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Key Points:

- Energetic particles at energies >40 keV have to be considered for the plasma temperature and pressure calculations
- Effective acceleration is due to interaction of charged particles with multiscale magnetic structures and/or electromagnetic fluctuations
- Direction of Interplanetary Magnetic Field leads to ion distribution asymmetries between Northern and Southern hemispheres

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Energetic Charged Particles in the Terrestrial Magnetosphere: Cluster/RAPID Results

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Abstract In this work, we review the results of observations by the Cluster/Research with Adaptive Particle Imaging Detectors (RAPID) energetic charged particle detector (~40 keV–1 MeV). The origin of energetic ions in the region upstream of the Earth's bow shock is compared under different solar wind conditions. We give a brief overview of the acceleration mechanisms of charged particles in the plasma sheet. Effective acceleration is associated with (multiple) interaction(s) of charged particles with multiscale magnetic structures and/or electromagnetic fluctuations, which are the consequences of reconnection or other plasma instabilities. The necessity of such acceleration mechanisms to reproduce the distributions of energetic particles on closed magnetic field lines is discussed. We review empirical models describing the distributions of charged particles. Several aspects of the dynamics of energetic particles during substorms and their influence on the dynamics of magnetic storms are shown. We advise to consider including the energetic particles at >40 keV in calculations of the plasma temperature and pressure during these dynamic processes.

Plain Language Summary A fundamental scientific question is how plasma in the universe is heated up and accelerated. Understanding acceleration at supernovae shocks, of cosmic jets or laboratory plasmas still has many open questions. Near-Earth space environment is an excellent laboratory to investigate plasma dynamics and to reveal the fundamental laws it obeys. Energetic plasmas are also hazardous for space satellites and play a key role in space weather. It is, therefore, necessary to study the energization of space plasmas, their distribution and consequences on the magnetospheric dynamics. In situ observations in the near-Earth space by the Cluster satellites and the energetic particle detector, Research with Adaptive Particle Imaging Detectors (RAPID), reveal new insights in plasma acceleration, unexpected features in its distributions, and effects on substorm and geomagnetic storm dynamics. These observations also help space weather applications to determine the level of energetic particle intensities.

1. Introduction

The terrestrial magnetosphere is an effective plasma accelerator. There are two main sources for the magnetospheric plasma: the solar wind and the ionosphere.

The solar wind ion population consists mainly of protons. The abundance of He⁺⁺ is in the range of 3%–6% with variations observed at times of up to 30% (Aellig et al., 2001; Borriani et al., 1982; Kasper et al., 2007; Neugebauer, 1981). The abundance of other heavy ions is <0.1% (including O⁶⁺) (Gloeckler & Geiss, 1989). The number of solar wind electrons maintains the charge neutrality in the plasma media. The energy of the solar wind at ~1 Astronomical Unit is about 1 keV with a Maxwellian core and a steeply falling power law part of the spectral distribution for protons (see Figure 1) and about tens of eV for the electrons which have harder distribution at higher energies than protons. The solar wind interacts with the magnetic field of the Earth, forms the bow shock and then enters into the magnetosphere via magnetic reconnection and Kelvin-Helmholtz instability. However, in the upstream region of the Earth's bow shock and in the plasma sheet region we observe strong hardening of the power law part of the proton spectrum compared to those

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Figure 1. The proton spectra in the solar wind measured by the Parker Solar Probe is indicated by the blue line. The slope of the black bar is equivalent to the spectral slope in the plasma sheet during quiet time taken from Kronberg et al. (2010). Adapted from McComas et al. (2016).

in the solar wind, see Figure 1. This implies strong proton energization. Electrons are also strongly energized in the plasma sheet.

The ionosphere delivers to the magnetosphere protons, He^+ , N^+ , O^+ , and the molecular ions NO^+ , and O_2^+ (Yau et al., 1991). The O^+ (or more precisely CNO group since many particle detectors cannot distinguish between those species) can dominate not only the mass density but also the number density, see Ilie and Liemohn (2016) and references therein. Therefore, it is considered as a main tracer of the ions of ionospheric origin (Kronberg et al., 2014). Electrons flow out from the ionosphere to keep overall charge neutrality. However, their plasma characteristics are not well studied yet (Borovsky et al., 2020). The ionospheric charged particles outflow on the open and closed magnetic field lines into the magnetosphere. The temperature of the outflowing ionospheric ions in the lobes is about 7 eV (Kronberg et al., 2014). The observed temperature of oxygen ions in the plasma sheet is between 3 and 20 keV on average (Lennartsson, 1989; Malykhin et al., 2020; Ohtani et al., 2011). This means that the oxygen ions are strongly energized in the plasma sheet.

Energized particles play an important role in the dynamics of the terrestrial magnetosphere. Moreover, the investigation of energetic particles is a clue for the exploration of the plasma dynamics of the Solar System (Wilken et al., 1997). Along with magnetic field measurements, they helped to reveal the existence of the radiation belts, the magnetopause, the magnetosheath, the bow shock and the plasma sheet in the magnetospheres of different planets. Here, by energetic we mean electrons in the range from 40 to 400 keV and ions from ~ 30 keV to 4 MeV. These energy ranges are determined by the capabilities of the energetic particle detector Research with Adaptive Particle Imaging Detectors (RAPID) on the Cluster mission. Such energetic particles can affect the plasma tem-

perature and pressure, and as a consequence, the whole dynamics of the magnetosphere starting from small scales such as wave properties and plasma instabilities toward the large scale dynamics of the magnetic storms and substorms.

Another crucial aspect is the effects of such energetic particles on space observations and space weather. Electrons at energies up to 50 keV can cause, for example, to spacecraft anomalies related to surface charging (Matéo-Vélez et al., 2018; Thomsen et al., 2013). The protons at energies of ~ 100 keV can enter inside X-Ray telescopes and produce erroneous signals, leading to loss of astrophysical and cosmological observations (Fioretti et al., 2016).

It is, therefore, necessary to study the origin of energetic plasma, which is mainly related to the investigation of acceleration mechanisms leading to the observed spectra hardening, distribution of energetic plasma and consequences of its presence on the magnetospheric dynamics. In this work, we present the related results from the observations by the Cluster/RAPID instrument which is described in Section 2.

The capabilities of multipoint spacecraft measurements and the combination of observations by the RAPID experiment with other instruments and other spacecraft missions together with the long duration of the Cluster mission are well suited to advance the following problems related to energetic charged particles: (a) the origin and details of acceleration of the energetic particles in the region upstream of the bow shock, considered in Section 3; (b) the acceleration of charged particles in the plasma sheet, discussed in Section 4; (c) the distribution of the energized plasma on closed magnetic field lines beyond the radiation belts, considered in Section 5; (d) the effect of the solar cycle on the dynamics of the radiation belts, considered in Section 6; (e) dynamics during substorm phenomena, discussed in Section 7; and (f) influence of energetic ions and their composition on the dynamics of the magnetic storms, presented in Section 8. A summary of this review can be found in Section 9.

Cluster/RAPID observations have also helped to advance our understanding of the energetic particles behavior in the cusp region, in particular their spatial and temporal variability and the processes responsible for acceleration of the particles up to the high energies, see Pitout and Bogdanova (2021) in this issue.

2. Instrumentation and Methods

The Cluster mission consists of four identical satellites launched July–August 2000 into a highly elliptical polar orbit (initially $4 \times 19.5 R_E$) to explore all regions of the Earth's magnetosphere. The mission and its payload are described by Escoubet et al. (1997).

RAPID (Wilken et al., 1997) is an energetic particle spectrometer, measuring the 3-D distribution of electrons (39–400 keV) and ions (protons 28 keV–4 MeV, helium 137 keV–4 MeV, oxygen 270 keV–4 MeV).

The electrons are detected by three sets of three microstrip solid state detectors, each set being a “pin-hole camera” with a single entrance aperture, covering a total angular range of 60° . The sets, or heads, thus cover the full 180° in the halfplane containing the spin axis, with an angular resolution of 20° in the polar direction. Through the rotation of the spacecraft (period ~ 4 s) the measurements can be sorted into up to 16 azimuthal sectors of 22.5° . The energy of the electrons is determined by the signal strength in the absorbing solid state detector, and is sorted into up to eight energy channels.

The ions are measured in an independent detection system consisting of again 3 heads each covering 60° . Each head has an entrance aperture, a time-of-flight system, and a solid state detector to measure the incoming particle energy. Together, flight time and particle energy allow the ion mass and thus species to be identified. In addition, the incoming direction can be determined electronically to within 15° . Thus each ion head can be subdivided into four subdirections, for a total of 12 directions in the half-plane containing the spin axis. As for the electrons, the ion data can be sorted into 16 azimuthal sectors through the spinning of the spacecraft. The ion energies are sorted into up to eight energy channels.

Because of the relatively wide energy channels, it is not immediately obvious to which energy the measured differential flux is to be assigned. The answer is in fact dependent on the steepness of the spectrum. This issue of spectral analysis with wide energy channels is treated in depth by Kronberg and Daly (2013).

The energies measured by RAPID represent the high-energy tail of the full spectrum; the thermal energies are covered by the Cluster ion spectrometry (CIS) experiment (Rème et al., 2001). How these datasets can be combined is treated by Kronberg et al. (2010).

The energetic ions strongly affect the plasma pressure and temperature. One of the merits of the Cluster mission is a proper estimation of components of the plasma pressure and temperature using wide energy range covered by the particle instruments, a possibility to resolve composition and well cross-calibrated measurements. The plasma pressure during, for example, magnetic field dipolarizations (see Figure 4 on the left and more detailed discussion of this phenomena in Section 4) can be underestimated by a factor of >2 if the ions at energies >40 keV are neglected (Kronberg, Grigorenko, et al., 2017; Malykhin et al., 2020). This is especially true for the contribution of heavy energetic ionospheric ions. Such underestimations can compromise our understanding of physics of magnetospheric phenomena. For example, Nakamura et al. (2013) have shown that the pressure gradient force exceeding the Earthward directed $\vec{j} \times \vec{B}$ force led to the flow bouncing during a dipolarization event affecting the dynamics of the associated substorm. In that work, it was essential to consider the contribution to the plasma pressure of the energetic particles measured by the RAPID instrument. Another example: calculations of T_p/T_e in Grigorenko et al. (2016) showed that it is important to include energetic protons in the calculations of the temperature to avoid its underestimation.

Three-dimensional energetic ion sounding helps to determine the complicated motion of the nonplanar boundary surfaces impossible without advantages of multispacecraft analysis. Description of this method can be found in Oksavik et al. (2002); Zong et al. (2004).

All the Cluster data are readily available online at the Cluster Science Archive (<https://csa.esac.esa.int/csa-web/>). An overview of the RAPID data products is given by Daly and Kronberg (2010).

Figure 2. Left: Overview of the upstream region in a simulation with out-of-plane magnetic field fluctuations, indicating the extent of the ultralow frequency (ULF) waves in the upstream region. Black curves show magnetic field lines. Taken from Battarbee et al. (2020). Middle: Trajectories of Cluster satellites along the magnetic fields, which are shown by arrows. Right: Diffusion coefficient as a function of energy per charge for protons and helium in the region upstream of the Earth's bow shock. Taken from Kronberg et al. (2009).

3. Origin and Acceleration of Energetic Particles in the Region Upstream of the Earth's Bow Shock

The interaction of the supersonic solar wind with the terrestrial magnetic field forms the bow shock. The region upstream of the shock and the shock itself are associated with various particle acceleration processes. This region is of particular interest for our understanding the particle energization for phenomena that are common in the Universe such as supernovae shocks, heliospheric shocks and shocks in our Solar System.

Upstream of the Earth's bow shock one can observe the generation of low frequency hydrodynamic waves, see Figure 2 on the left. Furthermore, the so-called upstream events are seen in this region. These are events during which the enhanced intensities of energetic charged particles are observed, see Figure 3 on the right. One of the scientific questions of considerable importance for the energetic particle measurements with RAPID is the origin of these upstream ions (Wilken et al., 1997).

There are two sources of the upstream ions discussed. On the one hand, it is believed that these particles are scattered by the upstream waves leading to diffusive transport and Fermi-acceleration of the first order (Desai et al., 2008; Lee, 1982). To resolve details of the interaction between the bow shock, the upstream waves and energetic particles is a task of the Cluster mission according to Wilken et al. (1997). On the other hand, the upstream particles can leak from the magnetosphere during substorms (Keika et al., 2004; Sarris

Figure 3. Left: Cartoon is showing Alfvén waves embedded within the rarefaction regions of the High Speed Streams (HSSs) that follow Corotating Interaction Regions (CIRs). The rarefaction regions are associated with upstream events. Taken from Desai et al. (2008). Right: 1 h averaged proton intensity from the STEREO-A/SEPT antisunward sensor (Müller-Mellin et al., 2007) shows CIRs profiles on the scale of weeks and upstream events as small spikes on scales of hours. Taken from Kronberg et al. (2011).

Figure 4. Left: Observation of two dipolarizations (shaded in gray) of the magnetic field in the near-Earth tail. Top to bottom: time profiles of the thermal pressure of H^+ and O^+ ions calculated based on Cluster ion spectrometry (CIS)/CODIF observations (<40 keV) (shown by the gray lines) and time profiles of the pressure calculated considering the energetic component of the spectrum based on Research with Adaptive Particle Imaging Detectors (RAPID) observations (shown by the black lines); time profile of the B_z magnetic field component. Adapted from Malykhin et al. (2020). Right: Trajectories and energy variation with time of electrons, protons and oxygen (bottom) during the magnetic field dipolarization associated with multiple dipolarization fronts (top) for times t_d and t_{eff} . Taken from Parkhomenko et al. (2018).

et al., 1978). Substorms are associated with the magnetic field reconfiguration, charged particle acceleration and occurrence of polar aurora.

Diagnostic tools to resolve these questions such as RAPID together with other Cluster instruments such as CIS in combination with observations by other spacecraft can (a) measure simultaneously ions and electrons at different distances from the bow shock; (b) assess connectivity of the magnetic field to the Earth's bow shock; (c) measure density gradients using Cluster spacecraft constellation; (d) measure the ion composition; and (e) establish particle anisotropies.

We consider in this section two periods of the solar cycle, which demonstrate how solar wind conditions can affect the origin of the energetic particles in the region upstream of the bow shock.

3.1. Diffusive Acceleration: Solar Maximum

In Kronberg et al. (2009), details of the theory of the diffusive Fermi acceleration were examined using the multipoint observations of an upstream event from the Cluster mission, see Figure 2. An analysis of the density gradients of protons and helium has shown that they fall off exponentially with the distance from the bow shock independent of species and charge. This means that the dynamics of ions of different species is determined by the same mechanisms. The diffusion coefficient of the ion transport is linear dependent on energy per charge in accordance with the theory from Blandford and Ostriker (1978), see Figure 2. This study establishes that the first order Fermi acceleration mechanism leads to ion acceleration at energies from ~ 30 up to ~ 160 keV/e in the region upstream of the bow shock. The results agree well with the statistical study by Trattner et al. (1994) (without direct density gradient measurements) and at lower than ~ 30 keV/e proton energies with a study of the same event by Kis et al. (2004) (see Figure 2).

The uniqueness of the event studied by Kis et al. (2004); Kronberg et al. (2009) is its continuous observation of the upstream ions for many hours (~ 10). It has been shown that, to be observed, long-living stable Interplanetary Magnetic Field (IMF) conditions with direct connection to the bow shock are required, see for example, Lin et al. (1974); Scholer et al. (1979). Also, this acceleration mechanism is particularly efficient during a strong shock (at least up to Alfvén Mach number 10) (Giacalone et al., 1997). Such conditions are

typical for Coronal Mass Ejections (CMEs) which occur especially frequently during solar maximum. CMEs are tremendous eruptions of plasma from the Sun's upper atmosphere, which mainly occur during high solar activity. The emerging plasma bubbles, associated with these CMEs, have relatively stable long-living magnetic field directions and high propagation speed, forming strong shocks. This means that during CMEs Fermi-acceleration of the first order has favorable conditions and can be well observed as shown in Kis et al. (2004); Kronberg et al. (2009).

3.2. Magnetospheric Origin: Declining Phase of the Solar Cycle

During the declining phase of a solar cycle, the terrestrial magnetosphere often encounters fast solar winds, called High Speed Streams (HSSs). The HSSs overtake regular slow solar wind and form shocks named Corotating Interaction Regions (CIRs). HSSs are coupled with Alfvén waves, see Figure 3. The interaction between CIRs (associated with shocks and therefore enhanced solar wind dynamic pressure), the Alfvén waves in HSSs (associated with change of IMF B_z [Desai et al., 2008]) and the terrestrial magnetic field may trigger magnetospheric substorms. During substorms, a loss of charged particles from the magnetosphere is observed, as referred above.

During the declining phase of the solar cycle, in 2007, upstream events were discovered even at a distance of up to 1,750 R_E upstream of the Earth's bow shock by the mission STEREO-A (Desai et al., 2008). The origin of such events was at first unclear. A total of 117 such events were studied using data from STEREO-A, STEREO-B, ACE, Geotail, and Cluster satellites (Kronberg et al., 2011), see Figure 3. It was found that more than 50% of the upstream events have magnetospheric origin. The presence of oxygen ions, energetic electrons, particle flow in the sunward direction, and simultaneous occurrence of geomagnetic activity were the main characteristics to support this conclusion. During these events, the magnetic field direction was not stable because of the Alfvén waves, the connectivity to the bow shock was relatively short and, therefore, clear events with signatures of the first order Fermi acceleration were not observed by the Cluster satellites.

Another example of the oxygen upstream ions originated from the magnetosphere during the declining phase of the solar cycle can be found in Savin et al. (2014). In this work using RAPID observations it was demonstrated that solar wind and foreshock disturbances triggered by resonant oscillations in the outer magnetospheric regions (e.g., in the bow shock surface and the magnetosheath [cavity modes]) modulate oxygen outflow from the magnetosphere into the solar wind.

In summary, more examples are needed to systemize the effects of solar wind conditions on the origin of the energetic particles in the region upstream of the bow shock.

4. Charged Particle Acceleration in the Plasma Sheet

The near-Earth magnetotail region is another principal science focus of the Cluster mission in assessing the nature of the acceleration processes (Wilken et al., 1997). Particles trapped on closed magnetospheric magnetic field lines form the plasma sheet at the nightside. The plasma sheet is the main reservoir of the magnetospheric plasma. In the plasma sheet, the energy of ions and electrons can increase many orders of magnitude. Adiabatic mechanisms such as betatron and Fermi acceleration lead to energization in the plasma sheet during charge particle's drift toward the Earth. However, these acceleration mechanisms have limits. For example, Cowley and Ashour-Abdalla (1975) showed that because of adiabatic plasma convection in a dipolar field electrons/protons may get energies up to ~20/50 keV, respectively, at L-shell 6.

It is well established that the ions are effectively accelerated by nonadiabatic processes, for example, Büchner and Zelenyi (1989). Ion drift along quasisteady dawn-dusk electric field leads to acceleration of ions up to energies of ~100 keV (value of the cross-tail potential drop in the magnetotail during highly disturbed geomagnetic activity). Therefore, much Cluster/RAPID effort has been put into investigations of additional acceleration mechanisms that can boost particle energies from the range of ~30 to hundreds of keV to higher energies.

Many studies indicate that the energy increase is associated with the reconnection of magnetic fields and its consequences. Related mechanisms of electron acceleration were reviewed, for example, in Hoshino (2005); Birn et al. (2012). Advantages of multipoint Cluster observations help to delineate fine structures

of reconnection processes and to distinguish spatial and temporal changes. Observations of the electron beams flowing from diffusion region were reported by Åsnes et al. (2008a); Retinò et al. (2008). Wang et al. (2013) demonstrated that electrons can be effectively accelerated, while they are flowing into the X-line along the separatrix. These results imply that the electron acceleration region is significantly larger than the size of the predicted electron diffusion region in the classical Hall magnetic reconnection model.

The ion diffusion region is not regarded as an effective ion acceleration region (Birn et al., 2012). Therefore, consequences of reconnection such as plasmoids (closed magnetic field structures) and magnetic field dipolarizations (see below) may lead to strong ion acceleration. Luo et al. (2014) using merits of measurements of 3D particle distributions by the RAPID instrument showed that the ion acceleration is related to the presence of plasmoids and magnetic field dipolarizations. Grigorenko et al. (2015) showed that heavy ions will be more effectively accelerated than protons when they are trapped in a plasmoid associated with certain level of electromagnetic fluctuations at the corresponding ion gyrofrequency.

The dipolarization fronts are a consequence of magnetic field reconnection or other plasma instabilities which leads to sudden significant increase of the meridional magnetic field component on the scale of seconds to a couple of minutes (Nakamura et al., 2002; Runov et al., 2009), see an example in Figure 4, left plot at ~15:40 UT. Fu et al. (2012) and Liu et al. (2017) demonstrated that betatron and Fermi acceleration of electrons act behind the dipolarization fronts. For ion acceleration at dipolarization fronts modeling still predicts controversial results. For example, on the one hand, Delcourt et al. (1990); Greco et al. (2015) propose effective nonadiabatic acceleration for ions with gyrofrequency comparable to the timescale of the dipolarization front. On the other hand, Ukhorskiy et al. (2018) suggests that acceleration of ions injected into the dipolarization front is proportional to the ion charge but independent of their mass.

The magnetic field dipolarizations are observed on the prolonged scales of 10 min (henceforth called dipolarizations), see Figure 4, left plot interval II and upper right plot. This type of magnetic field dipolarization was distinguished from the dipolarization front by Nakamura et al. (2009) using Cluster observations. They can be either a result of the magnetic flux pileup of arriving dipolarization fronts in the near-Earth tail (Nakamura et al., 2009; Shiokawa et al., 1997) or a development of plasma instabilities (Lui, 1996; Pritchett & Coroniti, 2011).

During development of the dipolarization energetic electron fluxes increase due to betatron acceleration (Asano et al., 2010; Smets et al., 1999). Malykhin, Grigorenko, Kronberg, and Daly (2018) statistically demonstrated that during dipolarizations variations of suprathermal electron flux can be described by betatron mechanism in the energy range up to 90 keV. At higher energies, variations of electron flux do not correlate with the magnetic field variations. This means that other mechanisms (possibly nonadiabatic ones) are responsible for the electron flux variations in the higher energy range.

Some fraction of light ions can be accelerated up to energies ≤ 600 keV and some fraction of oxygen ions can be accelerated up to ~ 1.2 MeV during dipolarization (Malykhin et al., 2019). Such strong energy gains cannot be explained by acceleration at a single propagating dipolarization front associated with dipolarization. A possibility of multistage ion acceleration in the course of interaction with multiple dipolarization fronts superimposed on the dipolarization is suggested to explain acceleration of ions to such high energies, see Figure 4, upper right plot. The thickness of the fronts is less than a thermal proton gyroradius (Balikhin et al., 2014; Runov et al., 2009) which ensures the nonadiabatic acceleration of protons (Malykhin, Grigorenko, Kronberg, Koleva, et al., 2018; Parkhomenko et al., 2018), see Figure 4, bottom right plot.

Electromagnetic fluctuations in a wide frequency range play a role in particle heating and acceleration during dipolarizations (Nosé et al., 2014). For example, high-frequency whistler waves with frequencies between proton plasma frequency and electron gyrofrequency may lead to electron heating and to a decrease in the ratio of hydrogen to electron temperature (T_p/T_e), an important parameter for the current sheet dynamics (Grigorenko et al., 2016). Low frequency waves in the range between proton and oxygen cyclotron frequencies associated with dipolarization can also effectively accelerate ions. This was statistically shown by Ono et al. (2009) using Geotail observations. Details of such wave-particle interaction were discussed by Grigorenko et al. (2017) utilizing Cluster/RAPID observations. Different particle species such as protons, helium, and oxygen are accelerated by resonant interaction with electromagnetic fluctuations at the corresponding ion component gyrofrequencies.

Figure 5. Left: Comparison of the oxygen pressure before and during the substorm in simulations by (Fok et al., 2006) with observations of the oxygen intensities by Cluster from Kronberg et al. (2015). Taken from Kronberg et al. (2014). Right: Map of the cold ion sources in the polar region of the Northern hemisphere and associated sinks in the plasma sheet during different geomagnetic activities. Taken from K. Li et al. (2013).

In summary, the Cluster/RAPID instrument substantially contributed to the idea that, interaction of charged particles with multiscale magnetic field structures and/or electromagnetic fluctuations, which are the consequences of reconnection or other plasma instabilities, leads to effective acceleration. Multiple interaction with such structures boosts the energies even higher.

5. Energetic Particle Distribution on Closed Magnetic Field Lines Beyond the Radiation Belts

A considerable part of the charged particles from the solar wind and the ionosphere are trapped on closed magnetospheric magnetic field lines including the magnetotail on the nightside. Studying distributions of the energetic particles is essential for the understanding of their acceleration, the global magnetospheric dynamics and useful for space weather applications. The merits of the long-term observations of the Cluster mission made possible such statistical studies. Also, the polar trajectories of the Cluster allow coverage of a wider range of the region on the closed magnetic field lines than many other space missions.

The distributions of ions were studied before Cluster by space missions such as IMP 7 and 8, Interball and Geotail, see, for example, Meng et al. (1981); Sarafopoulos et al. (2001); and Ohtani et al. (2011), respectively. However, these studies did not completely agree on the distributions, did not investigate their dependence on the solar wind parameters and their spatial coverage does not fully overlap with those of Cluster. Therefore, the dependence of the distributions of the hydrogen and oxygen ions on such closed magnetic field lines on the geomagnetic activity, the solar wind dynamic pressure and the direction of the IMF using 7 years of Cluster observations was studied by Kronberg et al. (2012); Kronberg et al. (2015). The distribution of energetic ions (>274 keV) shows duskward asymmetry which is different from the rather symmetric distribution of the ions at bulk energies (~ 10 keV) during geomagnetically active times (Kronberg, Li, et al., 2017). Especially, strong asymmetry is seen in relation with AE-index and for oxygen ions, see Figure 5. The AE-index measures the strength of the currents in the auroral zone and indicates the strength of substorms (Nosé et al., 2017). Substorms are associated with magnetic field dipolarizations and plasmoid formations, which effectively accelerate charged particles as described in Section 4. An acceleration of the ions by non-adiabatic acceleration mechanisms (see Section 4 and Kronberg et al., 2015) and gradient and curvature drifts in the duskward direction can explain duskward asymmetry. The observations agree well with the models, see, for example, Figure 5. Another explanation of the duskward asymmetry is the distribution of cold ions with total energy <70 eV. During geomagnetically active times a large amount of cold ions populate the plasma sheet closer to the Earth and more duskward than during geomagnetically

Figure 6. Left: Oxygen intensities with energy from 274 to 962 keV under southward Interplanetary Magnetic Field (IMF) with different IMF B_y directions in both the Northern and Southern hemispheres. The gray circles with antiparallel arrows indicate quadrants where the reconnection and location of diamagnetic cavity is expected. Right: Arrows indicate the Earth's magnetic field and the draped IMFs for each orientation. Shaded gray regions show under each IMF orientation where the most antiparallel components are located relative to the cusp region and where the diamagnetic cavity can form and trap the particles. Taken from Luo et al. (2017).

quiet times due to stronger convection (K. Li et al., 2013), see Figure 5. These cold ions can get effectively accelerated to many 100s of keV just within 10s of seconds, see, for example, Grigorenko et al. (2015), leading to duskward distribution of ions. This can also explain why duskward asymmetry is not observed at bulk energies for oxygen ions at distance $>10 R_E$ during geomagnetic active times (Maggiolo & Kistler, 2014): cold ions are accelerated so fast that they do not spend much time at ~ 10 keV energies. This mechanism should still be more thoroughly investigated.

It is remarkable that the distribution of the ions (>274 keV) also depends on the direction of the IMF within the ecliptic plane. One can observe higher ion intensities in the regions in which reconnection between the IMF and the terrestrial magnetic field is expected. This leads to asymmetric ion distributions not only between dawn and dusk but also between the Northern and Southern hemispheres, see Figure 6. It was expected that ion trajectories mainly obey gradient and curvature drift around the Earth and, therefore the distributions to be rather symmetric between the hemispheres. This was discovered by Luo et al. (2017) using 11 years of Cluster energetic ion (>274 keV) observations. As mentioned in Section 4, the ion diffusion region associated with reconnection does not accelerate ions to such high energies. On the dayside such asymmetry can be caused by the local acceleration in diamagnetic cavities (Nykyri et al., 2012) or entering of the particles accelerated in the upstream region of the bow shock via reconnection into the magnetosphere (Trattner et al., 2011), see Figure 6. Therefore, substorm related acceleration processes on the night-side are not the only source of asymmetries on the closed magnetic field lines.

The distributions of energetic electrons were studied before Cluster by space missions such as Vela, IMP 7 and 8, see Montgomery et al. (1965); Bame et al. (1966); Meng et al. (1981). These studies were controversial on acceleration mechanisms that lead to suprathermal energies and dawnward asymmetry of electron distributions. The question is, are adiabatic acceleration, Speiser acceleration and gradient, and curvature drift enough to explain the distributions or does one need additional acceleration mechanisms related to reconnection and wave-particle interaction? Åsnes et al. (2008b) using 4 years of Cluster/IES observations showed that in the terrestrial magnetotail invoking electron acceleration mechanisms related to reconnection and wave-particle interaction is generally not required. This conclusion opposes many Cluster studies mentioned in Section 4. Therefore, this topic can be considered as open for further investigations

A knowledge of energetic particle distributions is helpful for space weather applications such as spacecraft operations. Most models of particle fluxes were developed for the region within geosynchronous orbit, see, for example, Denton et al. (2016). Using long-term observations of the Cluster mission, an extension of the empirical model for electron fluxes (1 eV–40 keV) at geosynchronous orbit was derived by Denton et al. (2019). This model describes energetic electron fluxes from ~40–400 keV in the equatorial GSM plane ($Z = \pm 2 R_E$) and radial distance 6–20 R_E . For the protons, a recent model for radial distances 6–22 R_E was derived by Kronberg et al. (2021). This model can be useful in assessment of the soft proton contamination of the X-Ray telescopes, see, for example, Fioretti et al. (2016); Kronberg et al. (2020). Both models based on Cluster observations can predict average level of the energetic particle fluxes but are not able to predict short-time fluctuations related to acceleration processes mentioned in Section 4. This task is also very challenging in particular because of the spatially localized nature of the acceleration processes, see, for example, Luo et al. (2014).

6. Radiation Belts

The Van Allen radiation belts are a region with highly energetic (>100 keV) charged particles, mainly electrons and protons, trapped by the terrestrial magnetic field (mainly below 6 R_E). The radiation belts are hazardous for satellite operation. The charged particles with energies of tens to hundreds of keV, injected into the inner magnetosphere mainly from the plasma sheet, as a result of substorm activity (see Section 7), produce waves, and can be accelerated to higher energies. The particles with energies of hundreds of keV can accumulate at the surface of the spacecraft, leading to surface-charging effects, and can penetrate deep into instrument electronics causing satellite anomalies and instrument malfunctions by deep dielectric charging, see, for example, Baker et al. (1994); Baker et al. (2004).

Due to their importance for satellite operation, a large number of instruments have provided observations of the radiation belt populations, see, for example, Ginot et al. (2013); Denton et al. (2016). One of the longest continuous data sets of electron flux at energies 40–400 keV has been supplied by the RAPID/IES detector. The IES instrument was not specifically designed for radiation belt studies, and therefore is subject to background contamination by higher energy electrons and protons. The effect of the charged particle radiation belt environment on the RAPID/IES detector was investigated in Kronberg et al. (2016). For this, the IES detector was simulated in the Geant4 environment (Agostinelli et al., 2003). The percentages of the total electron intensity attributed to contamination were calculated for L-shells up to 9. The background-corrected measurements were compared to the observations by the MagEIS detector aboard the Van Allen Probes mission (Blake et al., 2013) during October–December 2012, and the ratio between the two data sets was close to 1.

Smirnov et al. (2019) compared the background-corrected electron flux measurements by the IES detector to those by RBSP/MagEIS in 2012–2016, both in terms of omnidirectional flux and flux at 90° pitch angle. It was found that the corrected Cluster measurements were close to the MagEIS observations during the 2012–2016 period. These background-corrected observations can be used in various scientific applications. Breuillard et al. (2015) derived energetic electron anisotropy to model the chorus wave power distribution in the outer radiation belt. Smirnov et al. (2019) presented a long-term analysis of electron flux dynamics during ~1.5 solar cycles in 2001–2016. It was found that the long-term trend of electron intensities at energies 40–400 keV in the outer belt exhibited a high positive correlation with the solar wind dynamic pressure and AE index (see Figure 7). A simple generalized empirical model which connects electron intensities at L-shells from 4 to 6 to the solar wind dynamic pressure was derived:

$$\log_{10} y = 0.35(\pm 0.1) + 0.5(\pm 0.18)x, \quad (1)$$

where x stands for the normalized solar wind dynamic pressure and y represents the logarithm of electron flux, normalized to their minimum and maximum values.

Trapped energetic particles in planetary magnetospheres undergo three types of periodic motion, namely the gyro-, bounce, and drift motion. Each type is associated with the corresponding adiabatic invariant (μ , K , and L^* , respectively), which are conserved when the magnetic field changes are slow compared to the motion periods. Electron flux, measured as a function of energy, position, and time, can be converted to phase space density (PSD), as a function of three adiabatic invariants. Analyzing the PSD behavior under the fixed

Figure 7. (a) The solar wind dynamic pressure, and (b) yearly averaged electron flux intensities by Research with Adaptive Particle Imaging Detectors (RAPID)/ion and electron sensor (IES). Adapted from Smirnov et al. (2019).

values of μ , K , and L^* , allows for a separation between adiabatic and nonadiabatic processes (see also a study by Åsnes et al., 2008b for the plasma sheet mentioned in Section 5), and helps to utilize observations from different magnetic latitudes. This is of particular interest for the Cluster constellation, due to its polar orbit. The method to calculate the adiabatic invariants and convert the RAPID/IES electron flux to PSD in the radiation belts was developed in Smirnov, Kronberg, et al. (2020). Figure 8 shows the long-term behavior of low- μ electrons along ~ 1.5 solar cycles and the 27-day averaged F10.7 and AE indices. F10.7 index (Tapping, 2013) follows the sunspot cycle evolution, while the AE index intensifies with higher occurrence of coronal holes and HSSs during the declining phase. At L -values from 4 to 6, the general PSD behavior closely resembles the variation of the AE index. The PSD values are higher during the declining phase of the solar cycle 23 (2004–2007), agreeing well with previous studies, for example, by (Baker et al., 2001; X. Li et al., 2001) which used 5/7 years of SAMPEX MeV observations. The PSD values also exhibit minimum values during the solar minimum in 2009, also referred to as the “radiation belts desert.” However, these results disagree with observations by Miyoshi et al. (2004) from the NOAA satellites from years 1979–2003, more than two solar cycles, that proposed anticorrelation for electrons at energies >300 keV with F10.7 index at L -shells from five to six during solar cycles 21–23. In Smirnov et al. (2019), the fluxes do not show any correlation with the index. This, therefore, suggests importance of further observations of the radiation belts. RAPID/IES mainly samples low- μ electrons, for which the substorm activity is of paramount importance. These results agree well with previous findings by Zhao et al. (2017) that observed a high correlation of PSD enhancements derived from the observations by Van Allen Probes with auroral geomagnetic indices, suggesting a direct transport of electrons from substorm injections, see next section.

7. Substorm Dynamics

Localized multipoint measurements by Cluster (“microscopic view”) in combination with other spacecraft missions make it possible to advance a major magnetospheric research objective: physics of substorms (Baker, Ergun, et al., 2002).

One longstanding issue in substorm physics is related to understanding of where and when a substorm process initiated. Simultaneous measurements from the GOES-8, POLAR, LANL, IMAGE, and Cluster indicated that magnetic reconnection in the investigated event formed in the midtail region (XGSE $\sim$ –18)

Figure 8. (a) Phase space density (PSD) for Cluster-1 to Cluster-4 under the fixed values of adiabatic invariants μ and K in 2004–2019; (b) AE and F10.7 indices. Adapted from Smirnov, Kronberg, et al. (2020).

substantially before magnetic field dipolarization near geostationary orbit and auroral substorm onset (Baker, Peterson, et al., 2002). Later, Sergeev et al. (2007) using TC2, GOES-10, LANL084, IMAGE, and Cluster reported that midtail reconnection and near-Earth magnetic field dipolarization may occur nearly simultaneously. RAPID electron observations helped to identify reconnection related regions. These studies illuminated the complexity of this question and necessity of further space missions such as THEMIS.

With help of energetic particle observations, one can reveal phenomenology and causes of particle injections at geostationary orbits associated with substorm dynamics. Such injections feed charged particles into the ring current and the radiation belts, the most important regions for the space weather effects. The origin of dispersionless injections, namely when particle fluxes increase simultaneously over a wide energy range, is controversial (Birn et al., 1997; X. Li et al., 2003; Gabrielse et al., 2014; Moore et al., 1981). A classic substorm event with several dispersionless injections was investigated using data from 15 satellites by Kronberg, Welling, et al. (2017). These were data from four Cluster satellites, three THEMIS satellites, six LANL satellites, and two Van Allen Probes. These data were complemented by the magnetic field observations measured by many stations at high latitudes from INTERMAGNET (St-Louis, 2008) and SuperMAG (Gjerloev, 2012) networks. In this study, it was shown that during different phases of the substorm event the reasons for the injections can be different: dynamic motion of plasma sheet structures during the growth phase, current wedge formation during the substorm onset and magnetic dipolarization fronts during the expansion phase. Only the injection associated with the substorm onset and formation of the current wedge filled the radiation belts and ring current with a substantial number of charged particles. An example of deep electron injection penetration during formation of the substorm current wedge using the simultaneous telescopic (IMAGE observations) and microscopic view by Cluster can be found in Baker, Ergun, et al. (2002).

During substorm activity field-aligned currents related to the magnetosphere-ionosphere coupling are formed. These field-aligned currents are associated with the magnetic field fluctuations at different frequency ranges. Modeling by X. Li et al. (2003) has shown that particles can be accelerated via magnetic drift-bounce resonant interaction with Pc5 waves in the inner magnetosphere. Zong et al. (2007) using multipoint Cluster/RAPID observations demonstrated the excitation of the energetic electron drift resonance at around 127 keV at the dayside inner magnetosphere during a substorm. Simultaneous observations by

multiple satellites in the study by Kronberg, Welling, et al. (2017) indicated that a so-called bump on the tail of the electron intensity spectra at around 120 keV is observed at the geosynchronous orbit but not in the tail region observed by Cluster. Observations and modeling in this study suggested that this effect occurs because of drift-resonant interaction with Pc5 waves generated by the field-aligned currents related to sub-storm dynamics. The origin of Pc5 waves in these two studies, however, is not necessarily the same.

8. Magnetic Storms

The accelerated particles in the plasma sheet (see Sections 4 and 7) move in the direction of the Earth and then drift around, forming the ring current. The ring current generates a magnetic field in the southward direction at the Earth's surface, namely a field in the opposite direction to the terrestrial magnetic field, produced by the Earth's dynamo. The terrestrial magnetic field will be reduced and this disturbance is called a magnetic storm, one of the most important signatures of severe space weather events. The ionospheric and energetic particles influence the strength of the magnetic storm (e.g., Hamilton et al., 1988; Keika et al., 2013; Krimigis et al., 1985). Both of these components are often neglected in the calculation of the plasma pressure and temperature as in the plasma sheet as well in the ring current. These parameters, however, are of crucial importance for the modeling of the magnetospheric dynamics (see an example in Nakamura et al., 2013), in particular reproducing correct ratio between the solar wind and ionospheric sources. Ion composition measured by the Cluster CIS and RAPID instruments and a possibility to build joint spectra of bulk and energetic particle distributions can help to improve these issues.

Haaland et al. (2010) showed that the power law part of the proton spectra (energetic part) becomes significantly harder in the plasma sheet during magnetic storms. Later, Kronberg, Grigorenko, et al. (2017) demonstrated that the plasma pressure in the plasma sheet and the ring current and as a consequence the Dst-index (represents the strength of the magnetic storm near the equator (Nosé et al., 2017)) are strongly underestimated when the ionospheric ions and ions at energies >40 keV are neglected. The Cluster observations in this study were compared with the Space Weather Modeling Frame (Tóth et al., 2012) simulations with two different ionospheric ion outflow models as an input and both have shown similar results. The space weather modeling, however, still can be improved by considering the more energetic part of the particle spectra. Pressure distributions observed by Cluster in the ring current are in agreement with later results by Van Allen Probe by Yue et al. (2018).

9. Summary

The multipoint observations of energetic charged particles by the Cluster/RAPID instrument in combination with other spacecraft missions substantially enhanced our understanding of dynamics of the terrestrial magnetosphere. The following results were obtained, to name a few:

It is well known that the energetic particles affect the plasma temperature and pressure. The Cluster results demonstrated that the energetic part >40 keV has to be considered during geomagnetically disturbed times in the calculations of the ion plasma temperature and pressure. Otherwise, the related physics, for example, in flow breaking region or in the ring current is incorrectly interpreted. Therefore, it is essential to include the energetic part and ionospheric heavy ions when estimating these parameters.

Charged particle energization mechanisms were thoroughly investigated. The results substantially contributed to the idea that interaction of charged particles with multi-scale magnetic field structures and/or electromagnetic fluctuations which are the consequences of reconnection or other plasma instabilities leads to an effective acceleration. Multiple interaction with such magnetic structures increases energy even higher.

Confirming that the distribution of the energetic ions on the closed magnetic field lines is strongly affected by the geomagnetic activity, Cluster demonstrated significant influence of the solar wind parameters. A substantial amount of ions escape the magnetosphere populating the region upstream of the bow shock, explaining the origin of more than 50% of upstream events during declining phase of the solar cycle. Surprisingly, the distribution is also affected by the IMF B_y direction leading to dawn-dusk asymmetries as well as to asymmetries between Northern and Southern hemispheres. This also implies the importance of

reconnection processes effects on the energetic ion distribution (>270 keV) not only at the night side but also at the dayside of the magnetosphere.

The radiation belts are effectively filled with electrons via injections during substorms onsets. A clear linear relationship between electron intensities from 40 to 400 keV in the radiation belts at L -shells four to six and the solar wind dynamic pressure/substorm activity was demonstrated for ~ 1.5 solar cycles.

A large data set of electron intensities in the radiation belts and ring current region is available for scientific investigations, thanks to the recently developed background-correction technique. The Cluster constellation is one of the longest ongoing missions in the Earth's magnetosphere, providing more than 20 years of observations. The IES detector, similar to that on Cluster, was carried by the Polar mission and is also included in the payload of the recently launched BeiDou GNSS constellation. The combined data set thus covers more than two solar cycles. It can be useful for the long-term statistical analysis of electron flux behavior in the outer radiation belt, and can be incorporated into the empirical models of the medium energy electron flux, for example, by Smirnov, Berrendorf, et al. (2020). Moreover, the electron fluxes converted to PSD can be used to set up boundary conditions for radiation belts modeling, as well as for data assimilation purposes.

The Cluster results also leave open some scientific questions. These are, for example, the effects of the solar wind conditions on the origin of the energetic particles in the region upstream of the bow shock; the origin of dawn-dusk asymmetries in distribution of charged particles in the plasma sheet; necessity of reconnection; and wave-particle interaction to explain the distributions; physics of substorm dynamics considering composition; and plasma pressure and temperature calculations in the wide energy range and improvement of particle intensity models by learning how to predict localized acceleration processes.

The vast amount of RAPID data collected within the last 20 years, available at the Cluster Science Archive, is welcoming future explorations.

Data Availability Statement

Data were not used, nor created for this research.

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