Delta T_{e\text{-betatron}}$  took place. Indeed, the last pronounced increase of  $T_{e\perp}$  is due to the betatron heating since  $\Delta T_{e\perp} \sim \Delta T_{e\text{-betatron}}$  (Figures 4b and 4c).

Coming back to the analysis of the PS dynamics between 13:20 and 15:40 UT, one can see that the last decrease of  $T_p/T_e$  down to  $\leq 4.0$  was observed during the interval III between 14:57 and 15:27 UT (see Figure 3). The  $T_p/T_e$  decrease was due to the decrease of  $T_p$  and increase of  $T_e$  taking place just before the start of the interval. As in period II the exact mechanism responsible for  $T_p$  decrease is unknown. Before the start of interval III a dipolarization front was observed between 14:50 and 14:56:30 UT. Thus, the observed electron heating in the beginning of interval III was produced by betatron mechanism [e.g., *Fu et al.*, 2011]. For protons we may assume that the observed decrease of their temperature can be related with the above mentioned effect of a finite spatial scale of the region of magnetic gradient.

The next magnetic dipolarization started around 14:57 UT. The  $B_z$  field reached its maximum value  $\sim 24$  nT at 15:05:39 UT. Two  $B_z$  pulses were detected within  $\sim 9$  min after the onset at  $\sim 15:03:20$  UT and at  $\sim 15:05:39$  UT. After the last pulse, which corresponds to the absolute maximum value of the  $B_z$  field reached in this event, the  $B_z$  remains large and fluctuates with the smaller amplitude until  $\sim 15:14:30$  UT. This period can be referred to the “turbulent” phase of dipolarization. The fluctuations of  $T_p/T_e$  observed during the “turbulent” phase and until the end of the dipolarization (at  $\sim 15:27$  UT) are hardly related to the gradient effects, since no  $B_z$  pulses are observed during this time. Within this period the broadband electrostatic emissions and ECH

are detected by the STAFF instrument. In this event the appearance of electron cyclotron fluctuations coincides with the local increase of  $T_e$  and decrease of  $T_p/T_e$  (this moment is shown by black arrow in Figure 3). At this time, electron anisotropy (Figure 3e) also decreases to 1.0, suggesting the pitch angle scattering of electrons.

Our observations show that in the course of magnetic dipolarization nonadiabatic mechanisms related to wave-particle interactions may contribute to electron heating and the decrease of  $T_p/T_e$ . Electrostatic broadband emissions with ECH and EME with frequencies up to  $f_{ce}$  may resonantly interact with electrons and cause their energization. In the next session we present the statistical analysis of the PS dynamics during the periods when the  $T_p/T_e$  became  $\leq 3.5$  and show that the majority of such events from our database are observed after dipolarization onset, when the  $B_z$  field is still large and enhancements of in EME and electrostatic fluctuations near  $f_{ce}$  are observed.

#### 4. Statistical Analysis of the $T_p/T_e$ in the PS of the Near-Earth Tail

We analyzed 160 intervals of the PS crossings by Cluster in 2001–2005 time period. In 86 PS intervals (~54%) strong variations and drops of  $T_p/T_e \leq 3.5$  were observed. In the majority of these cases (in 85 intervals) the drops of  $T_p/T_e$  were detected during magnetic dipolarizations. The majority of dipolarization events in our database do not represent the isolated earthward propagating dipolarization fronts but can be rather referred to the “final” dipolarization events discussed by Nakamura *et al.* [2009], which can be generated in the near-Earth tail due to the flux pileup. Indeed, the magnetic dipolarizations from our database represent prolonged enhancements of the positive  $B_z$  field (up to ~10–30 nT) having a duration from a few tens of minutes up to a few hours (see Table A1 in Appendix A). In the majority of cases the onset of these events and the following general growth of the  $B_z$  field are followed by multiple transient pulses of the  $B_z$  field, which are generally observed during the first 10 min after the onset and cease at the later phase of the dipolarization. In all these events, except one, the bunches of wave activity in the frequency range up to  $f_{ce}$  and higher were detected by the STAFF experiment simultaneously with the  $T_p/T_e$  decreases.

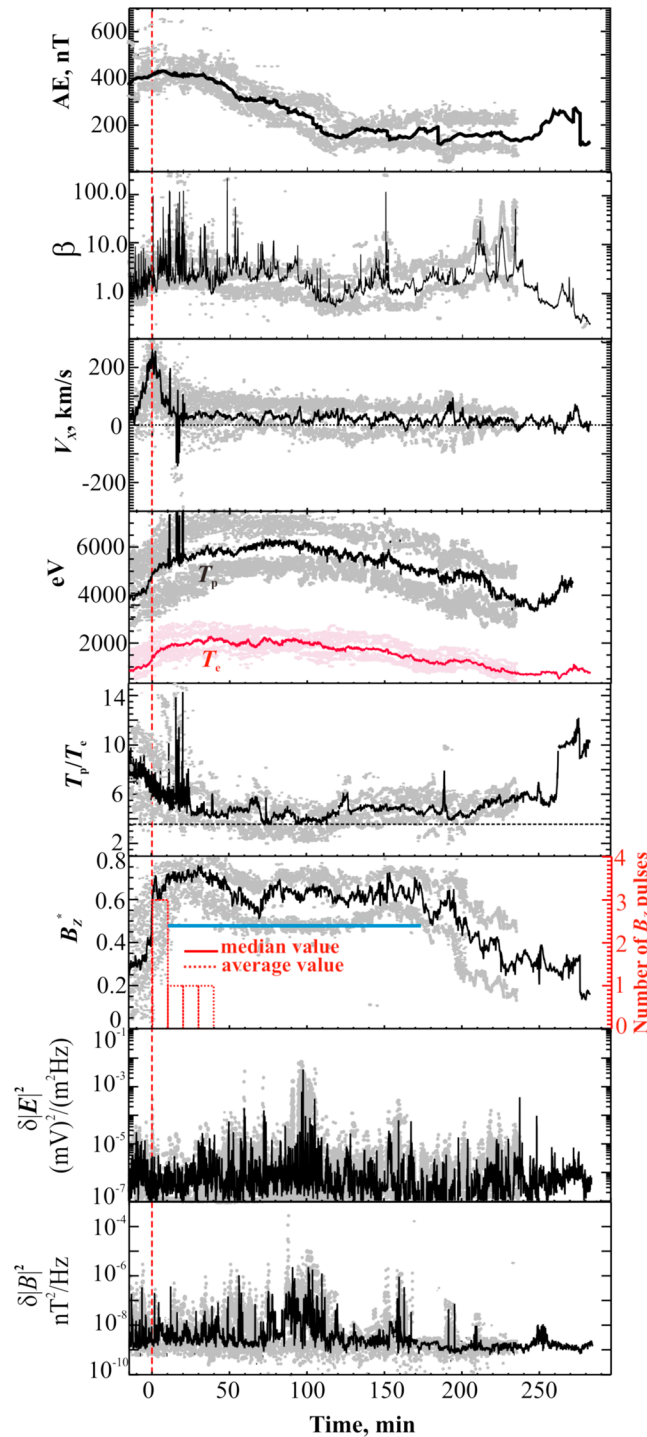
In Table A1 of Appendix A we listed these PS intervals containing the  $T_p/T_e$  drops below 3.5 and the simultaneous STAFF observations of wave activity. In the majority of these cases the decreases of  $T_p/T_e$  were associated either with the broadband EME or electrostatic emissions in the frequency range up to  $f_{ce}$ , which may heat electrons in the course of their resonant interaction with the wave modes near  $f_{ce}$ . In many cases ECH might also contribute to electron heating and to the corresponding  $T_p/T_e$  decrease.

In order to reveal statistically at which phase of magnetic dipolarization and under which conditions the  $T_p/T_e$  decreases, we apply a superposed epoch analysis to the PS intervals listed in Table A1. The epoch analysis was applied to the following parameters:  $B_z$ ,  $T_p/T_e$ ,  $T_p$ ,  $T_e$ , the  $X$  component of proton bulk velocity ( $V_x$ ), plasma  $\beta$ ,  $AE$  index, and the electric and magnetic field wave power  $\delta|E|^2(t)$  and  $\delta|B|^2(t)$  integrated within the frequency range  $[f_{pp}, f_{ce}]$ . For each event the  $B_z$  field was normalized to the maximum value of the  $B_z$  observed in a given event:  $B_z^*(t) = B_z(t)/B_z^{\max}$ .

As the epoch time ( $t = 0$ ) we use the dipolarization onset for each event similarly to the previous study by, e.g., Fu *et al.* [2012b]. But in our database the majority of cases represent rather complicated events with a multiple dipolarization pulses overlapped onto the general prolonged growth of the  $B_z$  field (see, for example, the dipolarization event observed between 14:03 and 14:35 UT in Figure 3). To choose the onset (the epoch) time, we use one of the following criteria. For the strong dipolarizations, in which the  $B_z^{\max} > 10$  nT, the epoch time is chosen as the moment of the first  $B_z$  increase with the amplitude  $\Delta B_z = B_{zi} - B_{z0} > 5$  nT, where  $B_{zi}$  is the value of the  $B_z$  increase and  $B_{z0}$  is the value of the  $B_z$  field averaged for 1 min before the increase. For a few week dipolarizations from our database with the  $B_z^{\max} \leq 10$  nT we choose the onset time as the moment of the first positive  $B_z$  increase with  $\Delta B_z \geq 0.5B_z^{\max}$ . In the epoch analysis we also include data up to 15 min before the onset.

In some dipolarization events the  $B_z$  field can transiently decrease after the onset and increase again within ten(s) of seconds denoting the presence of transient dipolarization pulse(s). We consider a variation of the  $B_z$  field observed after the onset as the  $B_z$  pulse if  $\Delta B_z > 5$  nT and  $\Delta B_z/B_{z0} > 0.5$ , where  $\Delta B_z$  is the difference between the peak value of  $B_z$  in the pulse and the value  $B_{z0}$  observed just before the pulse. It is worth noting





**Figure 6.** The results of epoch superposition analysis applied to the intervals listed in Table A1 (see Appendix A). (from top to bottom) The epoch profiles of  $AE(t)$ ,  $\beta(t)$ ,  $V_X(t)$ ,  $T_p(t)$ ,  $T_e(t)$ ,  $[T_p/T_e](t)$ , and the  $B_Z^*(t)$  and the power of electric and magnetic field fluctuations integrated with the frequency range  $[f_{pp}, f_{ce}]$ . The red dashed line indicates the onset of dipolarization in each event from our database. The horizontal blue line shows the “turbulent” phase of dipolarizations. The scatterplots of low and upper quartiles of the corresponding data sets used for the epoch analysis are displayed by the grey dots.

that in all events from our database the value of  $B_Z$  field observed after the onset and between the dipolarization pulses does not decrease below its initial level registered before the dipolarization onset. Thus, even in the presence of multiple  $B_Z$  pulses detected after the onset, the average  $B_Z$  field experiences a gradual growth up to the  $B_Z^{\max}$ , which in some events may last during tens of minutes.

Figure 6 shows the resulting epoch profiles. In order to demonstrate the spread of data used for the epoch analysis, we present in the corresponding panels of Figure 6 the scatterplots of low and upper quartiles displayed by grey dots. The zero epoch  $t = 0$  corresponding to dipolarization onset in each event is marked by the red vertical line. Along with the epoch profile of the  $B_Z^*(t)$  we show two histograms of the distribution of the average (displayed by the red dotted line) and of the mean (displayed by the solid red line) number of the transient  $B_Z$  pulses detected within each 10 min bin after the onset of dipolarization events from our database. It is seen that the maximum number of the  $B_Z$  pulses is observed within the first 10 min after the onset. After this time the mean value of the  $B_Z$  pulses calculated for the subsequent time bins is zero and the average value of the  $B_Z$  pulses is 1.0 within the next three 10 min bins and, then, becomes zero. Thus, following  $\sim 10$  min after the onset a number of transient  $B_Z$  pulses decreased by  $\geq 50\%$ , while the value of  $B_Z$  still remains large and experiences low-amplitude fluctuations. During this period the increase of wave activity in  $[f_{pp}, f_{ce}]$  range is observed. We mark this period by blue horizontal line in Figure 6 and call it as the “turbulent” phase of dipolarization.

The epoch profile of  $[T_p/T_e](t)$  experiences strong variations around dipolarization onset when the earthward and reflected high-speed flows are



observed. It is worth noting that the  $[T_p/T_e](t)$  epoch profile represents an averaged tendency of how  $T_p/T_e$  changes and its single variations (e.g., drops) are smeared. Plasma  $\beta$  experienced strong fluctuations from a few to hundred units around and just after the onset denoting the presence of density gradients. The epoch profiles of  $T_p(t)$  and  $T_e(t)$  change more or less synchronously that is consistent with the previous results reporting the increase of electron temperature with the ion temperature [e.g., Baumjohann *et al.*, 1989; Artemyev *et al.*, 2011]. However, electron temperature increases faster and reaches its maximum earlier than proton one. The intense electron heating is observed around and after the onset and during the period of fast bulk flow and the AE maximum. This confirms the importance of substorm-related processes in electron heating reported earlier by Sergeev *et al.* [2015]. The epoch profile of  $T_e(t)$  also shows that the maximum of electron temperature is prolonged in time and the “plateau” of large  $T_e(t)$  is observed during the first half of the “turbulent” phase of dipolarization, when the intensification of wave activity in high-frequency range (up to  $f_{ce}$ ) are detected.

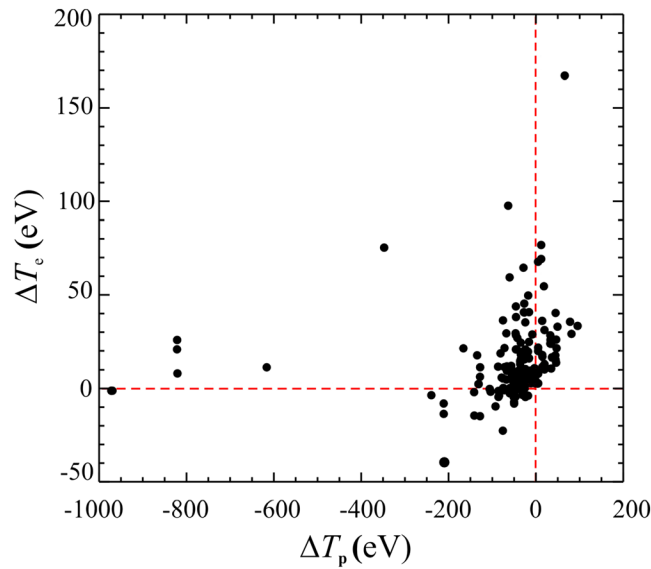
Our epoch analysis does not show the correlations between  $[T_p/T_e](t)$  and bulk flows. The maximum of  $V_x$  coincides with the dipolarization onset as it was observed before in numerous studies [e.g., Nakamura *et al.*, 2002]. Just after the onset, the positive and negative variations of  $V_x$  are observed denoting the registration of the reflected/diverged flows. During this time  $[T_p/T_e](t)$  fluctuates mainly due to  $T_p$  fluctuations. While dipolarization proceeds the  $V_x(t)$  decreases close to zero. This does not mean that flow bursts are not observed during this time. The small  $V_x$  may denote the superposition of the earthward and reflected flows and/or flow braking. At this later (“turbulent”) stage of dipolarization the increase of wave activity in  $[f_{pp}, f_{ce}]$  range is observed, and it roughly coincides with the decrease of  $[T_p/T_e](t)$  to the epoch minimum value.

Thus, we may suggest that the minimum of  $[T_p/T_e](t)$  is observed during the “turbulent” phase of dipolarization when the  $B_z$  field is still large and the wave activity is enhanced. This suggests that electron interaction with the high-frequency electrostatic and EME can be an additional mechanism providing local electron heating and affecting  $T_p/T_e$  during magnetic dipolarizations.

## 5. Discussion and Conclusion

In order to identify the PS processes which may affect electron and/or proton temperature and cause the decrease of  $T_p/T_e$ , we have studied 5 years of Cluster observations in the near-Earth tail at  $-19 < X \leq -7 R_E$  and  $|Y| < 15 R_E$  by using the  $|B_x| \leq 10$  nT as the criterion for PS selection. We have found and analyzed 160 intervals of PS crossings by Cluster. To avoid underestimation of  $T_p$  for the hot PS intervals, when the energy corresponding to the peak of proton flux exceeded 20 keV (~30% of the PS crossings in our database), we calculate  $T_p$  using both CODIF and RAPID observations [Daly and Kronberg, 2015; Kronberg *et al.*, 2015]. Below we summarize our main results:

1. The value of  $T_p/T_e$  averaged over the whole region of the PS under study is  $\sim 6.0$ . This result is more or less in agreement with earlier results obtained from the observations by other space missions [e.g., Baumjohann *et al.*, 1989; Kaufmann *et al.*, 2005]. However, our estimation of the average value of  $T_p/T_e$  is larger than the one obtained in statistical study of Cluster observations by Artemyev *et al.* [2011]. According to their results the  $\langle T_p/T_e \rangle \sim 3.5$ . We explain this discrepancy by  $T_p$  calculation using both CODIF and RAPID observations during hot PS intervals, while Artemyev *et al.* [2011] used only CODIF data.
2. The  $T_p/T_e$  value decreases toward the Earth from  $\sim 6.0$  at  $R \sim 18 R_E$  to  $\langle T_p/T_e \rangle \sim 3.0$  at  $R \sim 10 R_E$ , which is consistent with the previous results of  $T_i/T_e$  spatial behavior obtained by THEMIS observations [Wang *et al.*, 2012; Runov *et al.*, 2015]. Within the radial distances  $-9$  to  $-19 R_E$  no evident dawn-dusk asymmetry in the  $\langle T_p/T_e \rangle$  distribution is observed.
3. Within a single PS interval the value of  $T_p/T_e$  may fluctuate in a wide range from a few units to several tens of units. According to our observations the minimum trusted value (from instrument limitations of Cluster) of  $T_p/T_e$  in the PS is  $\sim 2.0$ . The decreases of  $T_p/T_e$  below 3.5 (the average estimation obtained by Artemyev *et al.* [2011]) were detected in 86 PS intervals from our database. In the majority of these cases (in 85 intervals) the drops of  $T_p/T_e$  were observed during magnetic dipolarizations.
4. The superposed epoch analysis applied to the dipolarization events in which decreases of  $T_p/T_e \leq 3.5$  were observed in the PS shows that the  $T_p/T_e$  experiences strong variations around the dipolarization onset and decreases after the onset, during the “turbulent” phase of dipolarization, when the  $B_z$  field in the CS is still



**Figure 7.** A scatterplot of variation  $\Delta T_e$  versus  $\Delta T_p$  at the moments of minimum  $T_p/T_e$  observation in the PS intervals listed in Table A1.

*Angelopoulos et al.*, 1992; *Runov et al.*, 2009]. For such periods the use of only CODIF observations may give values as low as  $T_p/T_e \leq 1.0$ . The visual examination of proton energy-time spectrograms showed that such low values are indeed mostly due to the unusually strong proton heating (with limitations owing to the CODIF upper energy threshold). Using RAPID measurements along with the CODIF data allowed us to obtain the reliable minimum value of the  $T_p/T_e \sim 2.0$  for the PS intervals from our database.

In almost all intervals from our database the decreases of  $T_p/T_e$  below 3.5 were detected in the PS during magnetic dipolarizations. The magnetic dipolarizations may represent earthward propagating fronts, which are generated by a downtail reconnection [e.g., *Sitnov et al.*, 2009; *Fu et al.*, 2013b]. Or they can be related with the CS reduction/disruption either due to the development of CS instabilities [*Lui*, 2004, and references therein] or in response to fast flow braking [e.g., *Sergeev et al.*, 2012, and references therein]. *Nakamura et al.* [2009] classified such events as the “final” dipolarization due to the flux pileup. The evolution of these events in time and space can be complicated and include multiple transient dipolarizations around and after the onset.

Many observations and simulations reported significant electron heating at and behind dipolarization fronts by betatron and Fermi mechanisms [e.g., *Fu et al.*, 2011; *Birn et al.*, 2013; *Birn et al.*, 2014, and references therein]. However, as it was shown in a theoretical paper by *Zelenyi et al.* [1990] and in simulations by *Birn et al.* [2013], ions, although nonadiabatic, undergo similar energization as electrons. Thus, generally, these major mechanisms of plasma heating hardly affect the  $T_p/T_e$ .

*Artemyev et al.* [2011] and *Wang et al.* [2012] proved statistically that the thermal characteristics of electron population and  $T_p/T_e$  value depend on the background state of the PS and, generally,  $T_e$  is higher and  $T_p/T_e$  is lower in hot PS. *Artemyev et al.* [2011] also demonstrated that  $T_e$  increases during the period of high-speed plasma flows. *Sergeev et al.* [2015] showed a preferential heating of electrons and drop of  $T_i/T_e$  during the periods of BBFs.

Our epoch superposition analysis showed that  $T_p(t)$  and  $T_e(t)$  change more or less synchronously in the course of magnetic dipolarization, which is consistent with results by *Artemyev et al.* [2011]. However, at the onset and just after the onset the  $T_e(t)$  increases more rapidly than  $T_p(t)$ . The intense electron heating coincides with the increase of the bulk  $V_X$  velocity at the dipolarization onset and with the increase of AE. This result is in agreement with the conclusion made by *Sergeev et al.* [2015] that the thermal characteristics of electrons are affected stronger than ion ones during substorm-related processes.

However, the minimum of the epoch profile of  $[T_p/T_e](t)$  is observed after the dipolarization onset during the “turbulent phase” of dipolarization when the  $B_z$  is still large and the intensification of wave activity in  $[f_{pp}, f_{ce}]$  frequency range is observed. First of all, we would like to check how instantaneous values of  $T_p$  and  $T_e$  change

large. The time interval of  $T_p/T_e$  drop below 3.5 coincides with the enhancement of electric and magnetic field wave power in  $[f_{pp}, f_{ce}]$  frequency range. This denotes that the high-frequency electrostatic and EME may play some role in electron heating and  $T_p/T_e$  decrease during magnetic dipolarizations.

Before discussing the results we would like to note that one should be very careful with the evaluation of the  $T_p/T_e$  value. The upper energy threshold (40 keV) of the CODIF instrument may result in underestimation of  $T_p$  and  $T_p/T_e$  values during active PS periods, when bursty bulk flows, dipolarization fronts, and other perturbations are observed [e.g.,

near the absolute minimum of  $T_p/T_e$  observed in the PS intervals with  $T_p/T_e \leq 3.5$ . In Figure 7 we present a scatterplot of  $\Delta T_e(i) = T_e(i) - T_e(i-1)$  versus the corresponding  $\Delta T_p(i)$  calculated for each PS interval from our database at the  $i$ th time moment at which the absolute minimum of  $T_p/T_e$  was observed. It is seen that in majority of cases from our database the minimum of  $T_p/T_e$  is reached due to the  $T_e$  increase and  $T_p$  decrease and generally the decrease of  $T_p$  is larger than the corresponding increase of  $T_e$ . Such anticorrelation in  $T_p$  and  $T_e$  changes is a puzzling feature. As it was mentioned before, under the presence of magnetic field gradient and the dawn-dusk electric field the adiabatic electrons, in the course of their betatron heating, and nonadiabatic ions, in the course of their nonadiabatic motion in the CS, obtain similar energy gain. The opposite signs of temperature changes observed for protons and electrons can be related to some kinetic effects of proton dynamics in the CS. *Birn et al.* [2014] mentioned the importance of microinstabilities operating at different kinetic scales which may affect ions and electrons at different ways. Another possibility is the presence of small-scale (less than proton gyroradius) magnetic gradients. In such case the full orbit integration is not applied and an observer can detect ions passing only that part of their orbits, at which they lose energy due to the motion antiparallel to the electric field. Also, the transient decreases of  $T_p$  can be due to the spacecraft crossings of different plasma tubes connected with different sources. The exact mechanism responsible for the transient  $T_p$  decreases in the course of magnetic dipolarization is an open question which deserves further investigation.

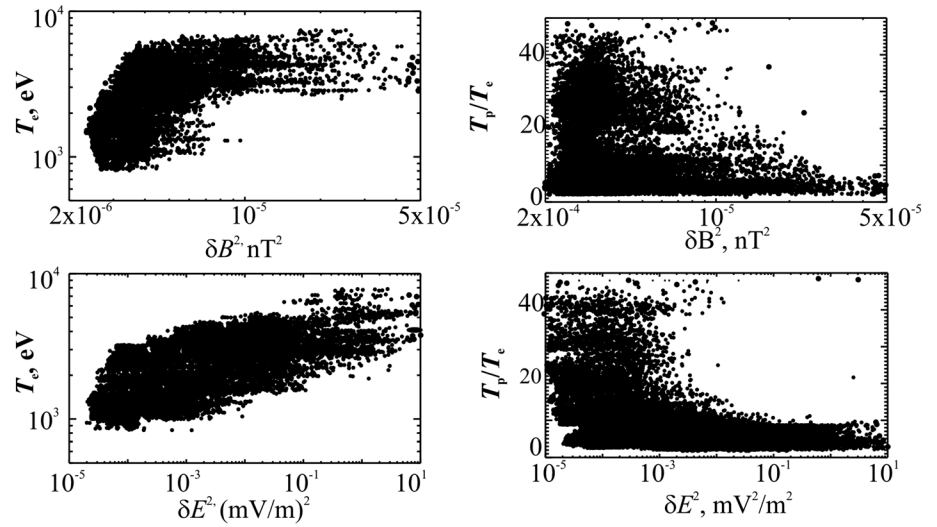
The analysis of STAFF observations of the electric and magnetic field fluctuations in the frequency range from 8 Hz to 4096 Hz permitted the identification of several wave modes, which generation coincides with the  $T_p/T_e$  decreases. These modes are listed in Table A1 for each PS interval from our database when the drops of  $T_p/T_e \leq 3.5$  were observed (see Appendix A).

In the majority of cases the decreases of  $T_p/T_e$  coincide either with the observations of broadband EME or broadband electrostatic emissions. The last includes ECH in  $\sim 50\%$  of events. The observations of these wave modes during magnetic dipolarizations were reported in previous studies [e.g., *Le Contel et al.*, 2009; *Deng et al.*, 2010; *Hwang et al.*, 2011; *Zhou et al.*, 2009; *Fu et al.*, 2014; *Zhang and Angelopoulos*, 2014]. The broadband EME comprise the whistler waves in the frequency range  $f \leq f_{pp}$ , which propagate outward from the CS almost parallel to the magnetic field, and oblique whistler waves in the higher frequency range  $f_{pp} < f \leq f_{ce}$ . For higher-frequency modes we observed an increase of the spectral index,  $|\alpha_E|$ , denoting the significant reduction of the electric field power at frequencies closer to  $f_{ce}$ . This may indicate energy transfer from the wave to resonant electrons.

*Khotyaintsev et al.* [2011] discussed the processes of wave-particle interaction in the flow braking region and showed that whistler mode waves can efficiently scatter electrons in pitch angles and, thus, increase the efficiency of betatron acceleration for some part of electron distribution. They also demonstrated that the particle interaction with whistler modes limits the electron anisotropy caused by the betatron acceleration at lower energies, so that the resulting distribution has limited anisotropy below  $\sim 2$  keV and is more anisotropic at higher energies. Our analysis of electron pitch angle distributions presented in section 3 showed similar features for the periods of the  $T_p/T_e$  drops associated with the ECH and broadband EME. We observe electron pitch angle scattering in the energy range below  $\sim 500$  eV and perpendicular anisotropy at energies from  $\sim 500$  eV up to several keV. Also, a pronounced flat-top electron distribution feature was observed for  $90^\circ$  pitch angle electrons in the energy range 0.1–3 keV, suggesting perpendicular electron heating.

The possibility of electron energization and scattering by ECH was discussed before by, e.g., *Farrell et al.* [2003] and *Zhou et al.* [2009]. Our analyses also showed that in many events the observation of broadband electrostatic fluctuations and electron cyclotron waves coincides with a local increase of  $T_e$  and a decrease of  $T_p/T_e$ . At such times the electron anisotropy  $T_{e\parallel}/T_{e\perp}$  also decreases to 1.0, suggesting efficient electron pitch angle scatterings.

However, it is rather difficult to reveal cause-and-effect relation between the generation of waves, kinetic effects in particle distributions, and particle energization. As it was discussed by *Fu et al.* [2011, 2012a, 2014], the perpendicular anisotropy of electron distributions that appeared due to the betatron heating can be a source for wave generation. However, the generated waves may, in turn, interact with the resonant electrons, so that at the later stage this process can become nonlinear. It is worth noting also that the particle anisotropy is not the only source of whistler waves. They can be generated also due to the presence of plasma



**Figure 8.** (left column) Scatterplots of  $T_e$  versus the power of electric and magnetic field fluctuations integrated with the frequency range  $[f_{pp}, f_{ce}]$  observed during the PS intervals listed in Table A1. (right column) The same for  $T_p/T_e$ .

density gradients and magnetic field gradients [e.g., *Le Contel et al.*, 2009, and references therein] which are formed in the course of dipolarizations. Propagating through the background plasma, these waves can interact with the ambient electron population and cause its heating.

Our analysis presented in section 3 showed that during some intervals of  $T_p/T_e$  decrease the periodical enhancement and damping of ECH and EME emissions in frequency range  $[f_{pp}, f_{ce}]$  are observed in spite of the almost permanent presence of the perpendicular anisotropy in electron distributions. Also, it was shown that the increases of wave power in  $[f_{pp}, f_{ce}]$  range more or less correlate with the local increases of electron temperature  $\Delta T_e$  (see Figures 4c and 4d). The strong increase of spectral index  $\gamma$  observed in the spectra of electric and magnetic field fluctuations in frequency range  $[f_{pp}, f_{ce}]$  range just before the minimum of  $T_p/T_e$  (see Figure 5) confirms the possibility of energy exchange between the waves and resonant electrons.

In Figure 8 we present the scatterplots of  $T_e$  (and  $T_p/T_e$ ) versus the power of magnetic and electric field fluctuations  $\delta B^2$ ,  $\delta E^2$  integrated in  $[f_{pp}, f_{ce}]$  frequency range for all time moments within the PS intervals in which  $T_p/T_e \leq 3.5$  was observed. Although data points are rather scattered, there is a tendency to observe larger  $T_e$  with the increase of the fluctuations power. This tendency is more clearly observed for the electric field fluctuations, which may indicate the role of high-frequency electrostatic emission in the electron heating. For  $T_p/T_e$  there is a tendency to observe lower values for the higher power of fluctuations. Again, this tendency is more clearly observed for the electric field fluctuations.

Summarizing our results, we may conclude that the processes of electron interactions with the ECH and EME emissions in  $[f_{pp}, f_{ce}]$  frequency range may play some role and provide some heating of electrons additionally to the major energization mechanisms like betatron and/or Fermi acceleration. Which mechanisms are responsible for the simultaneously observed  $T_p$  decrease during the periods of low  $T_p/T_e$  is still an open question and requires further studies. It is worth noting that the changes in  $T_p/T_e$  and the related changes in particle velocity distribution functions may, in turn, affect the CS dynamics and the development of plasma instabilities. These problems deserve special theoretical and modeling studies, which may shed new light on CS dynamics during magnetic dipolarizations.

## Appendix A

In Table A1 we list all the PS intervals when the  $T_p/T_e \leq 3.5$  was observed. In the majority of these cases the decrease in  $T_p/T_e$  was registered during magnetic dipolarizations. The analysis of STAFF observations of the electric and magnetic field fluctuations in the frequency range from 8 Hz to 4096 Hz permitted the

**Table A1.** A List of the PS Intervals When the  $T_p/T_e \leq 3.5$  Is Observed

Time Interval <sup>a</sup>	Magnetic Dipolarization	Wave Activity
22/7/2001 at 12:17–17:00 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves
26/7/2001 at 17:17–17:59 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves
26/7/2001 at 20:42–24:00 UT	yes	broadband electrostatic fluctuations ( $f \leq f_{ce}$ ), electron cyclotron waves
27/7/2001 at 03:44–07:00 UT	yes	broadband electrostatic fluctuations ( $f \leq f_{ce}$ ), whistler waves ( $f \leq f_{pp}$ )
27/7/2001 at 08:38–10:37 UT	yes	broadband electrostatic fluctuations ( $f \leq f_{ce}$ ), electron cyclotron waves
31/7/2001 at 18:00–21:37 UT	yes	broadband EME ( $f \leq f_{ce}$ ), electron cyclotron waves, whistler waves
8/8/2001 at 02:05–06:00 UT	yes	broadband electrostatic fluctuations ( $f \leq f_{ce}$ ), electron cyclotron waves
12/8/2001 at 18:05–19:00 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves
15/8/2001 at 01:47–02:15 UT	yes	broadband electrostatic fluctuations ( $f \leq f_{ce}$ )
15/8/2001 at 05:33–07:40 UT	yes	broadband electrostatic fluctuations ( $f \leq f_{ce}$ )
15/8/2001 at 08:05–10:11 UT	yes	broadband EME ( $f \leq f_{ce}$ ), electron cyclotron waves
22/8/2001 at 10:04–10:26 UT	yes	broadband electrostatic fluctuations ( $f \leq f_{ce}$ )
27/8/2001 at 04:15–05:50 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves, electron cyclotron waves
29/8/2001 at 11:25–12:36 UT	yes	broadband electrostatic fluctuations ( $f \leq f_{ce}$ )
7/9/2001 at 21:56–22:10 UT	yes	broadband electrostatic and EME ( $f \leq f_{ce}$ )
12/9/2001 at 13:15–13:45 UT	yes	broadband electrostatic and EME ( $f \leq f_{ce}$ )
15/9/2001 at 00:40–01:30 UT	yes	broadband electrostatic and EME ( $f \leq f_{ce}$ )
17/9/2001 at 08:14–10:07 UT	yes	broadband electrostatic ( $f \leq f_{ce}$ ) and electron cyclotron waves
1/10/2001 at 10:18–11:00 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves, electron cyclotron waves
1/10/2001 at 12:54–13:41 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves, electron cyclotron waves
8/10/2001 at 14:03–14:35 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves
8/10/2001 at 14:57–15:27 UT	yes	broadband electrostatic fluctuations, electron cyclotron waves
11/10/2001 at 03:37–05:30 UT	yes	broadband electrostatic and EME ( $f \leq f_{ce}$ ), whistler waves
20/10/2001 at 10:47–13:05 UT	yes	broadband electrostatic ( $f \leq f_{ce}$ ) and electron cyclotron waves
21/7/2002 at 03:40–05:00 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ )
21/7/2002 at 09:42–13:03 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves, electron cyclotron waves
21/7/2002 at 13:48–14:51 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ ), whistler waves, electron cyclotron waves
25/7/2002 at 22:26–23:58 UT	yes	broadband electrostatic ( $f \leq f_{ce}$ ) and electron cyclotron waves
26/7/2002 at 04:17–08:00 UT	yes	broadband electrostatic ( $f \leq f_{ce}$ ) and electron cyclotron waves
30/7/2002 at 17:53–19:05 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ )
10/10/2002 at 01:59–02:22 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ )
14/10/2002 at 12:20–14:10 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ ), electron cyclotron waves
14/10/2002 at 17:49–22:00 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ ), electron cyclotron waves
26/10/2002 at 07:03–08:22 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ )
20/7/2003 at 00:19–02:06 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves, electron cyclotron waves
20/7/2003 at 03:06–05:37 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ )
20/7/2003 at 06:19–11:00 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ )
24/7/2003 at 21:27–22:40 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ )
24/7/2003 at 23:03–24:00 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves
25/7/2003 at 06:59–08:39 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves, electron cyclotron waves
27/7/2003 at 13:45–15:24 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ ), electron cyclotron waves
29/7/2003 at 14:55–15:11 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ )
29/7/2003 at 18:33–21:31 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ ), electron cyclotron waves
1/8/2003 at 00:20–02:06 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ ), electron cyclotron waves
1/8/2003 at 03:37–05:06 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ )
1/8/2003 at 05:55–09:00 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves, electron cyclotron waves
5/8/2003 at 19:12–19:27 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ )
8/8/2003 at 10:26–11:30 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves
12/8/2003 at 21:30–23:10 UT	no	broadband electrostatic waves ( $f \leq f_{ce}$ )
27/8/2003 at 07:23–08:40 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ ), electron cyclotron waves
5/9/2003 at 15:21–16:30 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves, electron cyclotron waves
15/9/2003 at 04:27–07:50 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ )
24/9/2003 at 16:05–17:00 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ )
29/9/2003 at 10:22–11:25 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves
1/10/2003 at 15:29–15:32 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ )
8/10/2003 at 21:38–22:57 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves
11/10/2003 at 07:45–09:22 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ ), electron cyclotron waves
13/10/2003 at 11:40–13:10 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves
20/10/2003 at 15:35–18:10 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ ), electron cyclotron waves
3/8/2004 at 04:10–04:36 UT	yes	no evident wave activity
14/8/2004 at 22:00–23:00 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves



Table A1. (continued)

Time Interval <sup>a</sup>	Magnetic Dipolarization	Wave Activity
3/10/2004 at 16:43–17:55 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ ), electron cyclotron waves
3/10/2004 at 18:57–20:08 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves, electron cyclotron waves
6/10/2004 at 05:04–06:05 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves
8/10/2004 at 16:09–16:32 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves
11/10/2004 at 01:21:30–01:32 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ )
11/10/2004 at 01:39–02:20 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ ), electron cyclotron waves
13/10/2004 at 07:02–07:41 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves, electron cyclotron waves
15/10/2004 at 13:54–14:36 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ ), electron cyclotron waves
22/10/2004 at 17:10–17:34 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves, electron cyclotron waves
22/10/2004 at 17:35–18:10 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves, electron cyclotron waves
22/10/2004 at 18:12–18:33 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ ), electron cyclotron waves
22/10/2004 at 18:44–19:05 UT	yes	electron cyclotron waves
22/10/2004 at 19:28–19:31 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves, electron cyclotron waves
22/10/2004 at 19:32–20:35 UT	yes	electron cyclotron waves
7/8/2005 at 14:56–17:04 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves, electron cyclotron waves
9/8/2005 at 18:33–19:32 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ ), electron cyclotron waves
17/8/2005 at 00:38–02:16 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ ), electron cyclotron waves
21/8/2005 at 19:24–20:12 UT	yes	no evident wave activity
21/9/2005 at 14:13–14:19 UT	yes	broadband electrostatic waves and broadband EME ( $f \leq f_{ce}$ ), whistler waves
21/9/2005 at 14:21–15:35 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves, electron cyclotron waves
28/9/2005 at 17:31–20:44 UT	yes	electron cyclotron waves
1/10/2005 at 04:44–04:50 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ ), electron cyclotron waves
1/10/2005 at 04:56–05:35 UT	yes	broadband EME ( $f \leq f_{ce}$ ), whistler waves, electron cyclotron waves
15/10/2005 at 07:06–07:53 UT	yes	broadband electrostatic waves ( $f \leq f_{ce}$ )
17/10/2005 at 16:07–18:30 UT	yes	electron cyclotron waves

<sup>a</sup>Dates are formatted as day/month/year.

identification of wave modes, observed in the PS simultaneously with the  $T_p/T_e$  decrease below 3.5. These modes are also listed in the Table A1.

## Acknowledgments

We acknowledge Cluster Science Archive (<http://www.cosmos.esa.int/web/csa>), PI, and teams of CIS, PEACE, FGM, and STAFF instruments for providing the data. The Cluster data used in this study were downloaded from the Cluster Science Archive version 1.2.1 at <http://www.cosmos.esa.int/web/csa>. To obtain the data, one should start the CSA GRAPHICAL USER INTERFACE; then to download the data, just select the particular instrument and time interval. The work of E.E. Grigorenko, E.A. Kronberg, and P.W. Daly was supported by the Volkswagen Foundation (grant Az 90 312). P.W. Daly and E.A. Kronberg acknowledge the Deutsches Zentrum für Luft und Raumfahrt (DLR) for supporting the RAPID instrument at MPS under grant 50 OC 1401. N.Yu. Ganushkina and E.E. Grigorenko are thankful for the support received from the Academy of Finland as Space Cooperation in the Science and Technology Commission between Finland and Russia (TT/AVA). N.Yu. Ganushkina acknowledges that the part of the research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007–2013) under

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grant agreements 606716 SPACESTORM and from the European Union's Horizon 2020 research and innovation programme under grant agreement 637302 PROGRESS. E.A. Kronberg and N. Yu. Ganushkina thank the International Space Science Institute in Bern, Switzerland, for their support of the international teams on "Analysis of Cluster Inner Magnetosphere Campaign data, in application of the dynamics of waves and wave-particle interaction within the outer radiation belt" and "Ring current modeling: Uncommon Assumptions and Common Misconceptions." The work of N.Yu. Ganushkina was also partly supported by NASA award NNX14AF34G. Work at IRAP was supported by CNRS and CNES. L.M. Zelenyi acknowledges the Program I.7P of RAS and Russian Foundation for Basic Research (project 16-52-16009) for the support of his work.

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