The Dynamics Of The Terrestrial Radiation Belts And Its Links To The Plasmasphere

Viviane Pierrard[a,b] and Sylvie Benck[b]

[a] *Belgian Institute for Space Aeronomy (IASB), Space Physics, 3 avenue circulaire, B-1180 Brussels, Belgium*
[b] *Université Catholique de Louvain, Center for Space Radiations (CSR), 2 chemin du Cyclotron, B-1348 Louvain-La-Neuve, Belgium*

Abstract. The Earth's radiation belts comprise electrons with energies from 0.01 to 10 MeV and protons with energies from 0.1 to 500 MeV trapped in the terrestrial magnetic field. The outer electron belt (L>3) is highly variable with space weather. During geomagnetic storms, the electron fluxes vary of several orders of magnitudes and the outer belt penetrates closer to the Earth. The plasmasphere is also eroded during geomagnetic storms so that the plasmapause goes closer to the Earth. In the present work, we describe the main characteristics and the correlation that exists between the dynamics of the radiation belts and that of the plasmasphere, as we obtained with SAC-C and CLUSTER observations.

Keywords: Radiation belts, energetic electrons, dynamics, magnetic storms, space weather.
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INTRODUCTION

The energetic protons and electrons trapped in the magnetic field of the Earth can harm space-borne systems and astronauts. Therefore, understanding and forecasting radiation belt dynamics has crucial scientific and practical significance.

The electron belt is divided into a relatively stable inner belt and a highly variable outer belt separated by a slot region located between 1.8 and 3 Re depending on the energy [Li and Temerin, 2001]. The proton belt comprises very energetic protons located close to the Earth. It is quite stable except at very low altitudes where the expansion of the atmosphere can erode it [Pierrard and Borremans, 2012].

Based on spacecraft observations, we summarize here the main dynamic features of the electron belt.

RADIATION FLUX VARIATIONS DURING GEOMAGNETIC STORMS

Spacecraft observations show that the electron fluxes vary of several orders of magnitude during geomagnetic storms. This is well illustrated on Figure 1 showing in its three upper panels, averaged electron fluxes (with a time-resolution of 12 h) for three energy ranges measured by SAC-C/ICARE during October 2001- January 2002. The fourth panel shows the Dst index observed during the same time period.

The Argentinean SAC-C spacecraft was launched on 21 Nov. 2000 on a sun-synchronous orbit, with a Perigee/Apogee altitude of respectively 672/ 706 km, an inclination of 98.2° and a period of 98.7 min. The ICARE instrument gives quasi permanently information on the electron fluxes at LEO, detecting the electrons from 200 keV to 4 MeV and protons from 9 to 40 MeV [Falguère et al., 2002].

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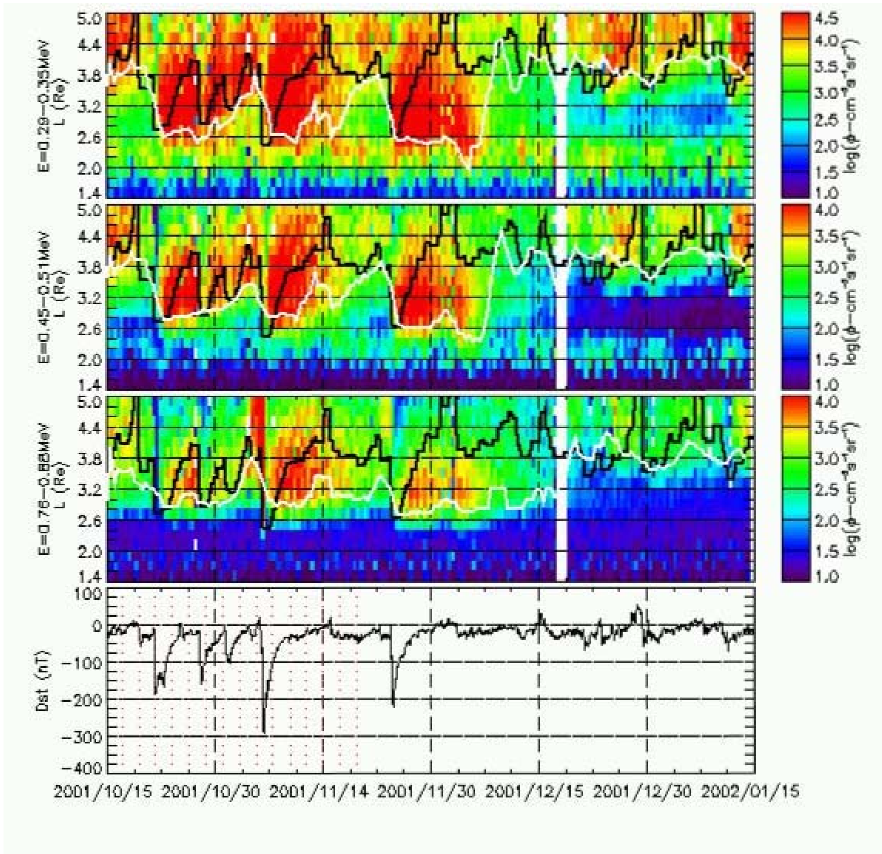

FIGURE 1. The three upper panels show the electron fluxes (time resolution 12 h) as a function of L (for 0.22 < B < 0.46 G) and time for three energy channels from the SAC-C/ICARE instrument. On top of this, the white curve represents the inner edge of the outer radiation belt defined as the L-value where the electron intensity is 40% of its peak. The superimposed black curve represents the daily minimum Lpp based on the empirical model from O'Brien and Moldwin [2003]. The lowest panel gives the evolution of the Dst index for the same time period.

It can be seen in Fig. 1 that magnetic storm events characterized by negative peaks of Dst index (panel 4) are directly associated to injections of electrons during the initial phase of the storms. These flux enhancements (red regions in the 3 first panels) remain during several days before the fluxes smoothly decrease [Benck et al. 2010] due to different loss mechanisms such as collisions with atmospheric constituents and deflection by plasma waves.

Based on such SAC-C observations completed with DEMETER/IDP measurements, an empirical dynamic model of the electron radiation belts has been developed [Benck et al., 2012]. This model is based on a steady-state flux level, flux enhancements probability during geomagnetic storms and flux decay-time constants that depend on the given energy and positions in space [Benck et al., 2010]

The storms are also associated to an inward motion of the outer belt, emphasized in the three upper panels of Fig. 1 by the white line that illustrates the inner edge of the outer belt, obtained as the L-value where the electron intensity is 40% of its peak.

DYNAMICS OF THE PLASMASPHERE DURING STORMS

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The plasmapause position has also an inward motion during geomagnetic storms and substorms due to the erosion of the plasmasphere driven by the convection electric field associated to solar wind variations [Pierrard and Lemaire, 2008]. To compare the position of the plasmapause with the inner edge of the outer radiation belt, we have also superposed on the first three panels of Fig. 1 the plasmapause location obtained with the model of O'Brien and Moldwin [2003] (black line). It represents the daily minimum plasmapause location Lpp based on the empirical Dst relation obtained from CRRES observations:

$$Lpp = 6.3\text{-}1.57 \log10|Dst| \qquad (1)$$

Other plasmapause models have been used as well [Pierrard and Lemaire, 2004; Pierrard and Stegen, 2008] and give very similar results while they depend on the geomagnetic activity index Kp. The plasmapause locations are also located in the inbound and outbound ranges of the plasmapause observed by CLUSTER during the same period.

During the main phase of the geomagnetic storms, the plasmapause goes closer to the Earth in a few minutes. The penetration of the outer belt follows the plasmapause erosion by several hours. The observations of Fig. 1 suggest that the innermost Lpp corresponds to the innermost limit of the outer radiation belt penetration. After the storm, the plasmapause comes back to larger radial distances in less than 3 days, while the inner edge of the outer belt remains close to the Earth during periods longer than 15 days. The most inward electrons stay at small L shells long after the plasmapause has moved outwards. During these 15 days following a magnetic storm, the link between the plasmapause and the radiation belt has disappeared and the outer radiation belt co-exists with the plasmasphere after a deep penetration. But during prolonged quiet periods, the inner edge of the outer belt and the plasmapause position are located at large radial distances around 4 Re and they also seem to present some correlation.

PLASMAPAUSE/RADIATION BELTS LINKS IN PREVIOUS WORKS

The plasmapause is more dynamic than the inner edge of the outer radiation belt, which explains why the 3.5 days averaged plasmapause is better correlated with the space radiation boundaries as observed by Goldstein et al. [2005]. Indeed, such plasmapause/outer belt boundary correlation has been noted by these authors using SAMPEX daily averaged fluxes of 2–6 MeV electrons and IMAGE/EUV 10-min global images of the plasmasphere. Goldstein et al. [2005] observed that in two events, severe erosion moved the plasmapause inside $L = 2$ and 2–3 days later the outer belt was situated at the location where normally the slot region is expected. Goldstein et al. found the inner extent of the outer belt correlated (to within a standard deviation of $\Delta L \approx 0.1$) with the 3.5-day running average of the plasmapause location and deduced a $\geq$3.5-day average loss time scale from pitch-angle scattering by plasmaspheric hiss and EMIC waves. Plasmasphere erosion provides the opportunity for energized electrons to persist as trapped radiation belt particles in a region normally devoid of these particles.

Baker et al. [2004] were pioneers to show that radiation belt populations are sensitive to the core plasmasphere distribution and specifically to the position of the plasmapause.

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Using SAMPEX observations, these authors reported that the outer Van Allen belt was compressed dramatically by a solar storm known as the 'Halloween storm' of 2003. From 1 to 10 November 2003, they noted that the outer belt had its center only 10,000 km from Earth's equatorial surface, and the plasmasphere as observed by IMAGE/EUV was similarly displaced inwards.

Li et al. [2006] also established a relationship between the position of the plasmapause and the internal border of the external radiation belt using SAMPEX observations for the radiation belts and CRRES observations as well as an empirical model for the plasmapause. They also observed that the inner edge of the outer radiation belt does not follow the plasmapause all the time but it is rather the initial penetration of the outer belt that follows the plasmapause erosion. After the plasmapause has moved outwards again, the most inward electrons stay at small L shells and slowly decay inside the plasmasphere. Although the explanations for this correlation are not yet precisely defined, they have outlined three mechanisms by which the plasmapause may play a role in shaping the outer electron belt: i) Pitch angle scattering of electrons by VLF and EMIC waves outside the plasmapause causing them to precipitate, ii) the plasmasphere may modify the characteristics of the ULF waves that diffuse particles radially inward and to higher energies, and iii) acceleration by VLF chorus may produce a flux peak just outside the plasmasphere as chorus is strongest just beyond the plasmapause.

CLUSTER ANALYSIS DURING A QUIET PERIOD

The previous correlations deduced by Baker et al. [2004], Goldstein et al. [2005] and Li et al. [2006] combined the results of different spacecraft. With CLUSTER, we can for the first time observe cold and energetic electron populations with the same spacecraft and directly compare the observed plasmapause with the observed edges of the radiation belts [Darrouzet et al., 2012].

The positions of the plasmapause found with the instrument WHISPER on CLUSTER (cold eV electrons) are compared to the positions of the outer electron radiation belt edges deduced from CLUSTER/CIS observations (electrons >2MeV) [Ganushkina et al., 2012] and those deduced from CLUSTER/RAPID observations (electrons in the energy range [244.1-406.5 keV]). The period of April 2008 to March 2009 has been chosen for the analysis because CLUSTER was then located at lower radial distances with a perigee as close as L=2 deep inside the plasmasphere and the radiation belts. This time period corresponds to a long solar minimum activity. The plasmapause position detected by WHISPER corresponds to the outer edge of the plasmapause since the instrument saturates when it penetrates in the plasmasphere and observes densities higher than 40 e^-/cm^3 [Darrouzet et al., 2009]. In our study, the radiation boundaries are chosen to be the middle value between the logarithm of the maximum outer belt flux and the logarithm of the minimum flux at both borders of the outer belt.

The average positions of the outer radiation belt boundaries found with the different CLUSTER instruments are summarized in Table 1, together with the minimum and maximum values observed during this geomagnetic quiet period. It is observed that the plasmapause positions are very variable and located quite far from the Earth (5.9 Re in average). This plasmapause position corresponds quite well to the outer edge of the outer

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belt for energetic electrons (>2MeV) observed by CIS (6.1 in average). Its dynamics is similar, even if the plasmapause position is more variable.

TABLE 1. Average positions of the electron population boundaries measured by the different instruments of CLUSTER for different electron energies during the quiet period from April 2008 to March 2009.

Instrument	Energy	Inner edge (Re)	[min,max]	Outer edge (Re)	[min, max]
WHISPER	1 eV			5.9	[3.7, 9.3]
CIS	>2 MeV	3.5	[2.9, 4.2]	6.1	[5, 7.5]
RAPID	244-406 keV	4.2	[3.7, 5.5]	8	[5.3, 11]

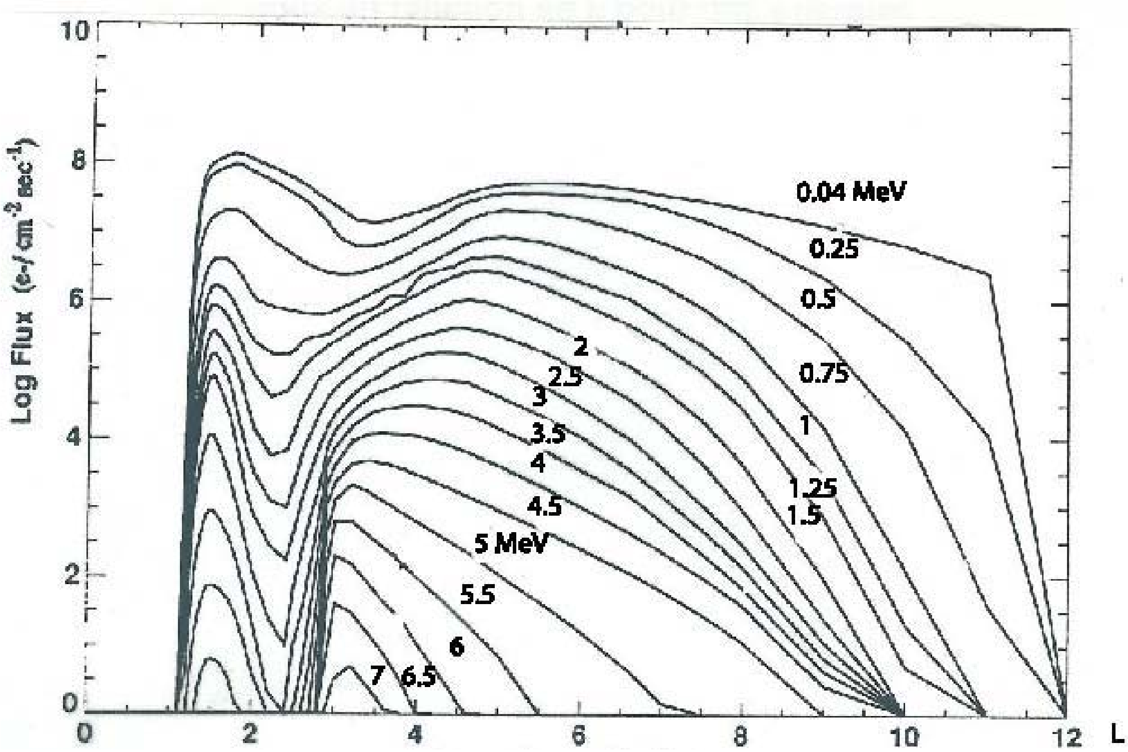

FIGURE 2: Electron flux as a function of L for the AE8 NASA model.

This highly dynamic behavior of the plasmapause boundary is well reproduced with the plasmaspheric model developed by Pierrard and Stegen [2008] and that was recently coupled to the ionosphere [Pierrard and Voiculescu, 2011].

It is observed that the inner edges are less variable than the outer edges. Moreover, the inner and outer edges of the electron belt depend on the energy of the particles. They are lower for energetic electrons (lower with CIS than with RAPID).

This is not surprising if we consider static models like AE8 [Vette, 1991] for instance. Figure 2 shows the integral fluxes obtained with this AE8 empirical model as a function of the McIlwain parameter L for different energies. One can see indeed that the edges are located at higher radial distances for low energy electron populations than for higher energy. The inner edge of the outer belt for E>3 MeV is located around 3 Re in the AE8 model, what is clearly closer to the Earth than the average observed position of the plasmapause [Pierrard and Cabrera, 2006, Darrouzet et al., 2009]. The edges of the outer belt are not very sharp except for the inner edge of energetic electrons (> 3 MeV).

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CONCLUSIONS

A correlation between the plasmapause position and the outer radiation belt boundary is observed with CLUSTER measurements for energetic electrons (>2 MeV) during prolonged quiet periods. During geomagnetic storms, the plasmapause and the outer belts go closer to the Earth and the inner edge of the energetic electrons can be related to the plasmapause position. But during the recovery phase, these positions are very different since the plasmasphere refills in a few hours while the outer belt takes several days to decay for L>2.5 [Benck et al., 2010]. The correlation between the radiation belts and the plasmapause depends also on the energy range of the electrons.

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