

Faculté des sciences

Study of the terrestrial radiation belts (using PROBA-V/EPT and RBSP/MagEIS)

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Abstract

The Van Allen radiation belts were first discovered in the 1950's with the launch of the first satellites. Since then, the need for satellites has become increasingly important for human activities. However, the radiative environment in which they evolve is a threat for all spacecraft as well as for astronauts. The radiation belts are toroidal regions filled with high energy particles, mainly electrons and protons trapped in the magnetic field of the Earth. The state of the belts is highly dependent on magnetic activity induced by the solar wind and processes involved in their dynamics are very complex. Radiation belts have been studied for decades now, allowing to improve our models and theoretical understanding of those regions. The intensive investigation of the radiation belts led to the need of instruments that are able to perform high resolution measurements, such as the NASA Magnetic Ion Electron Spectrometer (MagEIS) onboard the Van Allen Probes or the ESA Energetic Particle Telescope (EPT), jointly developed by UCLouvain, BRIA-IASB and QinetiQ Space, carried by the PROBA-V satellite. Both instruments have provided (and still provides, in the case of the EPT) science data for several years.

The main objective of this work is to perform a comparison of simultaneous observations of the radiation belts from those instruments, despite the different orbit of the spacecraft. To this end, data from 2014 are used. A larger focus is brought on EPT measurements, which are used to characterize the main events that led to sharp variations in electron and proton populations during this year. Those observations are also compared to an empirical model of the belts based on previous averaged measurements.

The comparison of the two instruments is carried out for the outer belt electron fluxes on two time intervals of three months. It is also performed at different locations in the belts, for various energy and the effect of the pitch angle for equatorial electrons is investigated. On the one hand, for the first data set, ranging from January to March, observations of the two instruments are well correlated especially for low pitch angle value equatorial electrons. On the other end, for data taken between October and December, the correlation of the two instruments is decreased and more particularly near the inner edge. This decrease is found to most likely be caused by a difference in geomagnetic activity between the two periods.

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List of Acronyms

CME	Coronal Mass Ejection
CRAND	Cosmic Ray Albedo Neutron Decay
CSR	Center for Space Radiation
ECT	Energetic Particle, Composition, and Thermal Plasma Suite
DAM	Digital and Absorber Module
Dst	Disturbed storm time
EPT	Energetic Particle Telescope
ESA	European Space Agency
FoV	Field of View
HES	High Energy Section
IASB-BIRA	Institut royal d'Aéronomie Spatiale de Belgique/ Koninklijk Belgisch Instituut voor Ruimte-Aeronomie
IMF	Interplanetary Magnetic Field
LEO	Low Earth Orbit
LES	Low Energy Section
PROBA-V	PRoject for On-Board Autonomy Vegetation
RBSP	Radiation Belts Storm Probes
SAA	South Atlantic Anomaly
SC	Sudden Commencement
SEP	Solar Energetic Particle event
SPAND	Solar Proton Albedo Neutron Decay
ULF	Ultra Low Frequency
VAP	Van Allen Probes

Chapter 1

Introduction

1.1 Why study the radiation belts ?

Since the launch of the first satellites, mankind has and continues to increasingly rely on this technology. Satellites are crucial for our communication and navigation systems, weather forecasting, scientific experiments and many other applications. The energetic particles present in the radiation belts, as well as the very intense variability in those regions represent a non negligible hazard not only for the satellites themselves but also for all the instruments they carry. Moreover, space radiations represent a real danger for astronauts. It is thus important to understand this hazardous environment. The radiation belts have been studied for decades now, but they are far from being perfectly known yet. Many processes involved in the dynamics of the belts are still debated. Hence, high resolution and high fidelity measurements of the flux of energetic particles, such as the ones provided by the EPT or MagEIS, are required to improve the current theory of trapped particles as well as predictions for space weather.

The purpose of this introductory chapter is to give the reader the necessary theoretical background for the understanding of the other chapters of in this work.

1.2 Magnetic environment of the Earth

In the Sun's corona, the temperature exceeds 10^6 K so that some particles can escape the Sun attraction. The stream of particles leaving the solar atmosphere is called the solar wind, which is mainly composed by electrons and protons (with about 10% alpha particles). This plasma travels the interplanetary space at supersonic speeds, between 400 km/s near the neutral surface of the heliosphere and 800 km/s near the coronal holes. The solar wind also transports the magnetic field of the sun, forming the interplanetary magnetic field (IMF). The magnetosphere of the Earth results from the interaction of the geomagnetic field and the solar wind. The boundary between the space dominated by the IMF and the space dominated by the magnetic field of the Earth is called the magnetopause. On the day side of the Earth, the magnetosphere is compressed inward to about 10 Earth radii (R_E) due to the pressure of the solar wind. The position of the magnetopause in the day side strongly depends on the condition of the solar wind and can be pushed back to geostationary distances to the Earth ($\sim 6.6R_E$, with $1 R_E \approx 6371$

km) [Hannu E. J. Koskinen, 2022]. In the night side, the magnetosphere is stretched out up to $100 R_E$, creating the magnetotail. It is composed by two lobes of opposite magnetic polarity which are separated by the plasma sheet, composed by hot plasma of both solar and ionospheric origin [Pierrard, 2009]. This constitutes the outer magnetosphere.

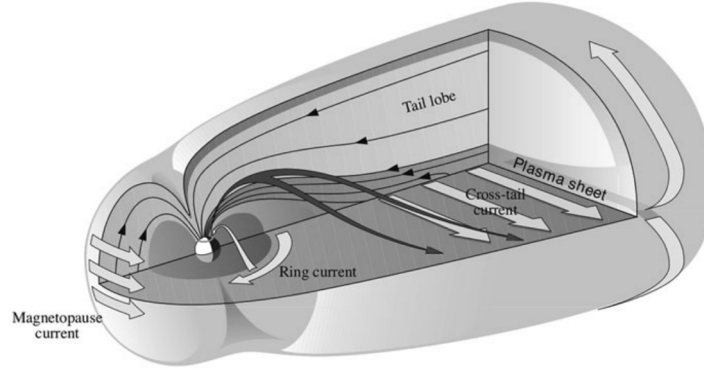


Figure 1.1: Magnetosphere of the Earth. Image from [Hannu E. J. Koskinen, 2022]

The inner magnetosphere is the region where the magnetic field is quasi-dipolar. In this region, one find a variety of particle species with various energy, as well as various spatial distribution:

1. The ring current is generated by the azimuthal drift motion of energetic particles. Electrons move in the eastward direction while positively charged particles move in the westward direction. Particles forming the ring current are located between $3-8 R_E$ from the Earth [Hannu E. J. Koskinen, 2022].
2. The radiation belts are mainly composed by high energy electrons and protons trapped in the quasi dipolar geomagnetic field. A more detailed explanation of the belts is given in the next section.
3. The plasmasphere is the most inner part of the magnetosphere. It is composed of cold and dense plasma (~ 1 eV) originating from the ionosphere. The limit of the plasmasphere is relatively well defined (rapid drop in the proton density) and is called the plasmopause [Hannu E. J. Koskinen, 2022].

All of those components of the inner magnetosphere spatially overlap and interact with each other. Specifically the plasmopause, whose position strongly depends on the magnetic activity, plays an important role in the dynamics of the outer belt electrons.

1.3 The Van Allen radiation belts

The terrestrial radiation belts were discovered in 1958 by James Van Allen and his co-workers with the launch of the first American satellite *Explorer 1*. The spacecraft was equipped with a Geiger-Müller instrument whose goal was to measure cosmic radiation. The instrument worked well up until an altitude of 700 km where the count of the Geiger

instrument suddenly dropped to zero. The satellite was travelling through a region where the radiations were so intense that the instrument was saturated [Pierrard, 2009].

The radiation belts are toroidal regions populated by high energy particles trapped in the magnetic field of the Earth. They mainly consist of electrons and protons (with a very small fraction of heavier ions). The energy range of particles in the radiation belt is comprised between ~ 30 keV to several hundred MeV for protons in the inner belt. There are two distinct radiation belts. The inner belt, located closer to the Earth extends up to $4 R_E$ in the equatorial plane. It is populated by both electrons and protons of varying energy. The outer belt, which extends from $4 R_E$ to $10 R_E$ in the equatorial plane, is composed in majority by electrons. This belt is much more variable in time than the inner one. The two belts are separated by a slot region, where the flux of particles is much lower. The position and the width of the slot, as well as the radiation belts depend on the energy of the electrons [Pierrard, 2009]. It is also interesting to note that a configuration with three belts was observed during one month for ultrarelativistic electrons ($E > 3.4$ MeV) [Hannu E. J. Koskinen, 2022].

1.3.1 South Atlantic anomaly

The geomagnetic field of the Earth is generated in its liquid core. The axis of the magnetic dipole is not aligned with the rotation axis, an angle of 11° separates them. In addition, the center of the dipole does not coincide with the center of gravity of the Earth. The center of the dipole is 500 km away, toward the northern Pacific. Due to the combination of both offsets (in angle and in position), the intensity of the magnetic field is minimum over the South Atlantic. Moreover, the magnetic dipole axis is the axis of symmetry of the radiation belts. Thus protons of the inner belt are able to penetrate deeper in the atmosphere over this region, which is called the south Atlantic anomaly or SAA. Besides, at a given altitude, the intensity of energetic proton fluxes are much higher over the SAA, which can have impact on LEO orbiting satellites [Pierrard, 2009].

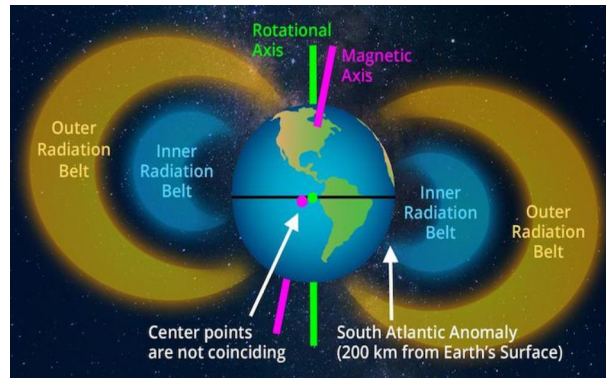


Figure 1.2: Schematic drawing of the Van Allen Radiation belts. The deeper penetration of the inner belt is also represented. This image was taken from <https://stellariasacademy.online/south-atlantic-anomaly/20/05/>

1.4 Motion of particles in the radiation belts

In the radiation belts, the plasma has a very low density, such that in good approximation, collisions between particles can be neglected and their motion is supposed to be independent from each other. The motion of charged particles is then driven by the Lorentz force acting on them, due to the presence of electric fields as well as geomagnetic field. The equation of motion of a given particle of mass m and charge q in the radiation belts is then given by,

$$m\mathbf{a} = q(\mathbf{E} + \mathbf{v} \wedge \mathbf{B}) + m\mathbf{g} \quad (1.1)$$

The solution of this equation is very complex but can be obtained numerically. However in order to get a better understanding and insight of the movement of trapped particles, some approximations can be made and their motion can be decomposed in three distinct (quasi-)periodic motions: the gyration motion around a guiding center, the bouncing motion along the magnetic field lines and the azimuthal drift motion [Pierrard, 2009].

1.4.1 Gyration motion

Considering a uniform and static magnetic field $\mathbf{B}$ pointing in the $\mathbf{z}$ direction, and neglecting other forces (like gravity and Coulomb force), the equation of motion of a non relativistic charged particles of mass m and charge q is given by,

$$m\frac{d\mathbf{p}}{dt} = q\mathbf{v} \wedge \mathbf{B} \quad (1.2)$$

The motion of the particle described by this equation can be split in two. First the particle orbits a guiding center in the plane perpendicular to the magnetic field. Second, the movement of the guiding center parallel to the magnetic field. [Hannu E. J. Koskinen, 2022] From the circular motion, it is possible to derive the expression of the gyro radius (also called Larmor radius),

$$\rho_G = \frac{mv_{\perp}}{|q|B} \quad (1.3)$$

where $v_{\perp}$ is the velocity perpendicular to the magnetic field. The gyro radius depends on the particle species, the energy as well as the intensity of the magnetic field. Thus, for a given particle which guiding center follows a given magnetic field line, its gyro radius is largest at the magnetic equator. The angular frequency of the gyration motion is given by the Larmor angular frequency,

$$\omega_G = \frac{v_{\perp}}{\rho_G} = \frac{|q|B}{m} \quad (1.4)$$

and the Larmor period is thus,

$$T_G = \frac{2\pi}{\omega_G} = \frac{2\pi m}{|q|B} \quad (1.5)$$

1.4.2 Bouncing motion between mirror points

Let's now consider the magnetic moment associated with the current created by the gyration motion of a particle around its guiding center. It can be defined as the ratio between the kinetic energy transverse to the magnetic field and the intensity of the magnetic field,

$$\mu_B = \frac{1}{2} \frac{mv_{\perp}^2}{B} \quad (1.6)$$

According to Faraday's law, the magnetic flux through the gyration loop of the particle is constant,

$$\phi = B\pi\rho_G^2 = \frac{2\pi m}{q^2}\mu_B = cst \quad (1.7)$$

Thus, μ_B is also conserved, and since the mass of the particle is constant,

$$\frac{v_{\perp}^2}{B} = cst \quad (1.8)$$

Due to conservation of the energy, and since $v^2 = v_{\perp}^2 + v_{\parallel}^2$, v is also conserved. The pitch angle of the particle is defined as the angle α such that $v_{\perp} = v \sin \alpha$. By the conservation of the magnetic moment and the definition of the pitch angle,

$$\frac{v^2 \sin^2 \alpha}{B} = cst \quad (1.9)$$

thus, for a given point at the equator and a point at higher latitude,

$$\frac{\sin^2 \alpha_{eq}}{B_{eq}} = \frac{\sin^2 \alpha}{B} \quad (1.10)$$

A particle moving from the equator (where the magnetic field is the weakest) to higher latitudes will see increasing intensities of the magnetic field. In order to satisfy the relation above, the pitch angle of the particle must also increase. This will be the case until the pitch angle value reaches 90° . At this point, all the energy of the particle is due to the perpendicular velocity (i.e. $v_{\parallel} = 0$) and the particle cannot go to higher latitudes, it is called the mirror point. The particle will then move back toward the equator [Pierrard, 2009]. This bounce is caused by the mirror force, created by the gradient of the magnetic field, acting on the magnetic moment of the particle (https://hiddensymmetries.princeton.edu/sites/g/files/toruqf1546/files/single_particle_orbits_sss_final.pdf).

If s is the position of the guiding center along the magnetic field line and if s_m and s'_m are the coordinates of the mirror points, the bounce period is given by,

$$T_b = 2 \int_{s'_m}^{s_m} \frac{ds}{v_{\parallel}(s)} = \frac{2}{v} \int_{s'_m}^{s_m} \left(1 - \frac{B(s)}{B_m}\right)^{-\frac{1}{2}} ds \quad (1.11)$$

1.4.3 Drift motion

As mentioned in Equation 1.1, particles in the radiation belts are also affected by external forces. If the external forces are perpendicular to the magnetic field (homogeneous and stationary), the particle velocity can be decomposed in a gyration velocity ($\mathbf{v}_L$) around the guiding center and the drift velocity of the guiding center ($\mathbf{v}_D$), such that $\mathbf{v} = \mathbf{v}_D + \mathbf{v}_L$. From Equation 1.1 it is possible to show that the drift velocity is given by,

$$\mathbf{v}_D = \frac{\mathbf{F} \wedge \mathbf{B}}{qB^2} \quad (1.12)$$

where $\mathbf{F}$ are the external forces. The drift velocity is always perpendicular to the magnetic field and the force creating it. The azimuthal drifting motion of particles can lead to the production of electric current which current density is given by,

$$\mathbf{J} = ne(v_F^+ - v_F^-) \quad (1.13)$$

assuming quasi-neutrality of the plasma. Here is the list of forces that lead to the drift motion of particles and their contribution to the formation of an electric current,

1. Gravity: $\mathbf{F} = m\mathbf{g}$. In this case, positively and negatively charged particles drift in opposite directions. Electrons drift to the West, while positive ions drift to the East. The drift velocity is proportional to the mass of the particle and is thus much larger for ions than electrons. This produces an electric current that flows in the opposite directions than the observed ring current.
2. Coulomb force: $\mathbf{F} = q\mathbf{E}$. In the presence of an electric field, the drift velocity of all species is the same. It does not contribute to the formation of an electric current. In addition to that, if the electric field in the magnetosphere is equal to the co-rotating electric field $\mathbf{E}_{corr}$, all particles will drift eastward with the same speed as the Earth's angular speed Ω_E . The co-rotating electric field is given by:

$$\mathbf{E}_{corr} = -(\boldsymbol{\Omega} \wedge \mathbf{r}) \wedge \mathbf{B} \quad (1.14)$$

3. Magnetic field gradient: $\mathbf{F} = -\mu_B \nabla B$. This is the force applied by an inhomogeneous magnetic field on the magnetic dipole formed by the gyration motion of the particles. In this case, the drift velocity is proportional to the mass as well as the energy of the particles. In addition to that, the drift of electrons and ions has opposite directions, electrons drift in the eastward direction and positive ions in the westward direction.

$$\mathbf{v}_B = \frac{-\mu_B \nabla B \wedge \mathbf{B}}{qB^2} \quad (1.15)$$

The guiding center approximation (i.e. the decomposition of the motion in the gyromotion and the motion of the guiding center) holds valid as long as the gyro radius of the particles is much smaller than the characteristic variation distance of the magnetic field, i.e.

$$\rho_G \ll \frac{B}{|\nabla B|} \quad (1.16)$$

The guiding center approximation is also valid if the drift velocity is much smaller than the gyration velocity. For electrons and ions from 1 to 100 keV, the force due to magnetic field inhomogeneity is responsible for the creation of the ring current which in turn is responsible for the weakening of the geomagnetic field during magnetic storms.

4. Curvature of the magnetic field lines. The force in play here is the centrifugal force on the particle caused by the curvature of the field lines and is given by,

$$\mathbf{F} = \frac{mv_{\parallel}^2}{R_c} \mathbf{n} \quad (1.17)$$

where $R_c = \frac{B}{\nabla B}$ is the curvature radius of the magnetic force lines for rotational-less field and $\mathbf{n}$ is the normal unit vector of the field lines and directed outward. The drift speed of trapped particles thus becomes,

$$\mathbf{v}_{R_c} = -\frac{mv_{\parallel}^2(\nabla B)_{\perp} \wedge \mathbf{B}}{qB^3} \quad (1.18)$$

It is possible to combine the drift motion due to the magnetic force and the curvature of the field line to find an expression for the total drift velocity due to the magnetic field,

$$\mathbf{v}_B = \frac{m}{2qB^3}(v_{\parallel}^2 + v_{\perp}^2)\mathbf{B} \wedge \nabla B \quad (1.19)$$

Thus, electrons drift to the eastward direction while protons and ions drift in the westward direction.

5. Inertial force. This force appears when the drift velocity of the guiding center is not constant,

$$\mathbf{F} = -m \frac{d\mathbf{v}_D}{dt} \quad (1.20)$$

Thus if the ambient fields are stationary, i.e. $\frac{d\mathbf{E}}{dt} = 0$ and $\frac{d\mathbf{B}}{dt} = 0$ there is no variation in the drift velocity of the guiding center and thus $\mathbf{v}_I = 0$. However, if the electric field is not stationary the variation in the drift velocity is only due to the variation of the drift velocity caused by the electric field: $\frac{d\mathbf{v}_D}{dt} = \frac{d\mathbf{v}_E}{dt}$. Thus the drift velocity due to the inertial force is given by,

$$\mathbf{v}_I = -m \frac{\frac{d\mathbf{E}}{dt} \wedge \mathbf{B}}{qB^2} \wedge \frac{\mathbf{B}}{qB^2} = m \frac{\frac{d\mathbf{E}}{dt}}{qB^2} \quad (1.21)$$

This drift motion is called the polarisation drift and the resulting electric currents are called polarisation currents.

Particle	ρ_g	$T_g(s)$	$T_b(s)$	$T_D(min)$
Electron (1MeV)	320 m	7×10^{-6}	0.1	50
Proton (10MeV)	30 km	5×10^{-5}	0.65	3.2

Table 1.1: Typical numerical values for the gyration radius ρ_g , gyration period T_g , bounce period T_b and drift period T_D for electrons and protons of the radiation belts [Pierrard, 2009]

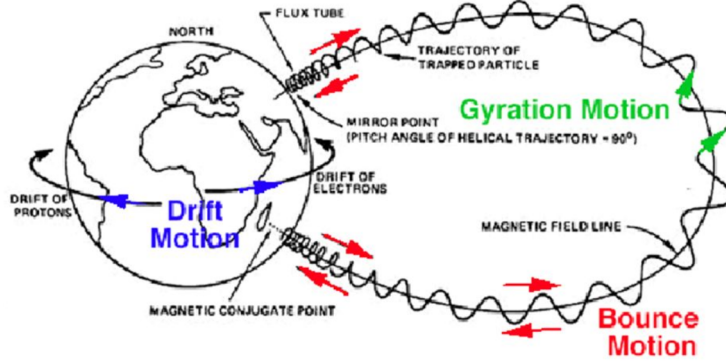


Figure 1.3: Representation of the superimposed motion of trapped particles in the radiation belts.

The total drift velocity of the trapped particles in the geomagnetic field is the sum of all the above mentioned velocities.

$$\mathbf{v}_{tot} = \mathbf{v}_g + \mathbf{v}_E + \mathbf{v}_B + \mathbf{v}_I \quad (1.22)$$

The importance of those components depends on the energy of the trapped particles as well as the intensity and variability of the electric and magnetic field [Pierrard, 2009].

1.5 Adiabatic invariants

As described above, the motion of trapped particles in the radiation belts can be decomposed in three separate (quasi-)periodic motions. In the context of Hamiltonian mechanics, it is possible to show for quasi-periodic systems that if $\mathbf{p}$ is the canonical momentum and $\mathbf{q}$ is the canonical coordinates, the following quantity,

$$I = \frac{1}{2\pi} \oint \mathbf{p} \cdot d\mathbf{q} \quad (1.23)$$

is an adiabatic invariant over the quasi-period [Hannu E. J. Koskinen, 2022] (a proof is given in [Ukhorskiy and Sitnov, 2012]). Such quantities are approximate constants of slowly varying systems (i.e. the variation time scale of the system is much larger than the period of the motion). To each (quasi-)periodic motion found in the belts, it is possible to associate an adiabatic invariant. However, in the belts, rapid variations of the

magnetic field can lead to non-adiabatic motion (i.e. violation of the adiabatic invariants) of particles and significantly contributes to particle losses in the population of the belts.

1.5.1 The first adiabatic invariant

The first adiabatic invariant is associated to the gyro-motion of trapped particles. If the guiding center approximation holds valid, and for $\boldsymbol{\rho}_L$ the canonical coordinate and $\boldsymbol{p}_\perp$ the canonical momentum,

$$I_1 = \frac{1}{2\pi} \oint \boldsymbol{p}_\perp \cdot d\boldsymbol{\rho}_L = \frac{1}{2\pi} \int_0^{2\pi\rho_L} mv_\perp dl = \frac{m}{q} \mu_B \quad (1.24)$$

where $\mu_B = \frac{mv_\perp^2}{2B}$ is the magnetic moment, is an adiabatic invariant. Thus the magnetic moment, and the magnetic flux through the gyration loop ($\phi = \frac{2\pi m}{q^2} \mu_B$) are constants of the motion. As the particle evolves in the magnetic field, its gyration speed will increase as the magnetic field intensity rises in order to satisfy the conservation of μ_B . This acceleration is called the betatron acceleration [Pierrard, 2009].

In practice, this adiabatic invariant is the less susceptible to be violated since the gyro-motion has the smallest period (see Table 1.1) which is almost always smaller than the characteristic time variation of the magnetic field.

1.5.2 The second adiabatic invariant

The second adiabatic invariant is linked to the bouncing motion of the particles between the two mirror points. In this case, the canonical coordinate is reduced to s , the position of the guiding center on the magnetic field line and the canonical momentum is reduced to the momentum parallel to the magnetic field $p_\parallel$. Thus,

$$I_2 = \frac{1}{2\pi} \oint p_\parallel ds = \frac{1}{2\pi} \oint mv_\parallel ds = cst \quad (1.25)$$

By definition of the pitch angle, $p_\parallel = p \cos \alpha$. For a particle at a mirror point, the pitch angle is equal to 90° , and the magnetic field line is given by B_m . By virtue of Equation 1.10, for all s

$$\frac{\sin^2 \alpha(s)}{B(s)} = \frac{1}{B_m} \quad (1.26)$$

Thus, the parallel component of the momentum can be expressed as,

$$p_\parallel(s) = p \sqrt{1 - \sin^2 \alpha(s)} = \sqrt{1 - \frac{B(s)}{B_m}} \quad (1.27)$$

Injecting this expression in the integral above results in $I_2 = 2pI$, where

$$I = \int_{s'_m}^{s_m} \left(1 - \frac{B(s)}{B_m}\right)^{\frac{1}{2}} ds \quad (1.28)$$

If the characteristic variation scale of the magnetic field is very large, the magnetic moment and the momentum are conserved and the integral I is constant.

So if the particle move in a region where the intensity of the magnetic field is higher, the mirror points will be located at higher altitudes and thus, the distance travelled between the two mirror points will be smaller. In addition to that, with the conservation of the second adiabatic invariant, the velocity of the guiding center increases. This acceleration is called the Fermi acceleration [Pierrard, 2009].

The violation of the second invariant can occur in region where the variation of the field are fast on distances close to the curvature radius, where the field lines are stretched and when the characteristic time scale of variation of the field are smaller than the bounce period (given by Equation 1.11).

1.5.3 The third adiabatic invariant

The third and last adiabatic invariant is associated with the azimuthal drift motion of the trapped particles. It expresses the conservation of the magnetic flux in the loop formed by a 360° drift motion of the guiding center. It can be expressed as,

$$I_3 = \frac{1}{2\pi} \oint \mathbf{A} \cdot d\mathbf{l} \quad (1.29)$$

where $\mathbf{A}$ is the potential vector of the field and $d\mathbf{l}$ is the infinitesimal arc of the drift path of the guiding center [Hannu E. J. Koskinen, 2022]. It can also be written with the form,

$$I_3 = \frac{1}{2\pi} \oint m v_D r d\phi \quad (1.30)$$

where v_D is the drift velocity of the particles, ϕ the azimuthal angle and r the radius of the drift orbit of the particle. Because this last adiabatic invariant is associated to the drift motion which features the largest period, it is the one that is the most frequently violated. This can happen if the variation of the magnetic field is more rapid than the drift period. Wave-particle interactions with ultra low frequency (ULF) oscillations of the magnetic field and small scaled spatial variation of the magnetic field lead to the non conservation of the third invariant. Those processes are involved in the non adiabatic acceleration of electrons in the outer belt [Pierrard, 2009].

1.6 Geomagnetic coordinates (B , L)

Due to the motion of the trapped particles in the geomagnetic field of the Earth, it is often convenient to introduce a new set of coordinates, the geomagnetic (B , L) coordinates. Those coordinates were introduced by McIlwain in 1961 [McIlwain, 1961] in order to solve the problem of mapping observed fluxes of energetic trapped particles. In this coordinate system, B is the intensity of the magnetic field at the point of measure and L is the McIlwain parameter or the magnetic shell parameter.

It gives, for a dipolar magnetic field, the distance at the equator of the magnetic shell of a trapped particle whose pitch angle is 90° at the point of measure [Pierrard, 2009]. The shell parameter is so useful because, by construction, it is constant along the magnetic field lines. Thus each values of L uniquely defines a drift shell on which particles evolve.

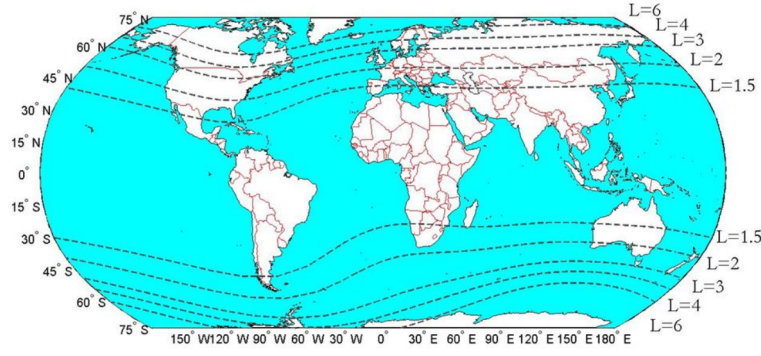


Figure 1.4: Constant L-shell projected on the surface of the Earth.

1.7 Physical processes in the radiation belts

The state of the radiation belts is determined by the balance between the sources of energetic particles and the loss processes affecting them. The difference in temporal, spatial and flux intensity variability between the inner and outer belts indicates that the physical processes occurring in those regions are different. This is due to the fact that the inner and outer belt feature non identical particle populations. In this section, a brief description of the main processes involved in both belts is presented.

1.7.1 Inner belt

The inner belt is mostly populated by high energy protons ranging from several MeV up to GeV. It is very stable in relatively short periods of time and shows variability only during large solar energetic particle (SEP) events that are simultaneous with magnetic storms. However, the inner belt varies in time with the solar cycles. The residence time of protons in the inner belt spreads from several years for proton whose pitch angle is close to the atmospheric loss cones, to several thousands of years for protons mirroring close to the equator [Hannu E. J. Koskinen, 2022].

There are two main sources of high energy protons for the inner belt, cosmic rays and SEP events. When very high energy protons collide with nitrogen or oxygen atoms of the terrestrial atmosphere, neutrons are produced by nuclear reactions. About 10% of the neutrons are traveling away from the Earth and decay into a proton and an electron. Those charged particles are then trapped in the magnetic field of the Earth and form the inner radiation belt. If the source of the incoming proton is cosmic rays, this process is referred as to cosmic ray albedo neutron decay (CRAND). However if the primary proton originates from a strong SEP event, the above mentioned process is called a solar proton albedo neutron decay (SPAND) [Pierrard, 2009]. Protons from SEP events that cannot penetrate in the neutral atmosphere can be directly trapped in the inner belt at $\sim L = 2 - 2.5$ and then radially transported closer to the Earth via radial diffusion.

The loss mechanisms in the inner belts mainly consist of charge exchange and nuclear reactions with neutral atoms present in the exosphere. During a charge exchange, a highly energetic proton collides with a neutral atom and an electron of the neutral atom is transferred to the proton. This leaves a relatively low energy proton that remains

trapped in the magnetic field and a very energetic atom that is no more influenced by the electromagnetic fields surrounding the Earth. Nuclear reactions and Coulomb collisions with ionospheric and plasmaspheric ions contribute to the gradual slowing of the protons [Hannu E. J. Koskinen, 2022].

1.7.2 Outer belt

The outer belt is populated by high energy electrons and is much more variable in time than the inner belt. The electron fluxes can vary in very short periods of time and so does the spatial extent of the outer belt. The main sources of the outer belt electrons are the solar wind and the ionosphere [Pierrard, 2009]. However, the energies of particles present in the solar wind ($\sim$ keV) and in the Earth ionosphere ($\sim$ eV) are much smaller than the one for radiation belts particles ($\sim$ MeV). There must exist some physical processes that allow the transport of electrons to the radiation belt as well as accelerating them to higher energies. If variations of the magnetic field occur on smaller time scales than the drift motion of the electrons, the violation of the conservation of the third adiabatic invariant causes radial drift motion in the belts. In addition, electrons of the radiation belts interact with plasmaspheric waves that are found in the plasmasphere. The wave-particle interactions have various affects on the electrons populations, such as radial diffusion (interactions with ULF waves) and accelerations (interaction with ULF waves, Whistler-Mode chorus waves) [Hannu E. J. Koskinen, 2022].

Losses of energetic electrons in the outer belt can occur through "real" loss of electrons to the magnetopause or the atmosphere or can be decelerated to very low energy, and thus becoming part of the background plasma. One way that leads to electron losses is the so-called magnetopause shadowing. If electrons of the outer belt are able to cross the magnetopause, they are no longer trapped in Earth's magnetic field and are lost in interplanetary space. The crossing of the outer belt drift shells and the magnetopause has various origins, mainly the drift shell radial expansion during the main phase of magnetic storms and the compression of the magnetopause in the radiation belts [Hannu E. J. Koskinen, 2022]. An other sink for the outer belt electrons is the precipitation in the atmosphere. Interactions between plasmaspheric waves and particles cause pitch angle scattering of the electrons in the atmospheric loss cone, i.e. sufficiently large pitch angle, so that the mirror point of the electrons is located in the atmosphere and they are lost through collisions. Energy scattering of electrons is also possible due to the wave-particle interaction with the various plasma wave found inside and outside the plasmasphere. After being decelerated, the electrons become part of the background low energy plasma [Hannu E. J. Koskinen, 2022].

1.8 Geomagnetic storms

Magnetic or geomagnetic storms are periods during which the magnetic field in the magnetosphere and near the Earth is strongly perturbed. Although it is not unique, the most common planetary index used to detect magnetic storms is the disturbed storm time index (Dst). This index characterizes the intensity of the horizontal component of the magnetic field at the surface of the Earth in equatorial regions. During a storm, the horizontal component of the magnetic field at the surface decreases. This is due to

the intensification of the equatorial ring current that tends to reduce the intensity of the geomagnetic field [Pierrard, 2009]. Stormy episodes are distinguished in the Dst time series by inverted peaks. There is no fixed threshold in the Dst that marks a magnetic storms. However, the value of -50 nT is often used as a lower limit for moderate storms. [Koskinen, 2011]. The time extent of geomagnetic storms is between several hours to several days. It corresponds to the time that is necessary to decrease the current density of the ring current by reducing the energy of ions and electrons that it contains but also by lowering its density through precipitation into the atmosphere [Pierrard, 2009].

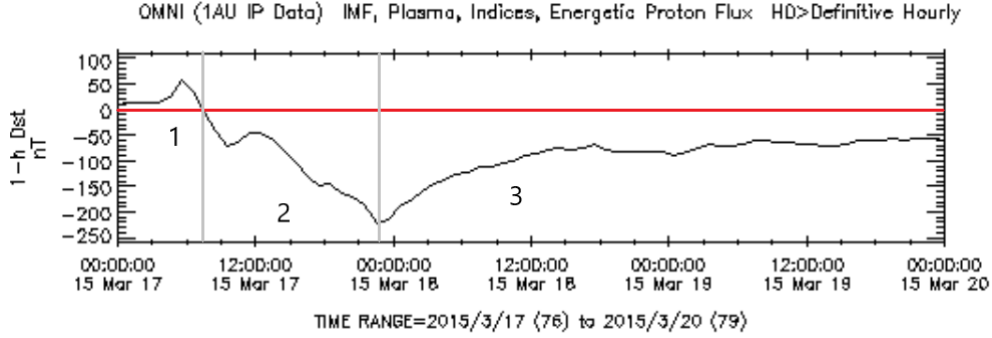


Figure 1.5: Evolution of the Dst index during the storm of March 17, 2015. The red line shows the constant zero value of the Dst. The different numbers correspond to the phases of the magnetic storm. 1. The initial phase with a sudden commencement (SC). 2. The main phase of the storm. 3. The recovery phase. This image has been generated on the NASA website: <https://cdaweb.gsfc.nasa.gov/index.html>

A geomagnetic storm unfolds in 3 phases,

1. The initial phase differs between storms. The length of the initial phase depends on the structure of the solar wind that drives the storm. If the IMF is directed southward, the initial phase is very short and the main phase of the storm is almost immediate. Some storms also begin with sudden commencements (SC), i.e a sudden increase in the Dst index before the main phase (see Figure 1.5). This commencement is due to the solar wind shock wave hitting the magnetopause [Koskinen, 2011].
2. The main phase is the period during which the horizontal component of the magnetic field and thus the Dst index reaches a minimum value. It is caused by the increase in density of the ring current as well as the acceleration of the particles forming it by the solar wind.
3. The recovery phase starts when the input of energy and particles of the solar wind comes to an end. The time spread of the recovery phase is much larger than for the main phase, it can last several days. The reason for such a gap in the main and recovery phase time scales is that the physical process leading to the loss of energetic particles in the ring current are much slower than during the injections.

The formation of magnetic storms at least requires that the IMF has a strong southward component for a relatively long period of time (~ 3 h) [Koskinen, 2011]. Several

phenomena can fulfill those conditions, such as fast solar wind or more extreme events like Solar Energetic Particle events (SEP). SEP events are characterized by the large flux increase of electrons, protons and heavier ions to energies much higher than average. In some very extreme events, protons energies can reach GeV [Klein and Dalla, 2017].

1.9 Satellites and instruments

1.9.1 PROBA-V

The Energetic Particle Telescope (EPT) is carried by the PROBA-V satellite, which is part of the PROBA (Project for On-Board Autonomy) program of the European Space Agency (ESA) and where the "V" stands for vegetation. The satellite was launched on 7 May 2013 from Kourou in French Guyana. PROBA-V was sent to a sun-synchronous LEO (Low Earth Orbit) polar orbit at an altitude of 820 km. The inclination of he orbit is 98.73° and the satellite descending node is 10:30 am local time. The period of PROBA-V is 101.1 minutes [Pierrard et al., 2014]

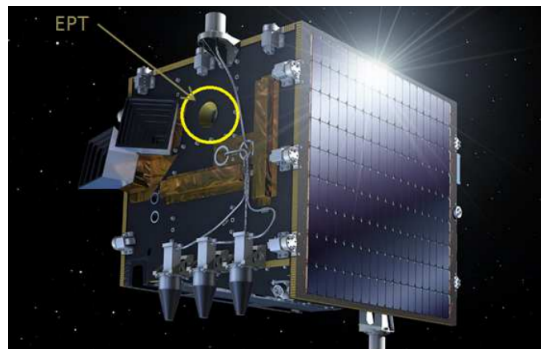


Figure 1.6: Image showing the PROBA-V satellite and the location of the EPT on it. (Image from [Pierrard et al., 2014])

1.9.2 Energetic Particle Telescope: EPT

The EPT was developed by the Center for Space Radiation (CSR) at UCLouvain in Belgium, with the collaboration of the Royal Belgian Institute for Space and Aeronomy and QinetiQ Space. It is a science-class spectrometer that was designed for real-time and contamination-free measurements of charged particles spectra in the space environment. The instrument is able to discriminate between electron, proton, alpha particles and heavier ions and of direct measurement of their energy spectra. The unique concept of the EPT allows for its compactness (dimension: $127.5 \times 162 \times 211.1 \text{ mm}^3$ and mass: 4.6 kg) as well as its low power consumption (5.6 Watt) [Cyamukungu et al., 2014]. The EPT is a charged particle spectrometer based on the $\Delta E - E$ telescope principle. The concept of the EPT is based on the Bethe-Block formula giving the relationship between the stopping power of a material and the energy of incident charged particles. By using this relation and by measuring the incident energy of a particle E as well as the amount of energy deposited ΔE on a thin detector it is possible to deduce which particle is detected

Channel	Electrons (MeV)	Protons (MeV)
1	0.5-0.6	9.5-13
2	0.6-0.7	13-29
3	0.7-0.8	29-61
4	0.8-1.0	61-92
5	1.0-2.4	92-126
6	2.4-8.0	126-155
7		155-182
8		182-205
9		205-227
10		227-248

Table 1.2: PROBA-V/EPT virtual energy channels for electrons and protons.

[Cyamukungu and Grégoire, 2011]. The measurement of the incident energy is based on the fact that the penetration depth in a material depends on the nature of the particle as well as its energy.

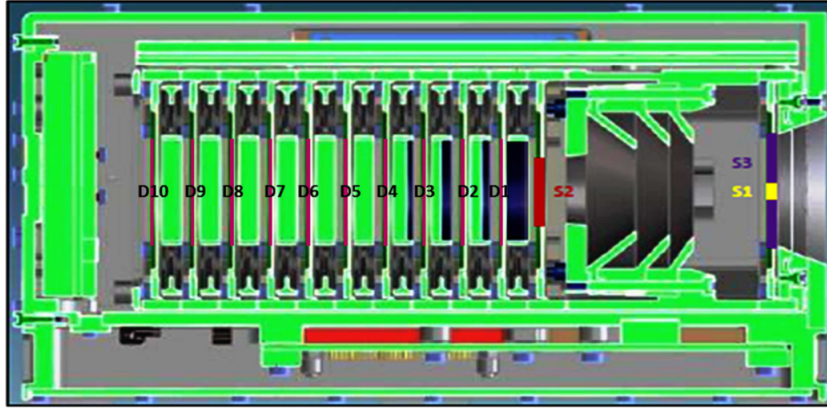


Figure 1.7: Layout of the position of the various sensors composing the EPT.

The EPT consists of 12 silicon sensors and includes two energy sections. The first section is the Low Energy Section (LES) which consists of the S1/S3 and S2 sensors, acting as classical $\Delta E - E$ telescope. S2 measures the incident energy E for which nine energy intervals are defined. S1/S3 measure the deposited energy ΔE , for this sensor, four deposited energy intervals are defined. This allows for the discrimination of electrons, protons, α -particles and heavier ions. [Cyamukungu et al., 2014]. The second section is the High Energy Section (HES) composed by the S2 sensor and the 10 Digital and Absorber Modules (DAM) [Cyamukungu and Grégoire, 2011]. The discrimination and energy determination of the incident particle can be performed with this set up alone, although the S1/S3 sensor is used to confirm the identification from S2, providing contamination-free spectra.

The field of view (FoV) of the EPT is determined by the position of the sensors. The S1/S3 and S2 sensor define a 52° FoV. In the HES, the FoV is reduced as the number of hit DAMs increases, down to 24° for protons hitting the last DAM [Cyamukungu et al., 2014].

For a given particle, the instrument allocates it in one of the so called physical channels, based on the nature of the particle, its energy and the first detector that is hit (S1 or S3). [Cyamukungu and Grégoire, 2011] [Cyamukungu et al., 2014].

The incident spectra, i.e. the differential flux as a function of energy, is computed from the counts in the physical channels with the efficiency matrix of the instrument. Those matrices are obtained for each particle type by simulating the EPT with the GEANT-4 model [Cyamukungu and Grégoire, 2011]. The incident spectra is given by virtual channels, given for electrons and protons in Table 1.2, corresponding to an energy bin of a given width. In practice, there are 6 channels for the electrons, 10 for the protons and 11 for the helium ions.

From the measurement of particle differential flux in units of $\#/(s \text{ cm}^2 \text{ sr MeV})$, it is possible to retrieve the integral flux of particle with the following relation,

$$\phi_{int}(E > E_0) = 4\pi \int_{E_0}^{\infty} \phi_{diff}(E) dE \quad (1.31)$$

where E_0 is a threshold lower energy, $\phi_{diff}(E)$ is the differential flux which depends on the energy of the particles. 4π is the solid angle of the sphere. The result is the so called integral flux that is measured in $\#/(cm^2 \text{ s})$. The integral flux opposed to the differential flux is independent of the energy, in the sense that it gives the flux of particles which energy is above a certain threshold (E_0). However, the differential flux measured by the EPT is not continuous because particle fluxes are recorded in discrete energy bins with a given width. Thus in practice, a discrete version of the above equation is used. It is given by,

$$\phi_{int}(E > E_0) = 4\pi \sum_{i=0}^N \phi_{diff}(E_i) \Delta E_i \quad (1.32)$$

with $\phi_{diff}(E_i)$ is the differential flux measured in the energy bin i and ΔE_i is the width of the channel i . This relation will be useful in order to compare the measurements performed by the EPT with models of the radiation belt as well as with the observations of the MagEIS, the instrument on-board the Van Allen Probes spacecraft.

1.9.3 Van Allen Probes: VAP

The Van Allen Probes (VAP), formerly called the Radiation Belt Storm Probes (RBSP), are a pair of NASA satellites launched on 30 August 2012 on an elliptic orbit with an inclination of 10° , near the magnetic equator. The apogee of the VAPs is at an altitude of 30600 km near geostationary orbit, which corresponds to $L \sim 6,6$ and the perigee at 600 km. Such an orbit allows the spacecraft to probe both inner and outer radiation belts across a relatively wide range of L values with a period of $T \sim 9h$. The initial mission of the satellites was planned to last 2 years, nevertheless both probes have remained in service until 2019. RBSP-A mission ended on October 18 and RBSP-B mission ended on July 19.

The goal of the VAPs was to investigate the inner magnetosphere of the Earth, including the ring current, radiation belts and plasma populations. Both probes were fitted with instruments to study particles, waves as well as magnetic and electric fields in the radiation belts [Boyd et al., 2019].

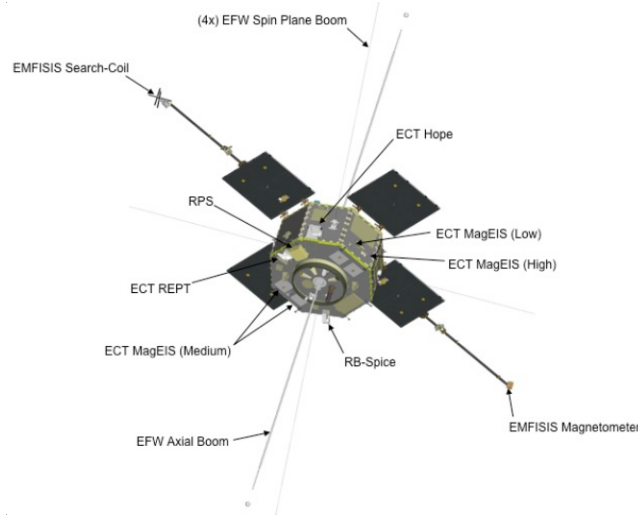


Figure 1.8: Image showing the Van Allen Probe with its onboard instruments [NASA, 2022].

The main onboard instrument of interest in the case of this work are the Energetic Particle, Composition, and Thermal Plasma Suite (ECT) allowing measurements electron and ion fluxes over a wide energy range [NASA, 2022]. The ECT suite consists of three different instruments, allowing particle flux measurement in an energy range from ~ 15 eV to ~ 20 MeV [Boyd et al., 2019]:

1. Helium Oxygen Proton Electron mass spectrometer (HOPE): ~ 15 eV - 51 keV
2. Magnetic Electron Ion Spectrometer (MagEIS): ~ 30 keV - 4 MeV
3. Relativistic Electron Proton Telescope (REPT): ~ 1.8 MeV - 20 MeV

1.9.4 Magnetic Electron Ion Spectrometer: MagEIS

The MagEIS electron spectrometer comprises 4 different units. The first one is called "LOW", and is used to measure electrons with an energy ranging between 20-200 keV. There are two units that allow the measurements of electrons of medium energy, between 200-1000 keV which are called M35 and M75. The last unit, "HIGH" is used for the measurement of high energy electrons, which energy sits between 1000-4000 keV. Unlike the EPT, MagEIS units use a constant magnetic field in the housing of the instrument in order to select electrons with respect to their momentum. With this design, protons are deflected toward the side of the wall, while electrons curve back into the detectors. The silicon solid-state detector of the instrument are arranged in a stack on the wall containing the aperture. Lower energy electrons are steered into the detectors that are closer to the entrance of the instrument, whereas higher energy one are detected further from the aperture. This momentum selection gives each detector an energy "passband" that was determined prior to the flight. The "LOW" as well as the M35 and M75 units have the same design but the thickness of the silicon detectors as well as the intensity of the magnetic field vary. The precise measurements of electrons energy in the detectors are performed by a pulse height analysis of the pulse current generated by the deposition

of the particle energy in the silicon. The concept of the "HIGH" section is similar to that of the other unit, but it differs from them by the intensity of the uniform magnetic field present in the instrument, a lower number of detector but with increased thickness [Claudepierre et al., 2015].

Chapter 2

Data description

The following section focuses on the description of the data and observations made by the PROBA-V/EPT instrument as well as RBSP-B/MagEIS during the year 2014. The 24th solar cycle was characterized by a double peak in the solar activity, the first and smallest one occurred in 2011 during the ascending phase of solar activity and the largest one occurred in 2014. Throughout this year, 6 SEP events were reported and the strongest one took place in early January. The measured proton flux (>10 MeV) was 1033 pfu ($= p^+ / \text{cm}^2 \text{ s sr}$, proton flux unit) and was caused by an asymmetric partial halo (<https://umbra.nascom.nasa.gov/SEP/>). Eventhough 2014 corresponds to a solar maximum, the geomagnetic activity in the magnetosphere was relatively quiet throughout the year. Geomagnetic activity was strongly enhanced during the declining phase of the solar cycle, a period during which very intense events occur at a higher frequency [Pierrard et al., 2020]. Throughout the year 2014, there were only 10 medium magnetic storms ($-100 \text{ nT} \leq \text{Dst} < -50 \text{ nT}$). In addition, in 2014, a single storm was characterized by a Dst index below -100 nT ($\text{Dst} = -119 \text{ nT}$). This strong perturbation was produced by a SEP on the 19th of February. This chapter is structured as follow. In the first section, the differential electron fluxes observed during the entire year are presented for both the EPT and the MagEIS instrument. The main characteristics of the observations are presented to the reader. The two next sections will respectively focus on the February storms, during which electrons dynamics is discussed in more depth and on the solar energetic particle event of January, during which proton injections are observed in the outer belt. Finally, observations of the EPT will also be compared to a model of the radiation belts. The model used is the AE-8 and AP-8 NASA model [Vette, 1991]. It is an empirical model based on observations of the belts from the 60s to the 70s.

2.1 2014 observations

2.1.1 Observations at LEO orbit

Differential electron fluxes measured by the EPT during 2014 in two different energy channels are shown on the two first panels of Figure 2.1. The bottom panel gives the Dst index registered during the year. A lack of data, i.e. the white area between June 27 and September 16, was caused by a failure of one of the EPT sensors. The origin of the problem of the detector remains unknown, since no large storm, nor SEP event were

observed at this time [Pierrard et al., 2019]. Both inner and outer belts, in addition to the slot region are clearly identified on this figure, especially for lower energy electrons. Fluxes in the first energy channel (0,5-0,6 MeV) are higher by up to two order of magnitude than fluxes measured in the channel 5 (1,0-2,4 MeV) in the outer belt, and up to four order of magnitude in the inner belt. The later is consistent with the observations of the energy spectrum of electrons in SAA performed by [Rosson Lopez and Pierrard, 2017]. This figures displays very well the different dynamics of the two belts. While electron fluxes in the inner belt remain mostly constant, very large variation of flux intensity and variation of the spatial extent of the outer belt are visible for both energies.

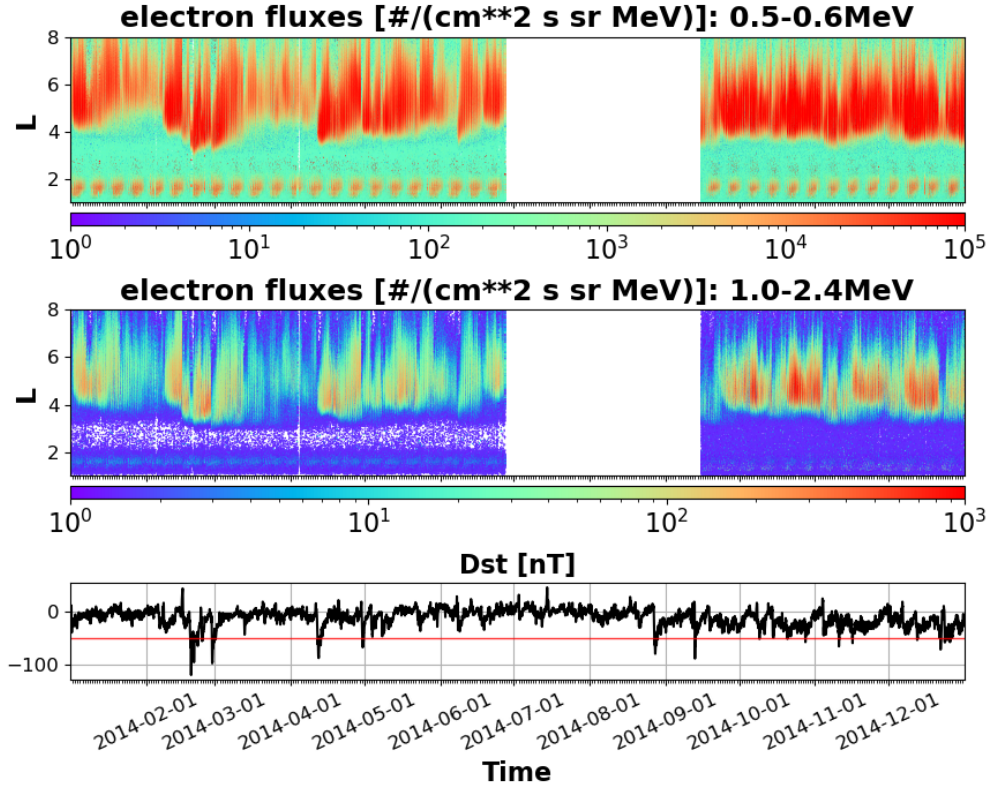


Figure 2.1: Electron differential fluxes as a function of time and parameter L measured by the EPT for the year 2014. The upper panel shows the fluxes measured in the lowest energy channel 0.5-0.6 MeV, the middle panel shows fluxes in the 1.0-2.4 MeV channel. The bottom panel displays the Dst index measured throughout the year.

From January to June, with the exceptions of the storms that took place in February and March, fluxes in the outer belt are lower than fluxes observed after September. This can be seen for lower energies but even more so for 1.0-2.4 MeV electrons. This can be explained by the fact that from September until the end of the year, magnetic activity is on average more intense than the one of the period between January and June i.e. the mean Dst is smaller for the last three months of 2014 ($\text{Dst}_{\text{Jan-Aug}} = -6,8 \text{ nT}$ and $\text{Dst}_{\text{Sep-Dec}} = -19,3 \text{ nT}$). Note however that during the last quarter of the year, while

flux intensity is in general higher, the variability of the fluxes is not as pronounced as in the first half of the year. In addition, this slightly higher geomagnetic activity is very small compared to that of 2015, which featured the most intense storms of the 24th solar cycle. Those events have been studied in depth by [Pierrard and Lopez Rosson, 2016]. Moreover, two times in the first half of the year, fluxes in the outer belt were lowering and the inner edge of the outer belt increased to higher values of L. At some occasions, the outer belt appears to be almost free of 1.0-2.4 MeV electrons. It is also interesting to note that the few most intense storms of 2014 mostly occurred between September and June 2014. Throughout the year, no storm were strong enough to allow the injection of 0.5 MeV electrons into the inner belt, let alone higher energy electrons.

In the inner belt, electron fluxes measured in the first energy channel increase and decrease periodically. This apparent periodicity in time of the inner belt population is purely due to the orbit of the PROBA-V satellite. Because the EPT is carried on a spacecraft travelling a LEO orbit, proton and electron flux measurements can only be performed in the SAA, where the inner belt penetrates closer to the Earth. Thus when the spacecraft is not over the SAA, fluxes are much lower. Moreover, the maximum L value of the outer edge of the inner belt depends on the energy of the electrons and it decreases with increasing energy [Pierrard et al., 2020]. This is visible in Figure 2.1, the upper L value for electrons in channel 1 is just under $L = 2$ whereas for electrons in channel 5, the outer edge is at $L = 1,7$. Flux intensity in the inner belt for lower energy electrons as well as for high energy ones is decreasing very slowly throughout the year.

2.1.2 Observation at magnetic equator

The measurements of electron fluxes performed by the Mageis instrument onboard RBSP-B are shown in Figure 2.2. Unlike the PROBA-V satellite, the Van Allen Probes (or Radiation Belt Storm Probes) carrying the MagEIS are orbiting the Earth on an elliptic orbit near the magnetic equatorial plane.

Similarly to Figure 2.1, differential electron fluxes measured in two different energy channels of the instrument are displayed, the lower energy channel corresponds to 604 keV (558-639 keV) while the larger channel corresponds to 1064 keV (970-1279 keV) electrons. Those channels have been selected as close as possible to the EPT energy channels. The two dashed black lines give the period during which EPT data are not available. The data displayed on this figure corresponds to level 2 spin-averaged differential electron fluxes without any distinction of the pitch angle of the electrons. Such data are called spin-averaged because fluxes are averaged on each rotation of the RBSP spacecraft [Claudepierre et al., 2021]. Moreover, the data displayed here has been corrected from background contamination. Indeed, depending on the position of the Van Allen Probes and on the energy channel, measurements from MagEIS can be altered either by bremsstrahlung X-ray radiations caused by the interaction of high energy electrons with the material of the spacecraft or by proton populations. In the outer belt, lower energy channels are affected by X-ray radiations, while in the inner belt, MeV energy electrons cannot be distinguished from high energy protons [Claudepierre et al., 2015]. This is the reason for the lack of observation in the inner belt for 970-1279 keV electrons in Figure 2.2. Such an issue for the discrimination of particles is avoided by the EPT due to its different design [Cyamukungu and Grégoire, 2011]. For lower energy electrons,

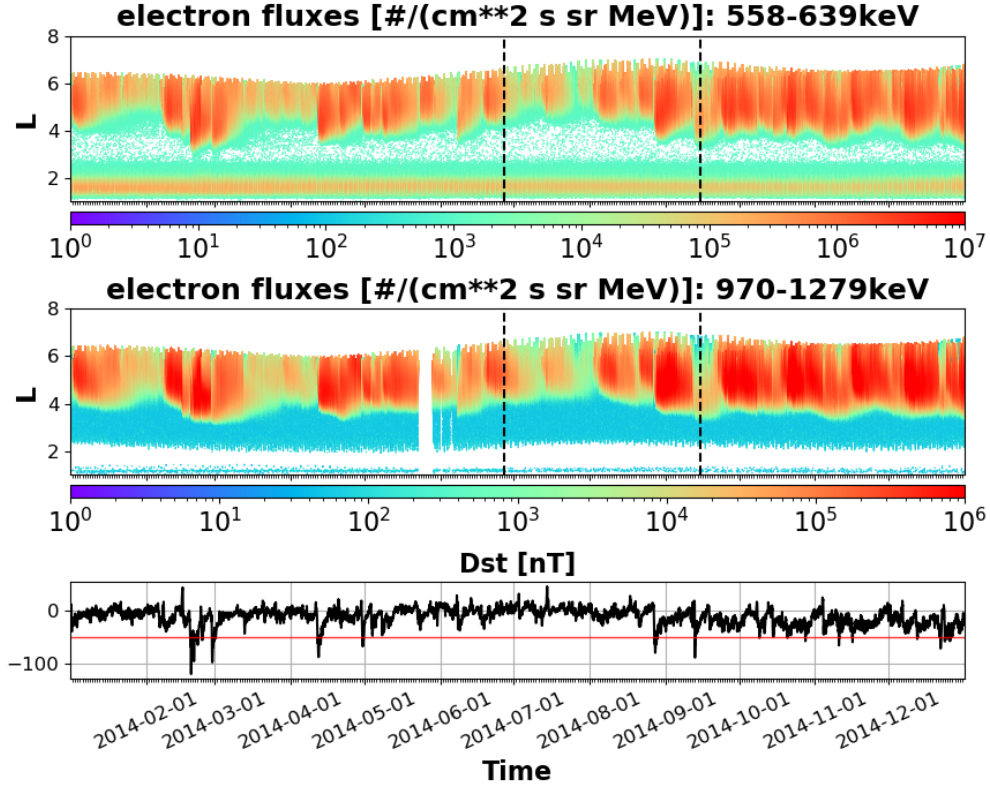


Figure 2.2: Level 2 corrected electron differential fluxes as a function of time and parameter L measured by RBSP-B/MagEIS for the year 2014. The upper panel shows the fluxes measured in the energy channel 558-639 keV and the middle panel shows fluxes in the 970-1279 keV channel. Vertical dashed line gives the period of time during which EPT data are not usable. The bottom panel displays the Dst index measured throughout the year.

observations made by MagEIS are similar to that performed by the EPT. Both inner and outer belts are clearly visible. Moreover, the variation of flux intensity and the variation of the position of the inner edge of the outer belt are in agreement with EPT observations. Due to the position of the apogee of the Van Allen Probes orbit ($L \sim 6$), the outer edge of the outer belt cannot be detected by MagEIS at all time. However, during the main phase of the more intense storm of 2014, the decrease in flux at high L ($L \geq 5$) can be identified. For the 1064 keV electrons, the lower limit of the outer belt is located at similar L value than what is observed by the EPT. The main difference between observations of the two instruments is found in flux intensity. For a given L value that does not correspond to the slot region, low energy electron flux intensity recorded by MagEIS are up to two orders of magnitude higher than for EPT and up to three orders of magnitude larger for 1 MeV electrons. The reason for this difference is related to the motion of trapped particles in the belts and will be discussed in the next chapter. Throughout the year, low energy electron flux slowly decreases in the inner belt, as shown by the EPT

measurements. Nonetheless, MeV electrons are not detected in the inner belt by MagEIS during 2014. Mageis data shows that during the recovery period of the EPT, fluxes in the outer belt are relatively low in both energy channels, except for late August and early November, when a moderate storm occurred and higher fluxes are observed.

2.2 February storms

2.2.1 Flux map

Because the orbit of the PROBA-V satellite is a LEO orbit at a constant altitude of 820 km, it is possible to plot radiation belt fluxes on the world map. Such a representation is shown on Figure 2.3 and Figure 2.4 which show the electron fluxes at 820 km of altitude as a function of latitude and longitude for energy channel 1 and 5 during January and February respectively. The black dashed lines represent the drift shell corresponding to $L = 4$ and the dotted line is the L-shell corresponding to $L = 1.7$. Eventhough Figure 2.3 and Figure 2.4 are displaying clear differences, the overall global large scale structure is similar in both cases. At high latitudes, both in southern and northern hemisphere, there exist thin bands of high flux intensity for all longitudes. Those regions are called the polar horns and correspond to the penetration of the outer belt in the atmosphere [Pierrard et al., 2014]. The South Atlantic Anomaly is clearly identified in the southern hemisphere and corresponds to the region where the inner belt is the closest to the Earth. Electron fluxes measured in the northern hemisphere, over North Africa and Europe are lower than in the southern hemisphere. This is due to the counterpart of the SAA. As particles penetrate deeper in the atmosphere over the SAA, a larger fraction of trapped particles are lost in the atmosphere and cannot be detected in the northern hemisphere. The clear gap in fluxes just over Europe is not linked to the dynamics of the belts but to the data transmission to the ground station located in Redu (Belgium). While data is downloaded to the station, the instrument does not perform any measurements [Pierrard et al., 2014].

Electron fluxes measured in channel 1, both in the horns and in the SAA are significantly higher than channel 5. During quiet periods, as displayed in Figure 2.3, the inner edge of the outer belts sits at $L = 4$ for low energy electrons as well as for 1 MeV electrons. During January 2014, fluxes in channel 5 are generally very low. However, the southern part of the SAA features enhanced fluxes compared to the northern part. This region of maximum flux closely follows the shell $L = 1.7$. Such observations are also made for fluxes measured in channel 1.

During geomagnetically more active periods, the polar horns widens and fluxes are increased in both channels, especially for 1 MeV electrons. Moreover, the lower edge of the northern horn and the upper edge of the southern horns extend to lower and higher latitudes respectively. This corresponds to the penetration of electrons of the outer belt to lower L values. On the other hand, fluxes in the SAA do not significantly vary between January and February. Note that throughout 2014, fluxes in the SAA are very low and keep lowering throughout the year. The constant depletion of electron populations in the inner belt are well seen for observations taken over long periods of time. Flux enhancement in the inner belt occurs only during very large storms, for which increased electrons flux can penetrate as low as $L = 2$. Such low fluxes in the SAA during 2014 are

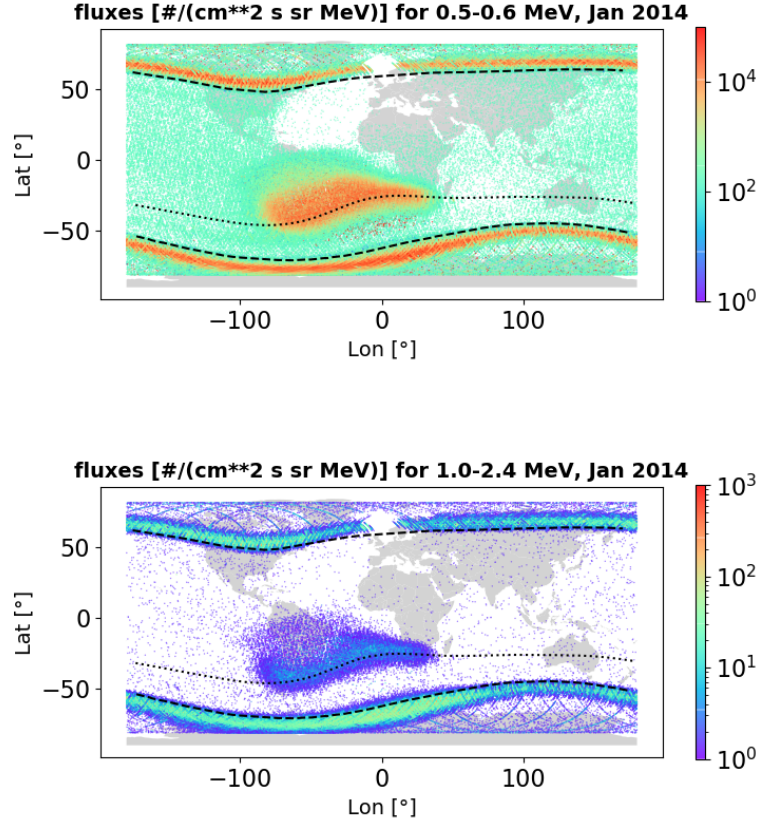


Figure 2.3: Differential electron fluxes observed by PROBA-V/EPT during January 2014 in two energy channels. Top panel corresponds to channel 1 (0.5 – 0.6 MeV) and the bottom panel corresponds to channel 5 (1.0 – 2.4 MeV) The black dashed and dotted lines correspond to the constant shells $L = 4$ and $L = 1.7$ respectively.

thus not surprising since the last injection occurred in 2013 and only for electrons with an energy of 500 keV.

2.2.2 L-time plot

February was the most perturbed month of 2014 during which four storms can be identified, the largest one took place on the 19th with a minimum Dst of -119 nT. After this event, during the recovery phase, another perturbation occurred reducing the Dst index from -50 nT to -90 nT. However flux observation during both the 19th and the ‘recovery storm’ are missing in Figure 2.5. On the February 23, a storm with a minimum dst value of -50 nT is observed. Finally, the last relatively intense geomagnetic storm was observed on the 27th with a lowest dst of -96 nT. Both largest February storms were caused by solar energetic particle events.

February data shows recurrent dropout event of various intensities during the most disturbed time period. Dropouts are characterized by the sudden decrease (in few hours) of electron flux observed in the outer belt by several order of magnitude. Extended study

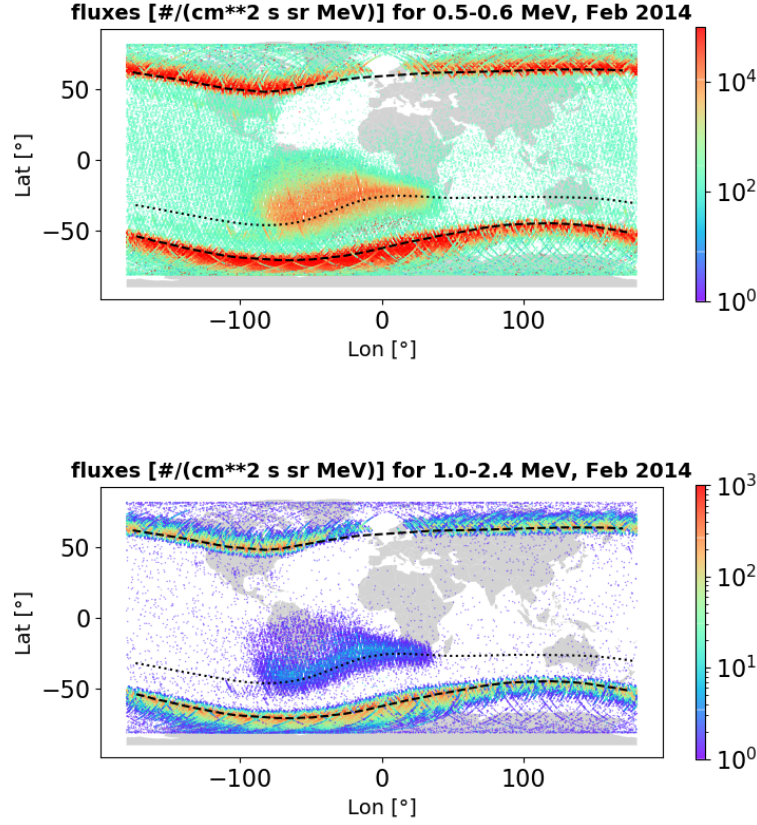


Figure 2.4: Same as Figure 2.3 but for the month of February 2014. The same energy channels are displayed.

of such events between 2013 and 2019 was conducted in [Pierrard et al., 2020]. Dropouts are observed during February storms in both channel 1 and 5. In addition, the minimum L value of the upper edge of the outer belt is the same in both energy channels. Dropout events start at high L values and the minimum L value of the outer edge of the outer belt is reached before the inverted Dst peak. The value of this minimum in L depends on the intensity of the storm. It is smaller for stronger storms [Pierrard et al., 2020]. After the sudden depletion of outer belt electrons, flux intensification starting at lower L than the minimum L value of the dropout is observed in both 0.5 MeV and 1 MeV electrons. In general, injection of electrons to lower L only happens for larger storms, such as the ones of 19th and 27th. After February 16th, while the Dst index reached a minimum value of -30 nT, dropout at L = 6 as well as a lowering of the inner edge of the outer belt are observed. This event is associated to a solar flare, which can be seen in the sudden impulse in the Dst time series (i.e. abrupt increase of the Dst). The inner edge of the inner belt then gradually increases to high L as the slot region widens during the recovery phase of the storm. After the moderate storm of February 23rd, recorded fluxes of electrons in the channel 5 are the highest in the outer belt. However, their population is largely affected by the dropout caused by the following storm and such high fluxes are not reached again.

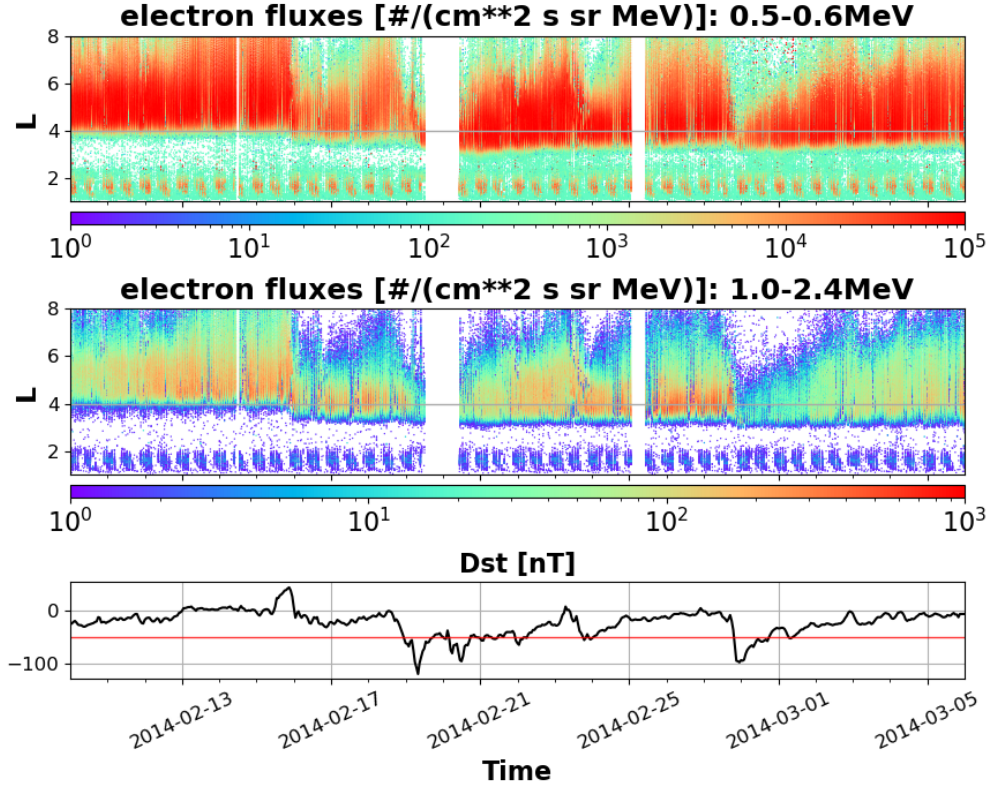


Figure 2.5: Similar to Figure 2.1 but for data from February 10 to March 5. The grey lines in the two upper panels give the constant value $L = 4$

The physical processes that can lead to the sudden depletion of electrons in the outer belt can either be adiabatic or non adiabatic. The adiabatic loss process is caused by the Dst effect. During the main phase of the storm, as the density of the ring current becomes larger, the magnetic field of the Earth rapidly weakens. When the variation time of the magnetic field is larger than the period of the drift motion of electrons, the 3rd adiabatic invariant must be conserved. In this case, in order to maintain this quantity constant, the electrons move radially away from the Earth and their energy decreases. Because this processes is adiabatic, during the recovery period, as the Dst increases, electrons move radially inward and their energy increases. This motion has been shown in numerical simulations performed by [Pierrard et al., 2021]. The loss of electrons due to non adiabatic processes can be attributed to either magnetopause shadowing or pitch angle scattering to the loss cones by wave-particle interactions.

2.2.3 Comparison of the observations with AE8 model

Figure 2.6 displays in the top panel the integral electron fluxes (> 0.5 MeV) on the world map as predicted by the AE8 model during maximum solar activity. The model is able to reproduce the SAA and the polar horns well, however, it does not show the reduced fluxes

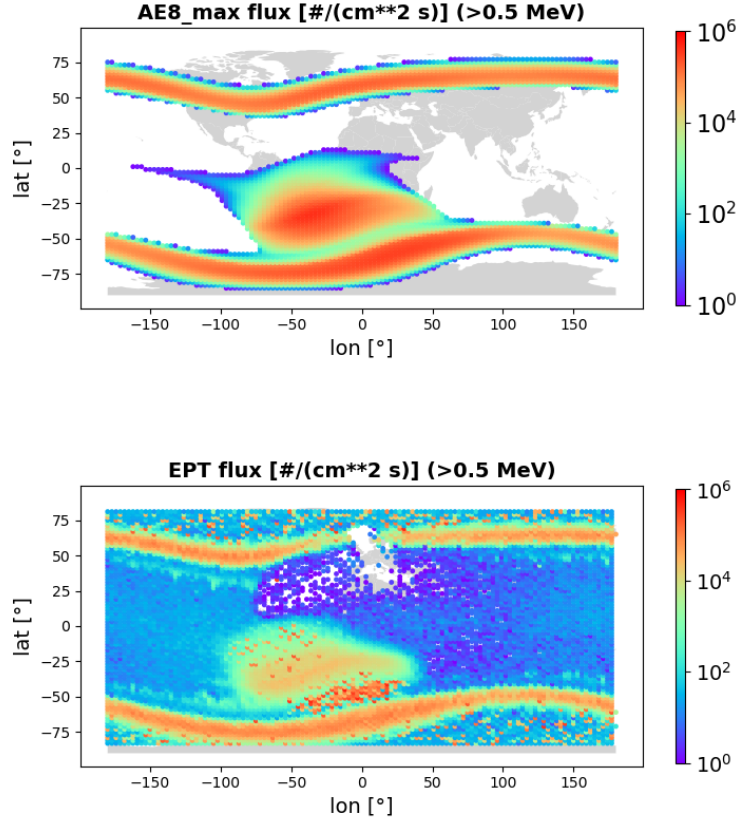


Figure 2.6: Upper panel shows the integral electrons flux (> 0.5 MeV) predicted by the AE8 model during a solar maximum. Bottom panel shows the averaged integral electron flux (> 0.5 MeV) observed by the EPT during February 2014.

in the northern hemisphere caused by the counterpart of the SAA. The bottom panel in this figure shows the integral flux of electrons (>0.5 MeV, computed with Equation 1.32) measured by the EPT during February and averaged on longitude-latitude bins ($3^\circ \times 2^\circ$) corresponding to the resolution of the model. The SAA and its counterpart as well as the horns are well visible. There is also a region between the SAA and the southern horn of high intensity fluxes. They are not very representative of the mean flux in the bin throughout February, they are due to measurements performed during the storms and should not be directly compared with the AE8 model. The shape of the SAA predicted by the model is not the same as it is observed by the EPT. Eventhough the "heart" (i.e. where fluxes are higher) is similar, the "arm" extending in the Pacific ocean at the equator is not seen in the measured data. The same structure extending over Africa is also only seen in the model.

The average of the EPT observations on bins similar to those of the model allows a direct comparison between them. Such a comparison is shown on Figure 2.7. On this figure, blue indicates that the model overestimate electron fluxes whereas red indicates an underestimation of the flux. In general, the model tends to overestimate electron fluxes in the SAA and in the horns, especially for maximum of solar activity. However,

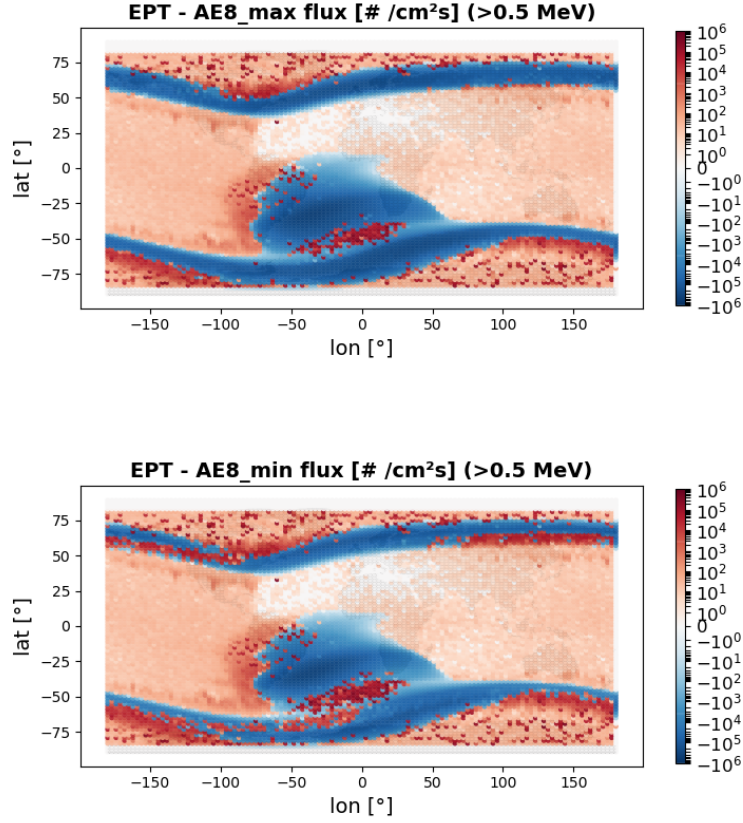


Figure 2.7: Difference between the averaged integral electron flux (> 0.5 MeV) on $3^\circ \times 2^\circ$ longitude-latitude bins and the integral flux (> 0.5 MeV) predicted by the AE8 model. In the top and bottom panels, maximum and minimum solar activity are considered in the model.

fluxes measured by the EPT are higher than predicted in the most western part of the SAA. The position of the observed SAA fluxes does not overlap perfectly with the one of the AE8 model. This is a manifestation of the motion of the SAA (3° per year) in the westward direction as a consequence of the secular motion of the geomagnetic field [Pierrard et al., 2014]. Higher fluxes measured by the EPT are also seen in the outer edges of the polar horns at various latitude. This is also due to the fact that the simulated and measured fluxes in the horns do not perfectly overlap in this regions. Nevertheless, when considering the model for minimum of solar activity, more intense fluxes are observed inside the horns.

2.3 January SEP events

While being mostly constant in the inner belt, during Solar Energetic Particle (SEP) events, strong variations in proton flux can be observed at high L values. In general, SEP events are responsible for the formation of geomagnetic storms in the inner magnetosphere, as the two event that occurred at the end of February and lead to the most

intense storms of the year. On the contrary, the SEP event of January did not lead to geomagnetic perturbations. Indeed, eventhough slight dropout event can be seen in January (with the outer edge of the outer belt never reaching values below $L = 5.5$), electron fluxes during this time period were lowering and the inner edge of the outer belt was reaching higher L values. In addition to that, in January, no inverted peaks of the Dst are observed.

2.3.1 Flux map

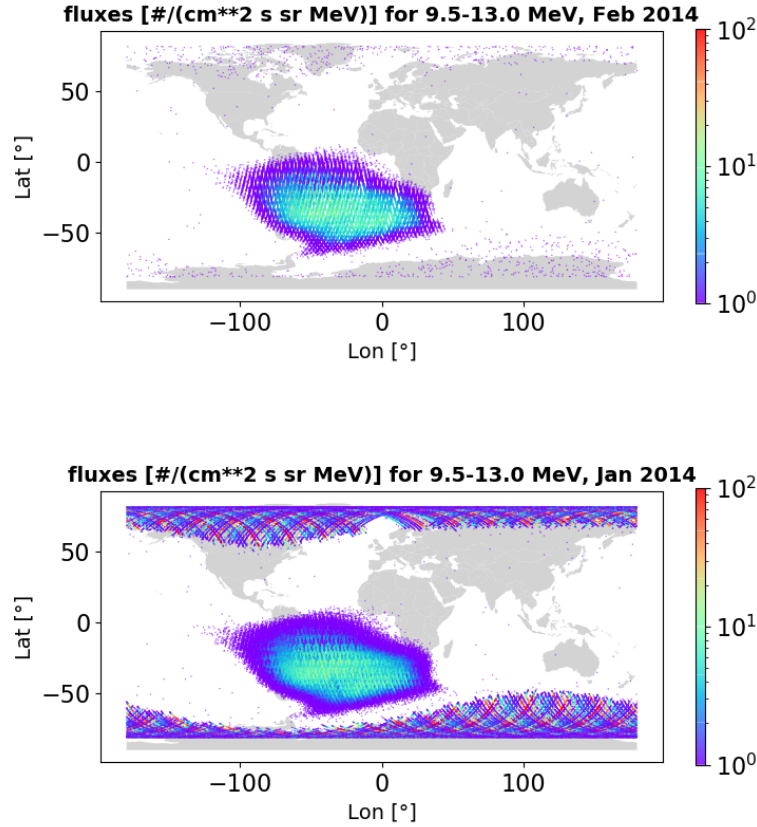


Figure 2.8: Proton fluxes observed by the EPT in the first energy channel (9.5-13.0 MeV) during two different time periods. Top panel shows proton flux between February 1 and February 15 which features no SEP events. Bottom panel shows the same fluxes through the month of January.

In early January 2014, two successive solar energetic particle events occurred in small period of time. The first event, caused by an asymmetric partial halo, took place on the 6th of January and the second one, featuring similar causes, occurred on the 9th of January. Proton fluxes observed in channel 1 (9.5-13 MeV) during the month of January are displayed on the bottom panel of Figure 2.8. The south Atlantic anomaly is well distinguished. Moreover, high fluxes of energetic protons are observed at very high latitudes. Such fluxes are not observed during quiet periods (top panel of Figure 2.8).

They correspond to the injection of very energetic protons in the magnetosphere of the Earth. In contrast to high latitude regions, proton fluxes in the SAA are not increased during the SEP event.

2.3.2 L-time plot

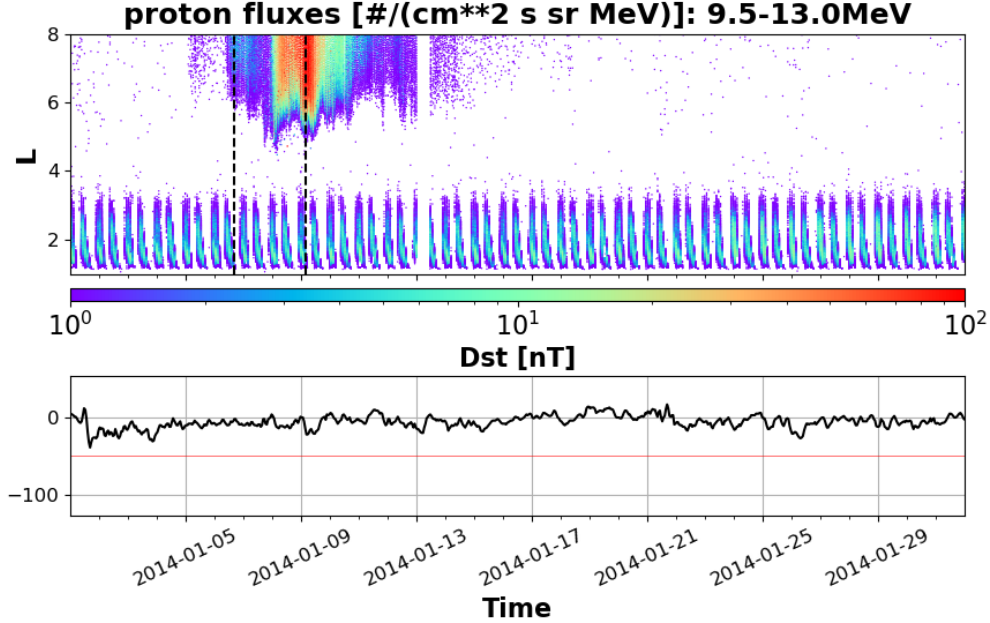


Figure 2.9: Differential proton fluxes observed by the EPT in energy channel 1 (9.5-13 MeV) during January 2014. The two vertical dashed lines give the time during which the SEP events occurred (found on <https://umbra.nascom.nasa.gov/SEP/>). The bottom panel shows the evolution of the Dst index throughout the month.

Proton flux measured in the first channel (9.5-13 MeV) throughout January plotted as a function of time and the parameter L is shown in Figure 2.9. The two SEP events are indicated by the vertical dashed lines. As it was already observed on the flux map, fluxes in the inner radiation belt (in the SAA) remain constant throughout the month, even during the SEP events. Similar to electrons, the L value of the outer edge of the inner belt depends on the energy, and decreases with increasing energy. The outer belt is completely free of energetic protons except during, and after the injection of protons after the SEP events. Between January 5 and 9, several injections of protons took place, such that proton fluxes observed during this time period remain high and even increase at high L values. During the event of January 9, observed proton fluxes are the highest. However, protons don't penetrate to lower L values. Only after this event, proton flux intensity decreases. The depletion of high energy proton starts at lower L values and gradually increases in time. After the last injection, high L region are fully free of protons after 6 days.

2.3.3 Comparison of the observations with AP8 model

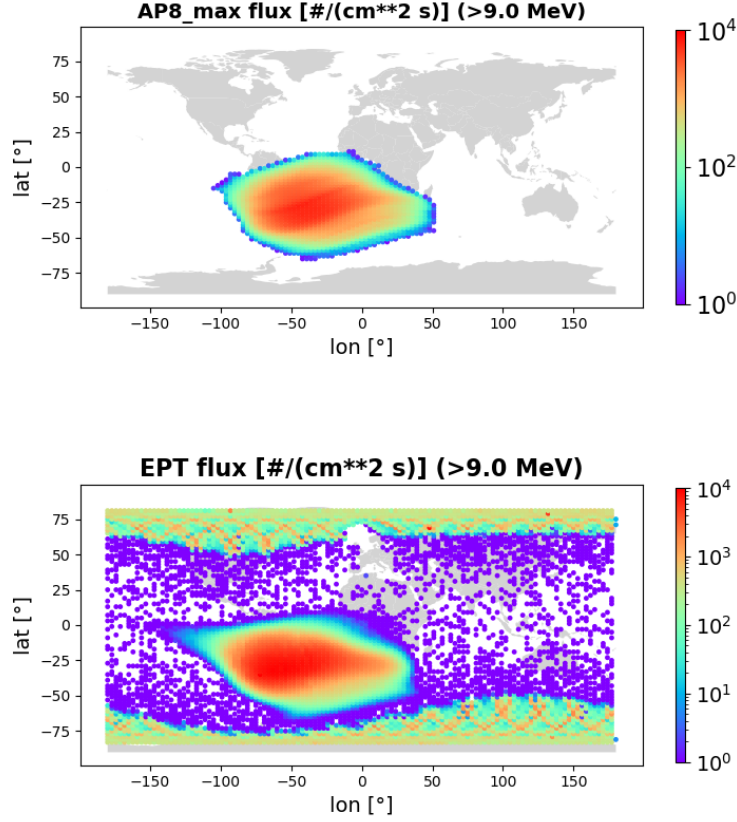


Figure 2.10: Integral proton fluxes (>9 MeV) as a function of longitude and latitude. Top panel shows fluxes predicted by the AP8 model under maximum solar activity. The bottom panel shows the average (on $3^\circ \times 2^\circ$ bins) of the observed proton fluxes during January by the EPT.

Proton fluxes (>9 MeV) predicted by the AP8 model under condition of maximum solar activity at 820 km of altitude is shown in Figure 2.10 (top panel). On the same figure, the bottom panel displays the integral proton flux observed by the EPT under the same spatial average as for the electrons in the previous section. The model represents well the SAA at this altitude, but is not displaying any proton fluxes at high latitude. This shouldn't be a surprise since the model doesn't take SEP injection into account. Moreover, the shape of the SAA predicted by the model is slightly different to the one that is observed. Especially, near the equator, measured proton fluxes extend further in the westward direction than it is simulated. In both model and observations, fluxes in the most southern region of the SSA are less intense than the northern one.

As for electron fluxes, the difference between measured and AP8 integral proton fluxes is displayed on Figure 2.11. Here again, red color indicates that observed fluxes are higher than predicted ones and conversely, blue indicates that AP8 fluxes are more intense than the observed ones. The difference between the top and the bottom channel is the solar

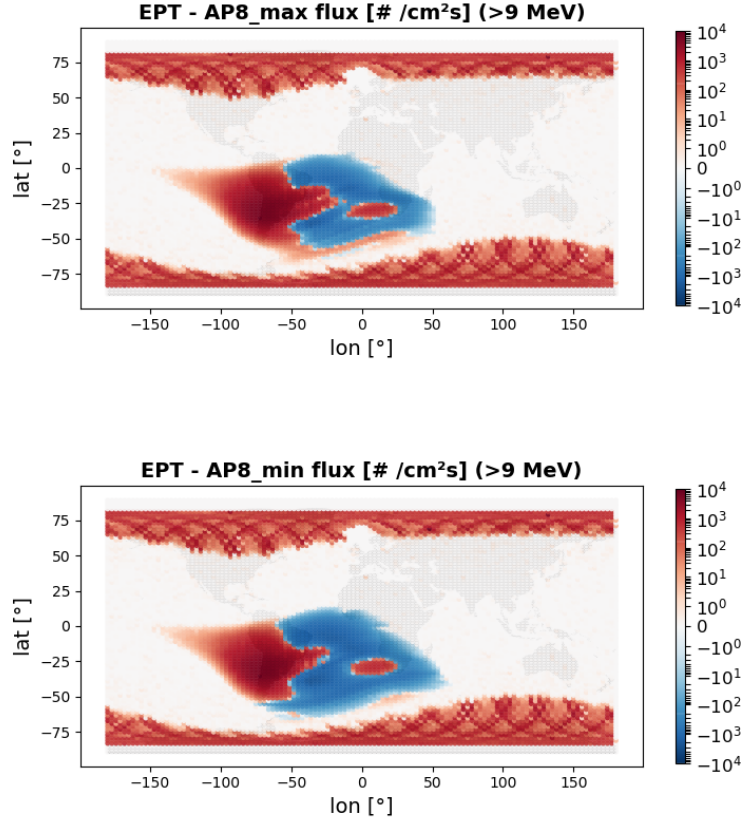


Figure 2.11: Similar to Figure 2.7, but for proton flux (>9 MeV). Top panel shows the difference between observation and the model considering maximum of solar activity while bottom panel considers minimum of solar activity.

activity considered in the model. In both cases, intense fluxes are seen by the EPT at high latitudes due to the SEP event. Unlike the case of electrons in the SAA, for which the model almost always overestimates the flux, the SAA in the case of protons is split in two regions. In both panels, fluxes in the western half of the SAA are higher than predicted while fluxes in the eastern half of the SAA are mostly overestimated by the AP8 model, with the exception of the small region centered on ($0^\circ\text{W} - 25^\circ\text{S}$). Higher observed fluxes in the western part of the SAA and lower observed fluxes in the eastern part of the SAA can be expected due to the westward drift of the SAA in time. However, this effect is very small and only affect the edges of the SAA. The AP8 model, thus underestimate proton fluxes in the left half of the SAA, while the right half is overestimated. In the latter, the lowering of the flux intensity with decreasing latitudes starts at higher latitude in the model, but is less abrupt than in the observations. This leads to the formation of the "red island" in the eastern part of the SAA observed in Figure 2.11.

2.4 Conclusions

The year 2014 was relatively quiet in term of magnetic activity compared to the following years. From January to June magnetic activity was low on average, although this period saw the largest storms, especially in February. Conversely, the rest of the year was characterized by a higher magnetic intensity, with lower Dst value on average, but major events occurred in this time period. This can also be seen in the flux intensity measured by the EPT and MagEIS throughout the year, with more intense electron fluxes toward the end of the year. The EPT is used to study in more details some particular events of 2014, for both protons and electrons. Due to the lack of injections of electrons to very low L values, the very stable nature of the inner belt is clearly displayed, even for the storm of February 19th. However, the variations of electron flux in the outer belt with the magnetic activity are well observed for the February storms. Moreover, EPT observations can be plotted on the world map, giving another representation of the radiation belts at low altitudes. The effect of magnetic storm is also clear on the polar horns, which spatial extent increase with the magnetic activity. Because the inner belt is only probed by the EPT in the SAA, no variations of the flux was found in the SAA during the storms of February. Similarly, for protons, SEP events of January were investigated. The event of January 9th was the most important of the year, leading to the injection of a large amount of energetic protons in the outer belt. This injection is well observed on the world map too, characterized by high proton fluxes at high latitudes. During this event, fluxes in the inner belt, and thus in the SAA, remained mostly constant. After a simple treatment of the measurements from the EPT, integral fluxes of both electrons and protons are directly compared with the NASA AE8 and AP8 empirical model. Because the model can only distinguish between maximum and minimum of solar activity, injections of electrons and protons during magnetic storms and SEP events respectively cannot be reproduced. However, it is able to well represent the main features of the radiation belts at low altitudes. For electrons, flux intensity in the horns is in general higher for the model than for the observations. This overestimation of the flux by the model is also seen in the SAA. The difference in flux intensity between the model and the observations is much larger in the SAA than in the horns due to lack of injection of electrons in this region in 2014. Due to more stable nature of the proton population in the inner belt, observed and simulated flux intensity in the SAA is much more alike than for electrons. While well represented, the shape of the SAA is not the same for the measurements of the EPT. Moreover, the observed SAA appears to be shifted westward compared to the simulated one because of the westward drift of the SAA in time.

Chapter 3

Comparison between PROBA-V/EPT and RBSP-B/MagEIS measurements

This chapter focuses on the comparison of the electron flux measurements in the outer radiation belt, performed by the PROBA-V/EPT instrument at low altitude and by the RBSP-B/MagEIS instrument near the magnetic equator. Note that the following discussion was inspired by the work of [Baker et al., 2019] in which a thorough comparison of the measurements of MagEIS and GOES-15 was conducted. In order to compare the observations of the instruments, the plot of the flux in function of time and the McIlwain parameter are very useful. While such representation of the data allows a qualitative analysis, a quantitative analysis is less evident to perform. Thus in this chapter statistical scatter plots of hour-averaged electrons fluxes are provided. The first section of this chapter focuses entirely on the comparison of the measurements of the EPT and the (level 2) spin-averaged fluxes observed by MagEIS which were briefly introduced in chapter 2. The comparison is carried out for different energy channels of the two instruments and at various position in the outer belts. Then, a similar comparison is performed but for (level 3) pitch angle resolved data from MagEIS. The motivation for this analysis is that low altitude fluxes should be more similar to the low pitch angle value electron fluxes measured at the equator due to the oscillation motion of trapped particles between the two hemispheres. Data used in those two sections are taken between January 1 and March 31 2014. In the last section of this chapter, the results of the above mentioned comparisons will in turn be compared to the results of a similar analysis but with data taken from October 1 to December 31, 2014. The two periods of time from which the measurements are used are such that one is before and the other one after the incident of the EPT.

3.1 Comparison between EPT and MagEIS L2 spin-averaged data

3.1.1 Comparison of the L-time plots

In the same way that electron fluxes are represented in the previous chapter, Figure 3.1 shows the differential electron flux measured by the EPT and MagEIS as a function of the McIlwain parameter L and time. While the orbit of the PROBA-V satellite allows the EPT to perform flux measurements at very high values of L , the apogee of the Van Allen Probes is located at $L \sim 6$. In this figure, only fluxes observed up to $L = 6.25$ are displayed, so that the EPT observations are constrained to regions of the belts accessible by the MagEIS instrument. Data displayed here extends from January 1st to March 31st 2014. The left and right panels are the same, except for the energy channels that are shown. Left panel displays channel 1 of the EPT (500-600 keV) and the 604 keV channel of MagEIS, while the right panel displays fluxes of higher energy electrons. The displayed channels are the EPT 5th channel (1000-2400 keV) and the 1064 keV channel of MagEIS. Similarly to the previous section, the measurements performed by MagEIS are spin-averaged and corrected from background contamination.

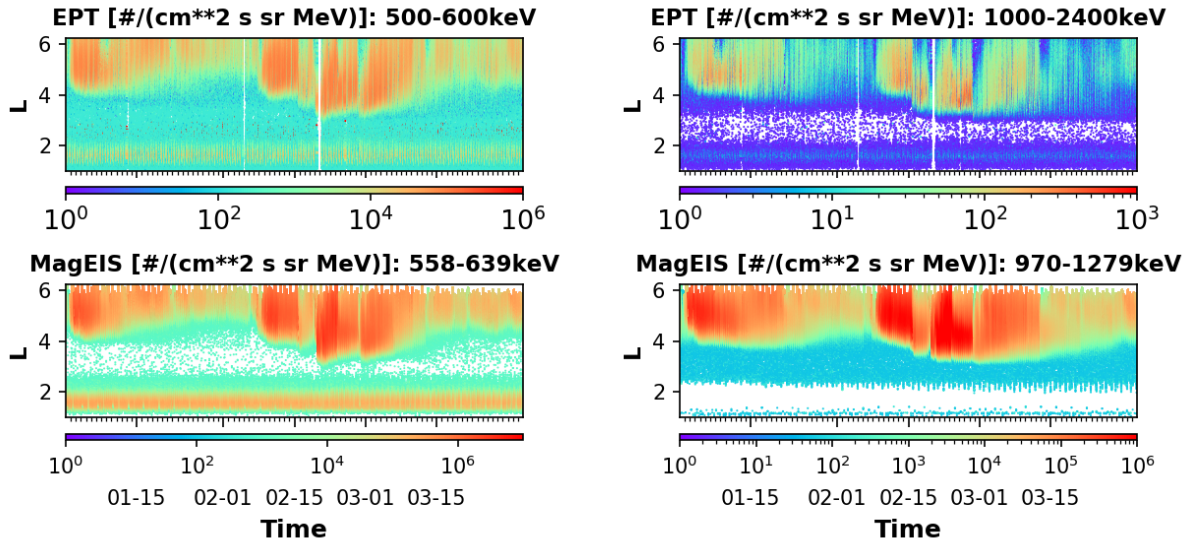


Figure 3.1: EPT and MagEIS corrected level 2 spin-averaged differential electron fluxes observed from January 1st to March 31st 2014 in similar energy channels for both instruments. Left panel shows relatively low electron energy (~ 500 keV), while right panels show fluxes of electrons in the mega electron volt energy.

In both panels, measured electron fluxes near the equator always appear more intense than at 820 km of altitude. The flux intensity measured by MagEIS in the 604 keV channel is one order of magnitude higher than the flux intensity measured for a similar channel by the EPT in both the inner and the outer zone. Moreover, in the outer belt, for the 1064 keV channel of MagEIS, observed fluxes are up to four order of magnitude larger than for closest corresponding channel of the EPT. The fact that fluxes measured by

MagEIS are always larger than the ones recorded by the EPT is not surprising. This can be understood by the motion of charged particles in the radiation belts. Indeed, electrons that have a pitch angle close to 90° mirror near the equator and thus never reach low altitude. This behaviour is confirmed by simulation of the gyromotion of relativistic test particles performed by [Pierrard et al., 2021]. Conversely, if the pitch angle of the electron is close to 0° , the electron is in the loss cone. In this case, the mirror point of the particle is at an altitude lower than 100 km. Thus, for such low pitch angle, the electron is lost in the atmosphere. An additional cause for the difference that is observed in flux intensity between low altitude and (near) equatorial measurements is due to the channel selection. In the outer belt, using RBSP-B measurements, [Zhao et al., 2019] showed that in 2017 $\sim 67\%$ of the electrons energy spectra is decreasing exponentially with increasing energy. In the inner belt, electron fluxes also sharply decrease with growing energy [Rosson Lopez and Pierrard, 2017]. Thus for a given physical location in the radiation belts, measurements of the differential flux of electrons in a 500-600 keV or 550-650 keV channel will not be the same. In this situation, flux intensity measured in the first channel will be larger than the flux intensity measured in the second one. Because the MagEIS instrument and the EPT do not share identical energy bins, this effect slightly affects the differential fluxes measured by the instruments. However, if the selected channels on both instruments are sufficiently close to each other, the dominant factor responsible for the difference in flux intensity is the pitch angle of the electrons.

Nonetheless, these figures show similar variations for fluxes measured by both instruments. During the storms that took place in February, electron flux increase is seen in the outer belt, for both equatorial and low altitude observations. During the main phase of the storms, the penetration of energetic electrons to lower L values occurs simultaneously at both spatial locations. The inner edge of the outer belt reaches the same L values for EPT and MagEIS. In addition to that, the decay of the flux at lower L value occurs in the same period of time at the two locations. In Figure 3.1, even though the outer edge of the outer belt is not fully visible due to the restriction of the range of L values ($L < 6.25$), dropout events are clearly visible in the EPT measurements. In the case of MagEIS, dropouts associated with the strongest storms are also observed. However, a number of those events are not observed near the equator while relatively pronounced at low altitudes. For example, a small depletion of electrons occurs at high L in the EPT measurements in early January but no sign of this event is recorded by MagEIS. This is even more visible for electrons in the 1064 keV channel.

3.1.2 Statistical scatter plots.

Data from the two instruments cannot be directly compared because the frequency at which they measure electron flux is different (every $2''$ for the EPT and between $5''$ and $7''$ for MagEIS). Thus, averaging the data over one hour intervals allows to give the evolution of electron fluxes with an identical time resolution for the two instruments. Such averages have been performed for period of three months, either from January to March or from October to December 2014. Those two time periods are chosen so that the former gives measurements before the incident of the EPT and the latter gives measurements after it happened. In order to allow a better quantitative comparison between the observations

performed by the two instruments, the computed hour-average fluxes have been directly plotted on log-log scale scatter plots. In addition to that, the outer belt was segmented in narrower 'shells', centered on a given value of L and with a width of $dL = 0.5$. Although relatively wide, this shell width allows to compensate for the rather small period of time used in this analysis. This ensures that enough points are present in the comparison. It is then possible to perform a linear regression on this new data in order to compute the Pearson correlation between the observations of the two instruments. The equation of the regression line is given by,

$$\log_{10}(\bar{\phi}_{EPT}^i) = \beta_0 + \beta_1 \log_{10}(\bar{\phi}_{Mag}^j), \quad (3.1)$$

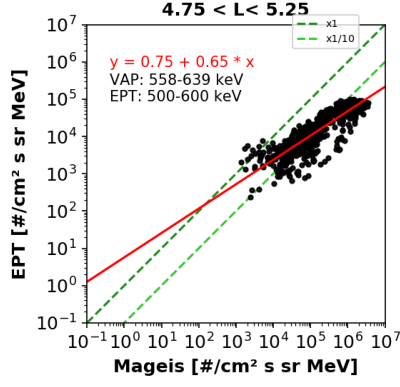
where $\bar{\phi}_{EPT}^i$ and $\bar{\phi}_{Mag}^j$ are respectively the hour-averaged differential electron flux computed from EPT and MagEIS, i and j denote the energy channel selected for the corresponding instruments, β_0 is the intercept the regression line and β_1 is the slope.

3.1.3 Differential flux comparison

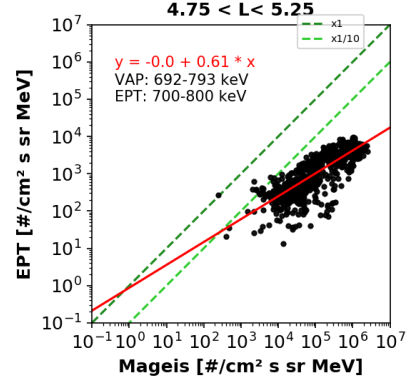
Energy dependence

Such flux-flux scatter plots are presented in Figure 3.2. In this figure, only fluxes measured in the 'shell' $L = 5 \pm 0.25$ and from January to March are taken into account. For each panel in this figure, hour-averaged differential fluxes of the EPT are plotted against hour-averaged differential fluxes from MagEIS, computed with level 2 corrected data. Those panels only differ from each other by the energy channels that are selected for each instrument. Note that only five of the six channels of the EPT are presented on this figure. Indeed, the second channel of the EPT (600-700 keV) is not similar to any other channels of MagEIS. The first four graphs share the same scale while the bottom graph features a different one because the intensity of ultrarelativistic electron flux measured by the EPT is much smaller than for lower energy electrons. Figure 3.2 shows that independently of electron energy, fluxes measured near the magnetic equator are almost always larger than the one measured at an altitude of 820 km. For both instruments, averaged fluxes become smaller as the energy of the electrons increases (the distribution of points moves progressively to the left and downward). However, as electrons become more energetic, the ratio between MagEIS and EPT fluxes also rises. A very sharp drop of the flux is observed for EPT when passing from channel 5 to channel 6 while for MagEIS (see last panel), even if the decrease is present too, it is much less important.

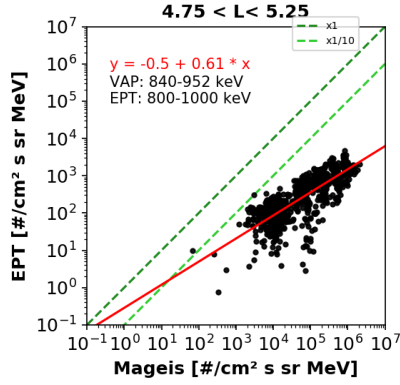
This behaviour is captured in the variation of the parameters of the linear regression as electron energy changes. The slope (β_1) is always below unity, and its maximal value is found at the lowest energy. In addition to that, both the slope and the intercept (β_0) diminish as the energy increases. The fast diminution of the intercept manifests the faster decay of the flux at low altitudes than near the equator. The same analysis was performed in other regions of the outer belt, namely at $L = 4 \pm 0.25$ and $L = 6 \pm 0.25$. The time period from which the data is taken is identical to that of Figure 3.2. The evolution of the averaged differential flux observed by both instruments is similar to the observations at $L \sim 5$. The fact that $\beta_1 < 1$ indicates that, in general, variation of the flux intensity is larger at the equator. The slope reaches minimum value for ultrarelativistic electrons (2400-8000 keV for the EPT and 2280-3008 keV for MagEIS). It shows that



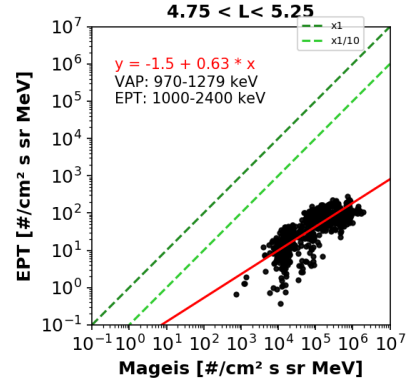
(a) corr = 0.86, SE = 0.015



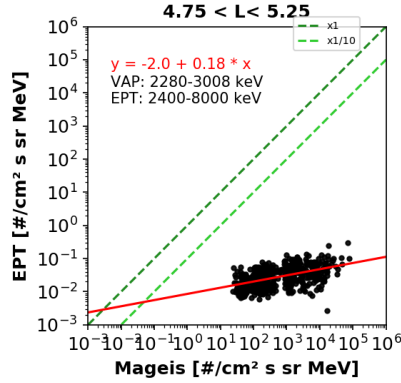
(b) corr = 0.78, SE = 0.018



(c) corr = 0.77, SE = 0.019



(d) corr = 0.79, SE = 0.019



(e) corr = 0.51, SE = 0.014

Figure 3.2: Scatterplot of the natural logarithm of the hour averaged differential fluxes from the PROBA-V/EPT versus RBSPB/MageIS for different energy channels when both spacecraft were at $L = 5 \pm 0.25$. On each graph, the parameters of the regression line are given in red and the Pearson correlation coefficient as well as the standard error on the slope are given underneath them. The green lines show the perfect linear relationship of slope one for a factor $\times 1$ and $\times 10^{-1}$.

the difference in the variation range of flux intensity between the two instruments is significantly larger at very high energy. However, some smaller vertical structures can be identified in Figure 3.2, especially in graphs (c) and (d). Those structures correspond to dropout events that are either measured by the EPT while MagEIS averaged fluxes remain mostly constant over some periods of time or observed by both instruments, but for which the event is more intense at low altitude. Note that the former case is much less frequent than the latter. For instance, in graphs (c) and (d), the first inverted 'peak' in EPT averaged flux at $\bar{\phi}_{Mag} \sim 10^4 n_e/(\text{s cm}^2 \text{ sr MeV})$ appears during the storms of February, during which dropouts going as deep as $L \sim 4$ are recorded. For such events, fluxes measured at low altitude decrease faster and to lower values than near geomagnetic equator. The second peak at $\bar{\phi}_{Mag} \sim 10^5 n_e/(\text{s cm}^2 \text{ sr MeV})$, on the same graphs is due to observations throughout the month of March. Eventhough this period is less geomagnetically active than February, EPT measurements show a number of small dropouts while MagEIS fluxes remain relatively constant in this region of the belts. In graphs (a) and (b) of the same figure, more intense decrease of averaged electron flux at low altitudes are also noticed, corresponding to the same events than for the other two plots. For ultra relativistic electrons however, no such structure appears on the scatter plots (see panel (e) of the same figure). In addition to the regression line coefficients β_0 and β_1 , the linear regression allows to give the Pearson correlation coefficient between the hour-averaged electron flux computed with the EPT and the one computed with MagEIS, as well as the standard error of the estimated slope. The correlation between the averaged fluxes at $L \sim 5$ is never below 0.77, except for ultrarelativistic electrons. To the extreme drop in flux intensity and the difference in the flux variation range is associated a sharp diminution of the correlation. With increasing energy, the correlation tends to slightly decrease, however for channel 5 of the EPT and the 1064 keV of MagEIS a slight increase is observed. This is also the case at $L \sim 6$ whereas at $L \sim 4$, a straight diminution is observed with the energy. The standard error on the slope is always small compared to the estimated value of the slope itself. However, it is largest for panel (c) and (d) for which structures associated with dropouts are more important.

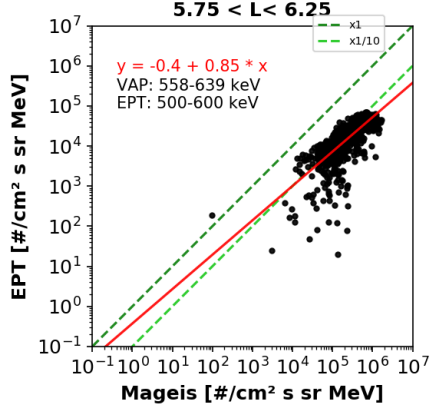
Dependence in the McIlwain parameter

As mentioned above, the comparison of hour-averaged differential flux from the two instruments can be performed in different regions of the outer belt(i.e. shells $L + dL$ centered on different L values). The results of this comparison is shown in Figure 3.3, which displays similar graphs as in Figure 3.2, only for two different energies but for various L values. The left column displays hour-averaged fluxes computed from channel 1 (500-600 keV) of the EPT and the 558-639 keV channel of MagEIS, while the right column shows fluxes from channel 5 (100-2400 keV) and the 970-1279 keV channel of EPT and MagEIS respectively. In this case, data is also taken between January and March 2014. As L grows and for both represented energy in Figure 3.3, averaged fluxes near the equator become increasingly larger compared to low altitude ones. This can be seen in the diminution of the intercept of the regression line with growing L values. Conversely, the slope of the line increases from lower to higher L values. This shows that, in outer region of the outer belt, variations of the electron flux at LEO and near the magnetic equator are more alike than close to the inner edge. Such variations of

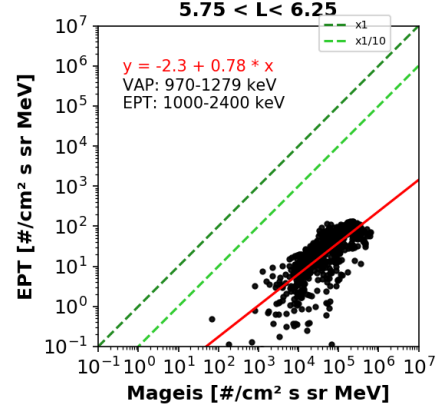
the regression parameters is found for all energies, except for ultrarelativistic electrons (i.e 2400-8000 keV for the EPT and 2280-3008 keV for MagEIS) for which this trend is the opposite. For such highly energetic electrons, as L increases, the difference in flux intensity observed from the EPT and MagEIS becomes slightly smaller. However, fluxes measured near the equator remain $\sim 10^5$ times higher than at 820 km. In addition to that, as L grows, the variation range of fluxes measured with MagEIS becomes larger while at low altitude, the variations of ultrarelativistic electron flux remains constant.

In the region comprising the inner edge of the outer belt, i.e for $L = 4 \pm 0.25$, averaged fluxes of low energy electrons computed from EPT data are closer to that computed from MagEIS. In some cases, fluxes of the EPT can even exceed them. It only occurs for this L value and energy during relatively quiet periods of time. Indeed, the low flux points in graph (e) of Figure 3.3 correspond to electron flux measurements throughout the month of January and late March, which are time periods characterized by the lowest magnetic activity for this data set. Yet, during the storms of February, electrons are injected in the lower parts of the outer belt as well as in a fraction of the slot region. During those injections, averaged fluxes near the equator rise faster and reach intensity of up to one order of magnitude higher compared to observations at low Earth orbit. A similar behaviour is found for higher energies.

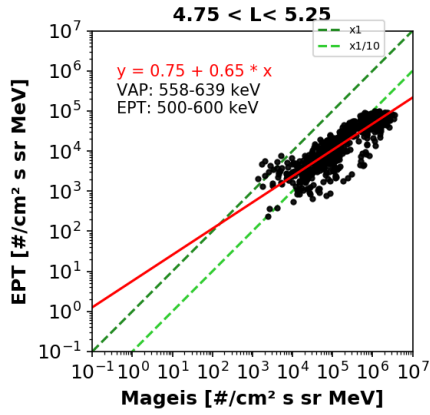
Note that as fluxes are measured in different regions of the outer belt, the evolution of the distribution of points in the flux-flux plots in Figure 3.3 displays various structures. First, during the time period considered, characterised by both quiet and stormy conditions, the variation scale of the flux intensity for both instruments is much wider at lower L values than at higher ones. Such values of L correspond to the region containing the inner edge of the outer belt. During quiet times, the intensity of the flux close to the edge is relatively small (see Figure 3.1), in fact much smaller than inside the belt. However, during the strong storms of February, the injection of electrons pushes the inner boundary of the outer belt in the slot region. Flux intensity at $L \sim 4$ then increases to similar level as for higher L values. In the case of ultrarelativistic electrons, the slope retrieved from the regression is the largest near the inner edge, also indicating that the difference in flux variation between the EPT and MagEIS is less important than for the outer regions of the outer belt. At $L \sim 5$ and $L \sim 6$, the distribution of points is very different than near the inner edge of the belt. This illustrates the different evolution of electron fluxes in the different regions of the outer belt. Indeed, near the inner boundary, fluxes are relatively low until injections lead to sharp flux increase, whereas higher in the outer belt, electrons fluxes remain more intense even during quieter periods. Yet, the upper limit of flux intensity is relatively constant in the outer belt. Thus at $L \sim 5 - 6$, the variation range of electron fluxes is narrower than near the inner edge. It is the case for both instruments. However, as it was mentioned above, dropouts events due to variation of the magnetic field strength are much more frequent at higher L values in the outer belt. While such events are observed by both EPT and MagEIS, the four upper graphs of Figure 3.3 shows that the depletion of electrons is faster and much more intense at low altitudes than near the equator during such events. It is evident in panel (a) ($L = 6 \pm 0.25$) of this figure. Although ~ 500 keV electron fluxes measured by MagEIS are limited at $\sim 10^3$ (e/ s cm² sr MeV), fluxes measured by the EPT drop to much lower values. At $L \sim 5$ and for the same energy range, more intense dropout at LEO than at the equator is less obvious, but remain visible. For ~ 1 MeV electrons, structures associated with



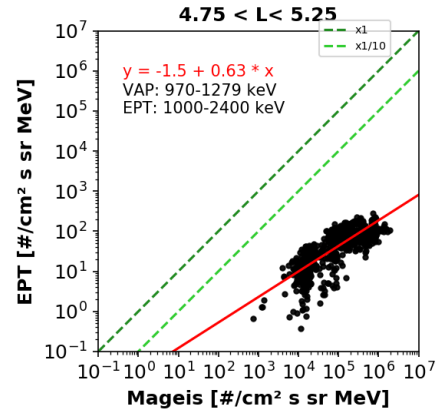
(a) $\text{corr} = 0.70$, $\text{SE} = 0.032$



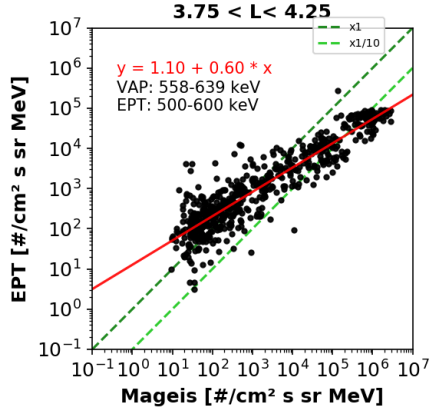
(b) $\text{corr} = 0.75$, $\text{SE} = 0.026$



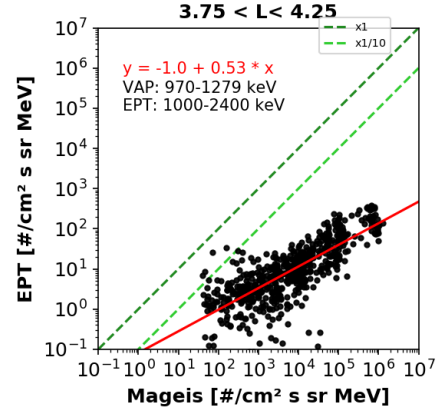
(c) $\text{corr} = 0.86$, $\text{SE} = 0.015$



(d) $\text{corr} = 0.79$, $\text{SE} = 0.019$



(e) $\text{corr} = 0.92$, $\text{SE} = 0.011$



(f) $\text{corr} = 0.79$, $\text{SE} = 0.017$

Figure 3.3: Similar to Figure 3.2 but for two different energies (~ 500 keV and ~ 1000 keV). Each row corresponds to a different location in the outer belt. From top to bottom, $L = 6 \pm 0.25$, $L = 5 \pm 0.25$, $L = 4 \pm 0.25$.

different flux variations observed by MagEIS and the EPT stand out for $L \geq 5$ (see panel (b) and (d) of Figure 3.3). While still being small relative to the value of the slope, the standard error is much larger near the outer edge than for other locations of the belts. This increase is due the larger disagreement between observations during dropout events, which are more important and more frequent in the region.

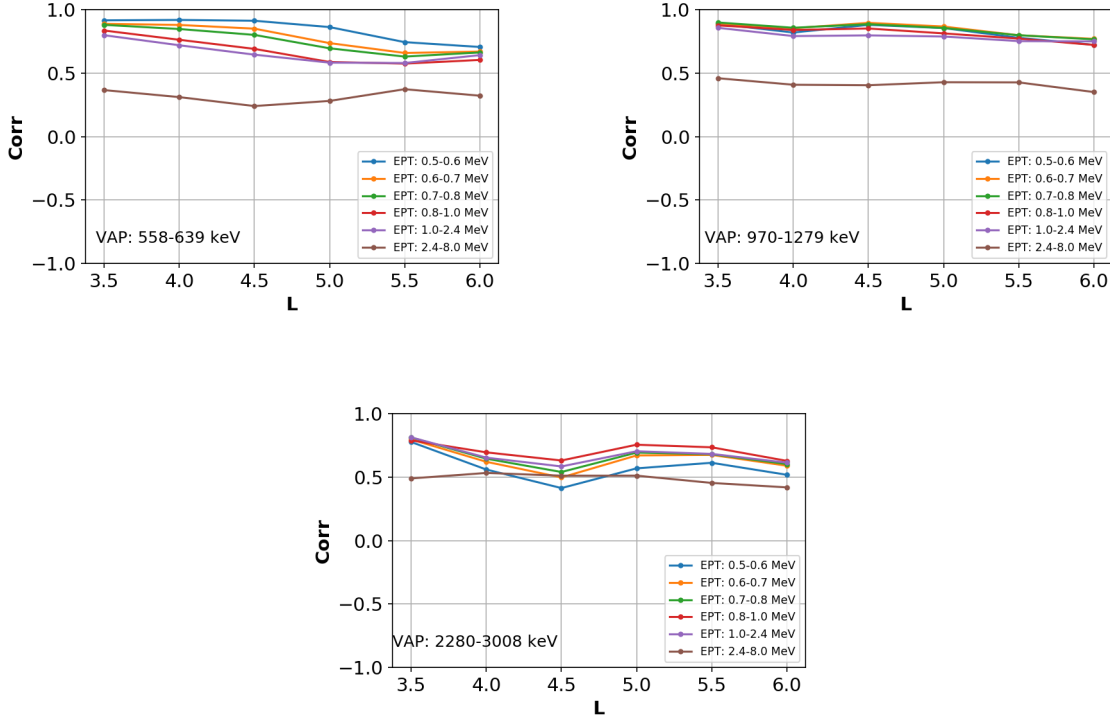


Figure 3.4: Evolution with respect to L of the Pearson correlation coefficient between the logarithm of hour-averaged electron fluxes computed from EPT data and MagEIS level 2 corrected data. In each graph, one of the channel of MagEIS is compared to all energy channels of the EPT. 558-639 keV, 970-1279 keV and 2280-3008 keV channels are represented from upper left, upper right and bottom respectively. The data used to produce this figure spreads from January to March 2014.

Evolution of the correlation in the outer belt

The correlation between the hour-averaged electron flux observed in all EPT channels and some MagEIS channels can be seen in the different panels of Figure 3.4. This figure not only exhibits the correlation between different channels of the two instruments, but also its evolution throughout the outer belt. It is expected for the correlation between two energy channels close from each other to be maximum, while becoming smaller as the "distance" between them gradually increases. This is confirmed for the 604 keV channel of MagEIS, on the top left panel of Figure 3.4. The maximum correlation is reached for all L values in the outer belt with the first energy channel of the EPT i.e 500-600 keV. As EPT energy channel grows, the correlation diminishes independently of L . The most significant drop in the correlation occurs for the highest energy channel of the EPT.

It never exceeds value of 0.5. This sharp drop in the correlation might be due to the different dynamics of ultra-relativistic electrons compared to relativistic electrons. With increasing values of L , the correlation with most of EPT channels decreases.

In the outer belt as a whole, the correlation between the 1064 keV channel of the MagEIS instrument and the 5th channel of the EPT (1000-2400 keV) is not maximum. Note however that the difference in correlation of channel 5 and the other four lower channels of the EPT is much smaller than for the 604 keV channel of MagEIS. It is also interesting to note that, comparing channel 5 of the EPT with all channels of MagEIS, gives a maximum correlation at most L values with the channel 1064 keV (the figure is not shown in this work). Note also that the correlation between this latter channel and channel 6 of EPT is improved at every location of the belt. For all channels, as L increases, the correlation slightly varies up to $L=5$, at which point, it decreases very slowly.

The last graph of Figure 3.4 compares the 2559 keV channel of the MagEIS with the EPT channels. An important decrease in the correlation with all EPT channels below 2400 keV is observed. Conversely, the correlation with EPT channel 6th is still improved at all L values. Nonetheless, except for the first channel of the EPT, the correlation of all EPT channels with an energy smaller than 2400 keV is higher than with channel 6.

3.2 Comparison between EPT and MagEIS level 3 pitch angle resolved data

3.2.1 Differential flux comparison

After a first comparison of the observations between the EPT data and the level 2 corrected data from MagEIS, a similar comparison is performed using the level 3 pitch angle resolved data from MagEIS. The reason for this new comparison is that fluxes of electrons with low pitch angle at the magnetic equator are expected to be more similar to those observed at low altitudes. In the outer belt, several types of pitch angle distributions were identified with use of RBSP observations. While they strongly depend on the energy of the electrons, location in the belt and on the magnetic activity, the minimum flux is always obtained for the lowest value of the pitch angle [Smirnov et al., 2022] [Shi et al., 2016]. As illustrated by Figure 3.5, in the radiation belts, the electron flux decreases as the pitch angle of the electrons becomes smaller. This decrease in the flux is observed for both energies displayed on this figure. For all pitch angle values, the variation of electron fluxes in the outer belt is very similar. The inner edge of the outer belt is found at the same L for all pitch angle values. However, dropouts occurring during the February storms are more intense for low pitch angle electrons. This is better seen for 1064 keV electrons for the February 27 storm. Next in this section, a similar analysis as the previous one is presented. However, in this case only fluxes of electrons with pitch angle comprised between $[0^\circ, 16.36^\circ]$ are used for MagEIS.

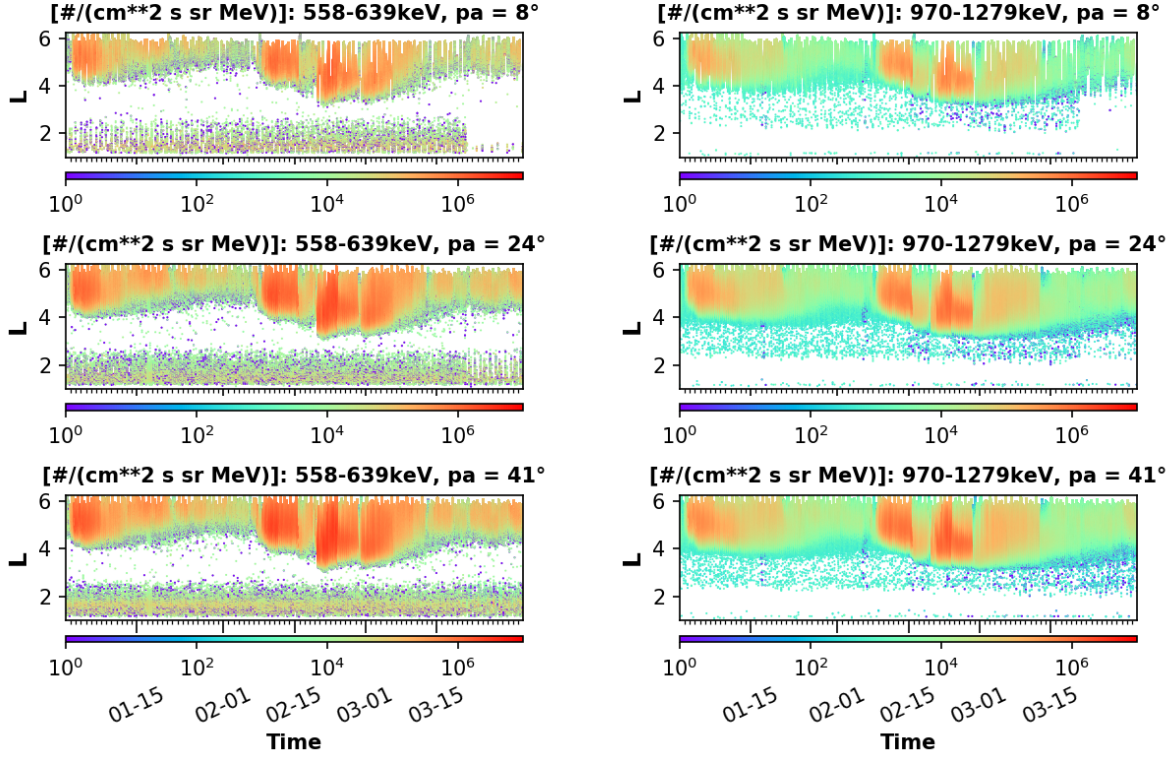


Figure 3.5: MagEIS corrected level 3 pitch angle resolved data as a function of time from January 1, 2014 to March 31, 2014. Left and right panel show differential fluxes in the 604 keV and 1064 keV respectively. From top to bottom, each row shows fluxes measured in increasing pitch angle bins, $[0^\circ, 16.36^\circ]$, $[16.36^\circ, 32.72^\circ]$, $[32.72^\circ, 49.09^\circ]$.

Energy dependence

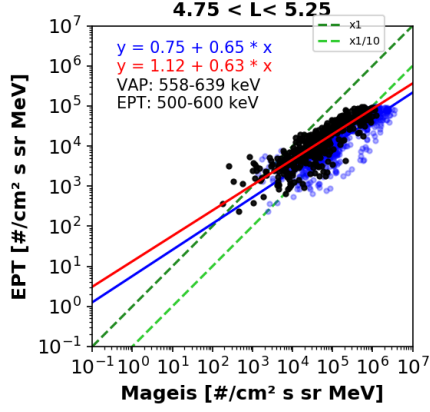
The various plots presented in Figure 3.6 share the same layout as the plots shown in Figure 3.2. The same time period is used for the comparison between EPT and pitch angle resolved MagEIS fluxes. The black dots on each plot show the hour-averaged differential flux at $L \sim 5$ for electrons with a pitch angle of $\sim 8^\circ$. As for the previous figure, a linear regression is performed on this data set. The regression line, in addition to the corresponding parameters are shown in red. The Pearson correlation as well as the standard error given below the graphs are the one computed with this linear regression. In order to clearly show the difference between the hour-averaged fluxes computed with level 3 and level 2 data, the latter is presented in blue on the graphs of this figure. The cluster of blue points are the same as the ones represented in Figure 3.2. In addition, the regression line for this data set as well as its parameters are represented in blue in the figure.

The evolution of the hour-averaged fluxes with respect to the energy is identical for the spin-averaged and pitch angle resolved MagEIS data. As the energy of electron increases, the difference between fluxes measured by the EPT and fluxes measured by

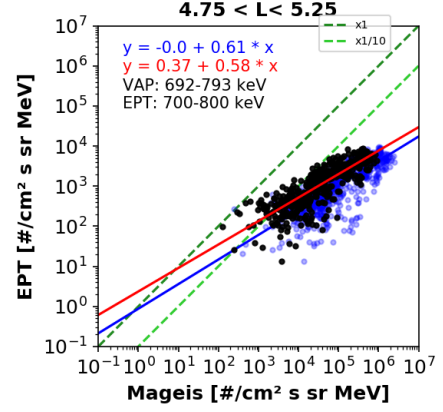
MagEIS decreases. However, for each energy channels, the intercept of the regression line for pitch angle resolved fluxes is always larger than for spin-averaged MagEIS fluxes. The distribution of points in black (i.e. $pa \sim 8^\circ$) is shifted to the left with respect to the fluxes that consider all pitch angle values. The shift in the dot distribution shows that the maximum value of the fluxes measured by MagEIS is lower for low pitch angle electrons. This is especially well seen for ultrarelativistic electrons (graph (e) of this figure). Thus, the intensity of the flux of electrons with low pitch angles near the magnetic equator is closer to the intensity of the flux measured at low altitude. But despite being more similar to low altitude fluxes, low pitch angle equatorial fluxes are still larger than those low altitude one. In addition to the left shift of the point distribution, note that some of the vertical structures that were observed in Figure 3.2 are not seen in the averaged flux computed from low pitch angle observations. This is more obvious for graph (a), (b), (c) of Figure 3.6. Most of the smaller dropouts that were observed by the EPT in March are now also observed by MagEIS for low pitch angle electrons. However, the intensity of the dropout observed by MagEIS is still less intense than for EPT. This is especially the case for the comparison with channel 5. As for level 2 MagEIS measurements, in plot (d) of the same figure, the dropouts that took place in March at low altitude are also not seen in the MagEIS low pitch angle electron fluxes. The identical vertical structures are thus still visible in that graph, but they appear at slightly smaller flux intensity ($\bar{\phi}_{Mag}$) than for level 2. Except for ultrarelativistic electrons, the correlation between the hour-averaged fluxes computed with low pitch angle electrons and the EPT is increased for all energies compared to that computed previously. Moreover, in a similar way than for level 2 data, the correlation with $\sim 8^\circ$ pitch angle electrons measured by MagEIS becomes smaller as the energy of the electron increases. Although, this does not hold true in all regions of the outer belt for which slight increase is found for ~ 1000 keV electrons.

Dependence in the McIlwain parameter

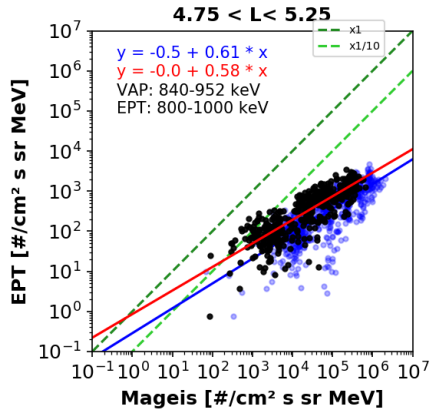
The comparison between low pitch angle electron fluxes measured by MagEIS and the EPT is also performed in different locations of the outer belt. This comparison is displayed for three "slices" of the outer belt (i.e. $L \pm dL$ with $L = 4, 5, 6$) and for two energy ranges in Figure 3.7. Like in the precedent figure, hour-averaged fluxes of level 2 MagEIS data are plotted in blue to allow a direct visualisation of the effect of the pitch angle on MagEIS measurements and on the comparison with low altitude observations. The slope of the regression line is again lower than unity for all L values and for all energies. This shows that, except for dropouts, the variation of the low pitch angle electron fluxes near the equator is faster and reach higher intensity than at low altitudes. However, this figure shows that the effect of the pitch angle is not the same at all L values in the outer belt. Independently of the energy, the left shift of the point distribution of low pitch angle electron fluxes compared to that of electrons with all pitch angle values is larger as the L value increases. Thus, intensity of the electron fluxes measured by MagEIS is more reduced in the outer region of the outer belt when electrons with pitch angle of $\sim 8^\circ$ are measured by the instruments. Eventhough considering fluxes of electrons with low pitch angle values has less impact close to the inner edge of the belt, this region is affected by this restriction in the observed electrons. First, for electrons measured in the 604 keV channel, the range of the flux intensity is reduced for low pitch angle electrons. In this



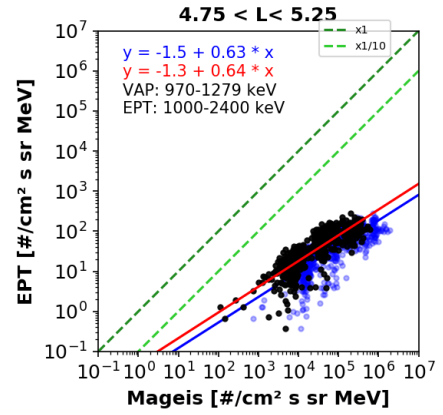
(a) corr = 0.88, SE = 0.016



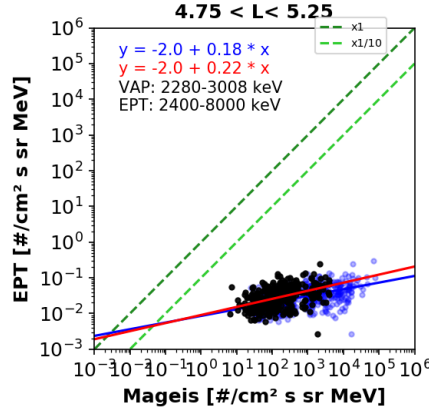
(b) corr = 0.83, SE = 0.019



(c) corr = 0.83, SE = 0.018



(d) corr = 0.83, SE = 0.020



(e) corr = 0.44, SE = 0.025

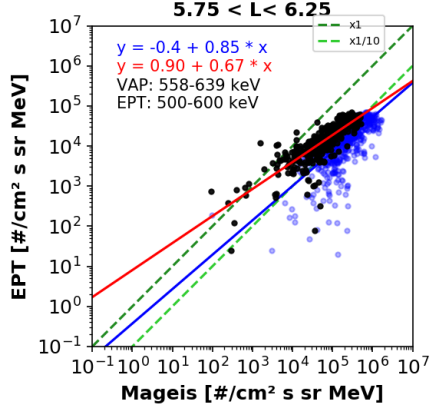
Figure 3.6: Same as Figure 3.2 but for level 3 data with low pitch angle ($pa \sim 8^\circ$) and level 2 data shown in black and blue respectively. Correlation and standard error are computed for low pitch angle $\sim 8^\circ$ fluxes.

case, the lowest MagEIS fluxes have a similar intensity as fluxes computed from the EPT. Note however that when using MagEIS flux measurements for low pitch angle electrons, the number of points in the comparison is lower, especially near the inner edge of the outer belt. This effect causes the lowering of MagEIS flux variation range. Nonetheless, the highest fluxes measured by MagEIS are slightly lower than for level 2 data. This is also observed for electrons measured in the 1064 keV channel. Independently of electron energy, at $L \sim 5$, the highest flux measured by MagEIS for electrons with pitch angle of $\sim 8^\circ$ is further reduced compared to spin-averaged fluxes. This difference is maximum at $L \sim 6$. This region of the belts is the one that is the most impacted by the restriction of measurements of low pitch angle electrons, not only in the flux intensity, but also in the shape of the distribution of points. It is clear from graph (a) and (b) of Figure 3.7 that fluxes of electrons with a pitch angle of $\sim 8^\circ$ measured at the equator is more susceptible to the smallest dropouts that occur in the outermost region of the outer belt and is in better agreement with the observations performed at an altitude of 820 km. Indeed, during the month of March, the dropouts that were not observed in the hour-averaged flux computed from spin-averaged data of MagEIS are now observed for low pitch angle electron flux. This lead to much less vertical structures on the scatter plot. Although less present, such structures can still be found on those two plots. On the one hand, for low energy electrons, the very intense dropout caused by the storms of February is again much more pronounced in the EPT measurements than for MagEIS. On the other hand, at $L \sim 6$ in January, two small dropout events were observed in electron fluxes measured by the EPT in channel 5, but in MagEIS observations of low pitch angle electrons in the 1064 keV channel, only one of those two events is seen. In this region of the belt, a substantial diminution of the slope of the regression line can be observed when taking low pitch angle fluxes rather than spin-averaged ones. This decrease is due to the reduction of the number of points corresponding to less intense or non observed dropouts by MagEIS compared to the measurements performed by the EPT. Because the lower regions of the outer belt are less impacted by the selection of low pitch angle values, such a variation of the slope does not appear at $L \sim 4$ and at $L \sim 5$.

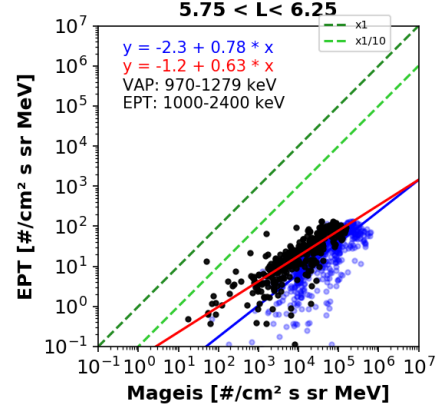
Evolution of the correlation in the outer belt

The evolution of the correlation between the hour-averaged flux computed from low pitch angle electron measurements of MagEIS in one energy channel and all channels of the EPT with respect to L is shown in Figure 3.8. The plots of this figure are the equivalent of the graphs seen Figure 3.4. For the three channels selected for MagEIS, the variation of the correlation with spin-averaged or small pitch angle fluxes is very alike. For the 604 keV channel, the diminution of the correlation with the EPT channels of increasing energy is also seen in Figure 3.8. Likewise, the reduction in the difference of the correlation between the channel 1064 of MagEIS and the first five channels of the EPT is observed in this figure. Regarding channel 2559 keV of MagEIS, the drop of the correlation with the EPT channels of energy lower than 2.4 MeV also appears clearly for low pitch angle electron fluxes.

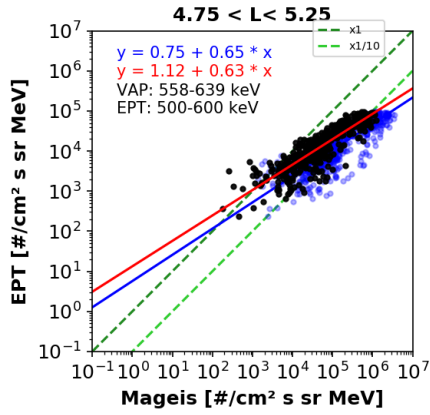
There are however some non negligible differences between the correlation of the EPT channels and MagEIS channels whether the pitch angle of the electrons is taken into



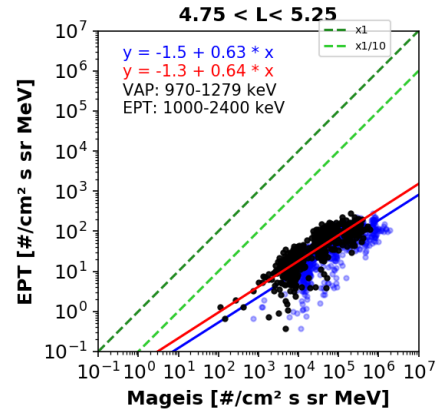
(a) corr = 0.81, SE = 0.025



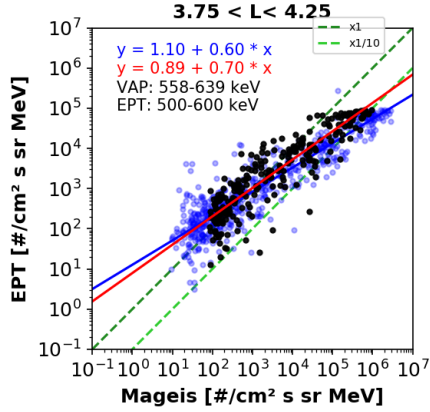
(b) corr = 0.82, SE = 0.023



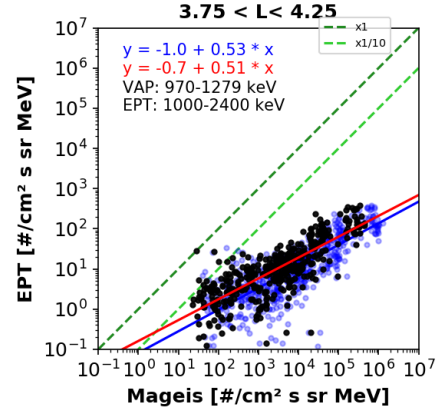
(c) corr = 0.88, SE = 0.016



(d) corr = 0.83, SE = 0.020



(e) corr = 0.90, SE = 0.021



(f) corr = 0.79, SE = 0.020

Figure 3.7: Similar figure as Figure 3.3. Black dots show hour-averaged fluxes computed with pitch angle resolved data ($pa \sim 8^\circ$). Blue dots show the averaged fluxes computed from MagEIS level 2 data. Correlation and standard error are computed for the pitch-angle resolved data. Data considered in this figure is taken between January and March 2014.

account or not. Starting with the 604 keV channel of MagEIS, compared to the spin-averaged results, an increase of the correlation is noticed with the first five channels of the EPT for large L values ($L \geq 5$). The rise of the correlation is larger as L becomes bigger, confirming that the consideration of low pitch angle electrons has a more important effect in the outer regions of the outer belt. Note however that for $L \leq 4.5$, the correlation with those channels is slightly decreased compared to the previous computations, but this decrease is much less important than the increase seen at high L . For instance, at $L = 4$ and for the 604 keV channel and channel 1 (500-600 keV) of the EPT, the correlation computed with small pitch angle fluxes is reduced by 0.02 while at $L = 6$, it grows by 0.11. Thus, the general diminution of the correlation with respect to L that appeared clearly in the first plot of Figure 3.4 is much less pronounced for low pitch angle fluxes. The correlation between the channel 6 of the EPT and the 604 keV channel is also much lower than with the other channels. Nonetheless, it is also improved in the outer part of the outer belt compared to previous computation. The correlation between the 1064 keV channel of MagEIS and first four channels of the EPT present a similar variation when it is derived with spin-averaged data or for small pitch angle electron fluxes. Note that the correlation with the 5th channel of the EPT is improved across the entire outer belt. The correlation between channel 6 of the EPT is also higher than with the 604 keV channel of MagEIS, but it is however more variable and reaches lower values than for level 2 data. Opposite to the 604 keV and 1064 keV channels of MagEIS, the correlation between the 2559 keV channel and channel 6 of the EPT is worse for all L in the outer belt when considering the low pitch angle fluxes for spin-averaged ones. In fact, this is the case with all EPT channels.

It is important to note that the number of points available to perform the comparison between the two instruments is lower when using the pitch angle resolved data from MagEIS. This is easily seen by comparing Figure 3.1 and Figure 3.5. In addition to that, as MagEIS channel energy increases, it lowers even further. While the number of points in comparison with low pitch angle and high energy electron fluxes is high enough to make the results statistically significant, it might have an effect of the correlation and the other parameters of the linear regression. The fact that the decrease in the correlation for small pitch angle fluxes occurs for every channels of the EPT seems to indicate that this is the case here. Nonetheless, the correlation between channel 6 and the 2559 keV channel is higher everywhere in the outer belt compared to the two other channels of MagEIS.

3.2.2 Integral flux comparison

Integral fluxes of electrons can be computed for both instruments by using Equation 1.32 in chapter 1. Because the integral flux is non longer dependent on the energy of the electrons, the comparison of the integral flux computed from EPT and MagEIS measurement is only performed for different values of the McIlwain parameter in the outer belt. As for the differential flux comparison, due to the nonidentical measurement frequency of the two instruments, fluxes are averaged over one hour. Thus, the integral flux (> 500 keV) is first calculated for each instrument and then, the average over one hour is performed. A similar analysis to that shown in Figure 3.7 was carried out but is not

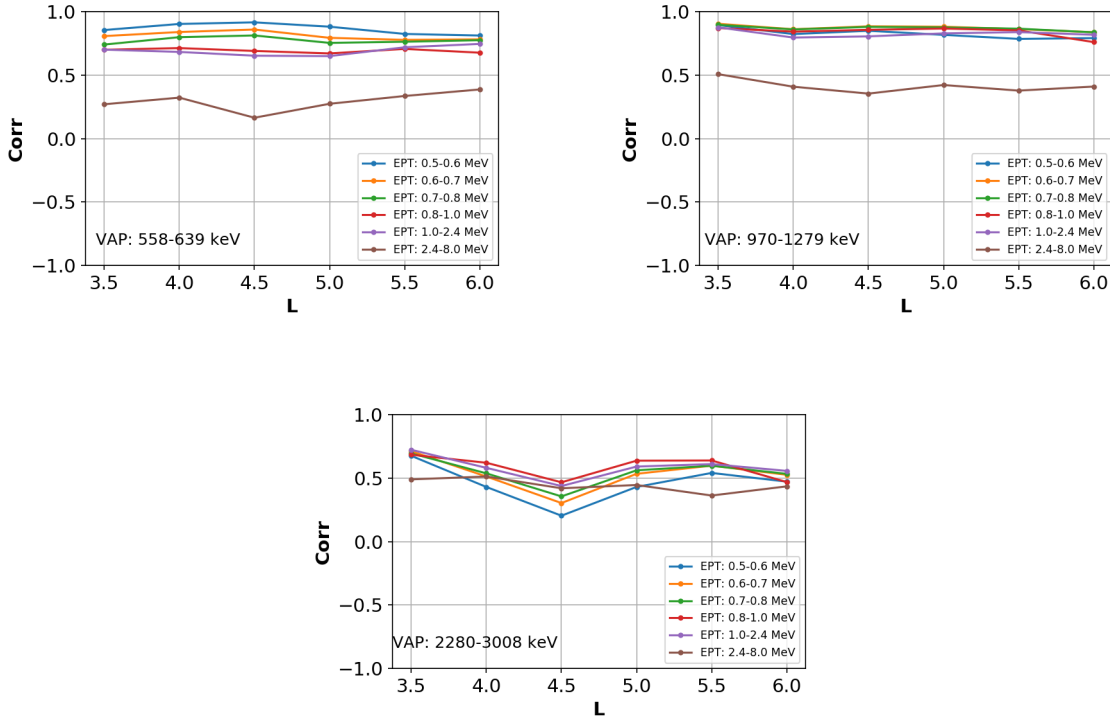


Figure 3.8: Evolution with respect to L of the Pearson correlation coefficient between the logarithm of hour-averaged electron fluxes computed from EPT data and MagEIS corrected data only considering electrons with a pitch angle of $\sim 8^\circ$. In each graph, one of the channel of MagEIS is compared to all energy channels of the EPT. 558-639 keV, 970-1279 keV and 2280-3008 keV channels are represented from top left to bottom respectively. The data used to produce this figure spreads from January to March 2014.

displayed here. The results are in agreement with the results obtained with the differential fluxes, which should not be surprising, as the integral flux is computed from the differential flux. The first observation is that the integral flux measured near the equator is almost always higher than that observed at low altitude. The only time that EPT fluxes are higher than the ones recorded by MagEIS is near the inner edge of the outer belt ($L \sim 4$), when both fluxes are relatively low. This is the case for both spin-averaged and low pitch angle electron fluxes. Also, the difference in flux intensity between the two instruments is reduced by considering flux of electrons with a pitch angle of $\sim 8^\circ$. Indeed at $L \sim 4 - 5$, while MagEIS spin-averaged integral flux is ~ 50 times higher than the integral flux computed with the EPT, small pitch angle fluxes are ~ 20 time higher. The same is true at $L \sim 6$ where MagEIS flux is ~ 30 times larger than for the EPT and becomes ~ 10 time larger when the integral flux is computed with $\sim 8^\circ$ pitch angle electrons. This also shows that in the outer part of the outer belt, the difference in flux intensity between MagEIS and the EPT is smaller than for the center and the inner part of the belt. This is true for both spin-averaged and pitch angle resolved data. As it was previously observed, the impact of the selection of low pitch angle electron fluxes is more important in the outer regions of the outer belt ($L \geq 5$). An improvement of the correlation is seen compared to the one computed with spin-averaged data, especially at

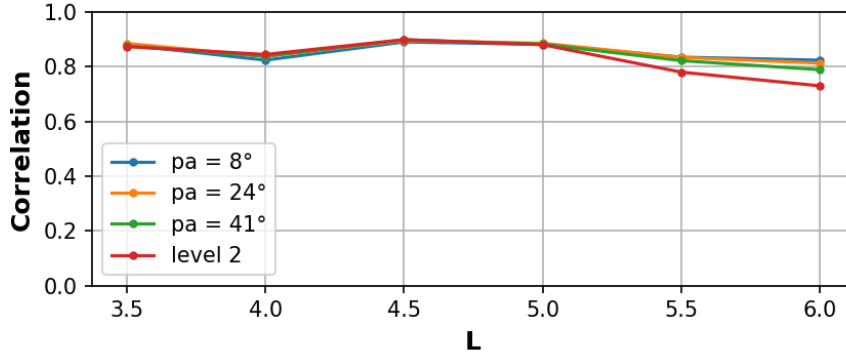


Figure 3.9: Evolution as a function of L of the correlation between the hour-averaged integral flux computed from the EPT data and hour-averaged fluxes from MagEIS for three different values of the pitch angle, as well as the spin-averaged data.

$L \sim 6$. Also, comparing small pitch angle fluxes with EPT observations at $L \leq 4.5$ leads to a very small decrease in the correlation.

The evolution of the correlation between the integral flux computed with MagEIS and the EPT as a function of L is presented in Figure 3.9. The correlation is computed for spin-averaged data as well as for different pitch angle values, namely $\sim 8^\circ$, $\sim 24^\circ$, $\sim 41^\circ$. It appears on this figure that for $L > 5$, even by considering electrons with pitch angle $\sim 41^\circ$ significantly improve the correlation between the instruments. Moreover, by considering successively smaller values of the pitch angle, correlation is further increased, but its small decrease, observed near the inner edge also becomes more pronounced. Again, it is much smaller than the gain in correlation seen at large L values. Note that the small decrease of the correlation at $L \sim 4$ is most likely caused by the diminution of the number of points used for the regression with the decrease of the pitch angle.

3.3 Comparison with the data taken from October to December 2014

The same investigation as in the previous sections was conducted for data taken from October to December 2014. The magnetic activity during this period is quite different than the one observed between January and March. Firstly, the averaged Dst index is lower than during the previous period and the measurements of the electron flux is higher for both instruments. Secondly, no storms like the ones of February are recorded in last three month of 2014, but two smaller events took place November 10 and December 21. Those events are associated to relatively strong dropout events observed by both instruments. Those storms were however not strong enough to inject electrons in the slot region.

3.3.1 Comparison of the differential flux

While notable differences between the comparison of the two instruments arise when compared to the earlier data set, some of the general behaviour of electron flux remains

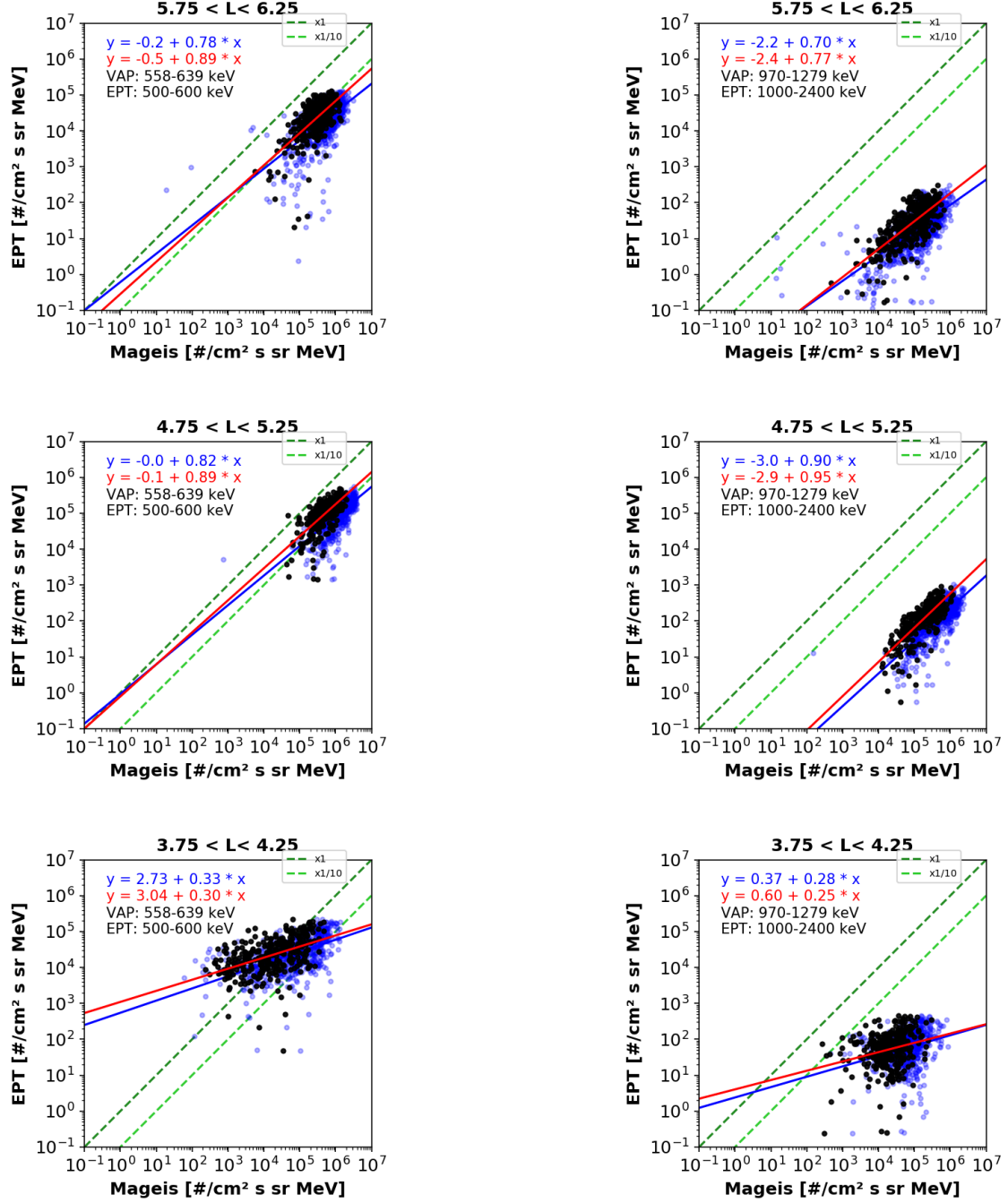


Figure 3.10: Same as Figure 3.7 but for data taken from October 1st to December 31st 2014.

true in this case. Namely, the much faster decrease in the differential flux intensity at low altitudes than near the equator with increasing energy, as well as the reduction in the difference in the intensity between EPT and Mageis averaged fluxes for low value of the pitch angle. Moreover, the vertical structures found in the previous scatter plots also appear in the distribution of points for $L \geq 5$ during this period. In addition to the dropouts caused by the two storms, a large number of smaller scale dropouts are observed throughout those months by the EPT. The intensity of those minor events is

considerably lower near the equator when using spin-averaged measurements of MagEIS. As shown in Figure 3.10, if MagEIS fluxes of low pitch angle electrons ($pa \sim 8^\circ$) are considered, the difference with fluxes measured by the EPT during dropouts is reduced. Only the dropouts associated with the two storms are much more intense at low altitudes.

The quantities computed with the linear regression on this new data set are however quite different than for the first three months of the year. The slope and the intercept of the line are directly given on the panels of Figure 3.10, blue for spin-averaged fluxes and red for low pitch angle fluxes. The correlation between the hour-averaged fluxes as well as the standard error of the slope are given in Table 3.1. The scatter plots displayed in Figure 3.10 show that for both low altitude and near the equator, the intensity of the flux is higher during those three months than previously observed. Moreover, it is quite visible that the variation range of the flux in this time interval is much smaller than in Figure 3.7, especially at $L \sim 4$. This can be explained by the difference in the location of the inner edge of the outer belt during the two periods considered. It is seen in Figure 2.1 that between January and March 2014, the position of the inner edge can reach the shell $L \sim 5$. When this occurs, electron fluxes measured at $L \sim 4$ are similar to that of the slot region. This behaviour is not observed between October and December leading to higher fluxes and reduced variation ranges for both instruments. However, the variation of the flux observed near the equator is much larger than at low altitude. This is the reason why the slope of the linear regression for this period is so small compared to the previous observations. Conversely, at $L \sim 5 - 6$, the slope of the regression is close to one for most channels, showing that the variations in the flux measured by both instruments are more alike in the outer regions of the belt.

		Level 2		pa = 8°		pa = 24°	
		corr	SE	corr	SE	corr	SE
L = 6	500 keV	0.62	0.034	0.65	0.053	0.66	0.046
	1000 keV	0.70	0.025	0.73	0.037	0.73	0.032
L = 5	500 keV	0.66	0.042	0.66	0.059	0.69	0.043
	1000 keV	0.76	0.030	0.77	0.046	0.80	0.033
L = 4	500 keV	0.55	0.020	0.47	0.033	0.54	0.024
	1000 keV	0.26	0.043	0.24	0.058	0.24	0.046

Table 3.1: Table giving the Pearson correlation coefficient and the standard error of the slope of the regression line between EPT and MagEIS hour-averaged differential electron flux at three locations of the outer belt. The parameters are given for two energies. They are also given for spin-averaged (level 2) MagEIS fluxes as well as for two values of the pitch angle.

The effect of the pitch angle selection on the correlation between the observations of the two instruments is similar than previously reported. If low pitch angle electron fluxes are considered, the correlation between fluxes at low altitudes and near the equator is improved in the outer regions of the outer belt, for values of L above 5. For the lower regions of the outer belt, a slight decrease is also observed (see Table 3.1). Note however that the correlation in this case is better for fluxes of electrons with pitch angles of $\sim 24^\circ$ rather than $\sim 8^\circ$. The reason for this is that as the pitch angle of electron decreases, the

frequency of missing data in the corrected measurement of MagEIS is higher. In addition to that, during the month of December, a very large fraction of the measurements is missing. This issue has much less impact for electrons with pitch angle of $\sim 24^\circ$. It explains the fact that for the minimal pitch angle value, the error on the slope is maximum everywhere in the outer belt and for both energies.

3.3.2 Comparison of the integral flux

Integral fluxes were also computed for both instruments during this period of time. The results of this comparison are very similar to the observations made with differential fluxes. Fluxes of electrons with an energy above 500 keV is also always higher near the equator, for both spin-averaged and pitch angle resolved data. However, the difference between the flux intensity measured by the EPT and MagEIS is reduced when considering electrons with low pitch angle values. For instance, spin-averaged fluxes of MagEIS at $L = 4, 5, 6$ are respectively 16, 42 and 60 times higher than for the EPT. But for pitch angle of $\sim 8^\circ$, MagEIS fluxes are respectively 6, 20 and 30 times higher than fluxes of the EPT. At $L \sim 4$, the correlation between the averaged integral fluxes of the two instruments is greatly reduced compared to the previous time period. This drop of the correlation is well observed on Figure 3.11, showing the evolution of the correlation between the hour-averaged integral fluxes measured by the EPT and MagEIS. As in Figure 3.9, the correlation is computed at different positions in the outer belt and for different values of the pitch angle for MagEIS measurements.

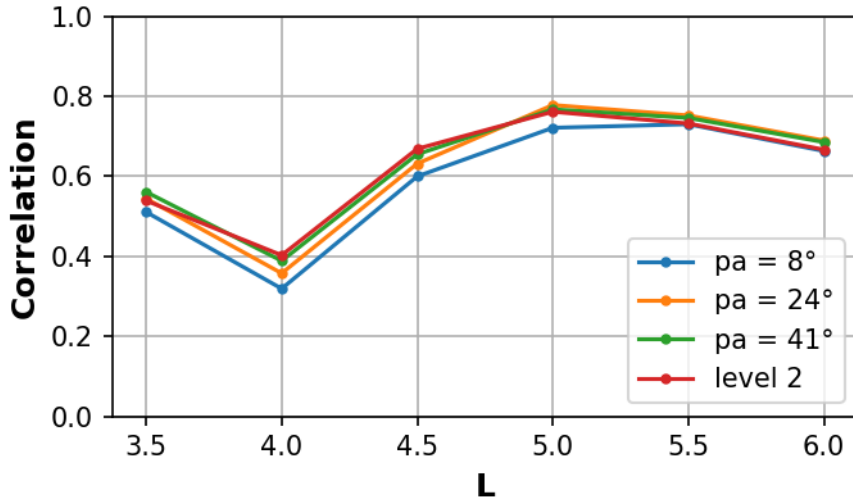


Figure 3.11: Same as Figure 3.9 with data taken from October to December 2014.

This figure shows that the minimum value of the correlation is reached at $L \sim 4$, independently of the pitch angle. Again, for all pitch angle values, the correlation increases to higher values as L becomes larger. The correlation is the highest in the middle of the belt at $L \sim 5$. The effect of the pitch angle on the correlation is also clearly seen in this graph. However, it is different than for the comparison from January and March. The best correlation at high L values is not obtained for the lowest value of the pitch

angle. Moreover, the correlation between the observations of the EPT and MagEIS is the lowest in most of the outer belt in this case. While a small decrease of the correlation was expected at $L \sim 4$, the correlation at higher L values is also reduced. The decrease at almost all locations of the belt is mainly due to the lack of measurements of low pitch angle electron fluxes during this period of time. That said, note that as in Figure 3.9 the correlation for $L \geq 5$ is improved when considering pitch angle of $\sim 24^\circ$ and $\sim 41^\circ$ compared to the correlation with spin-averaged data.

This figure shows that the correlation between the two instruments is largely decreased for the data taken between October and December compared to the results obtained for the first three months of the year. This drop of the correlation occurs everywhere in the outer belt, but especially near the inner edge. The decrease of the correlation could have two origins. The first cause can be the effect of the incident of the EPT leading to a poorer correlation between the measures. The second and most probable cause is the difference in the magnetic activity of the two time periods considered in this work. Indeed, the large variations observed in the flux of electrons during the storm of February by both instruments can be responsible for the improvement of the correlation. This can explain the drastic drop observed at $L \sim 4$, location at which the variations in electron flux differ the most between the two time periods.

3.4 Conclusions

The comparison of the measurements of energetic electron fluxes in the outer radiation belts was conducted with the use of two science class spectrometers, namely the EPT and MagEIS. This comparison was performed for various electron energies and locations in the outer belt. Moreover, the effect of the pitch angle for near equatorial electrons was tested for different time periods of the year 2014. An initial comparison of the level 2 hour-averaged differential flux from MagEIS and measurements of the EPT showed a decrease of the flux intensity with increasing energy. However a much faster drop in the flux intensity is observed at low altitude. This comparison also shows that the variation range of the flux is larger close to the equator than at low altitude. It is captured in the fact that the slope of the regression line is always smaller than one. However, it is quite apparent on the scatter plots that the observations of dropout events are not the same for the two instruments. This difference in the measurement of those events is reflected by vertical structures on the scatter plots, showing sharper decrease of the flux at low altitude. It also causes a diminution of the correlation and a larger error on the slope of the regression line. However, the difference between the observations is attenuated when comparing low altitude fluxes with equatorial fluxes of low pitch angle ($\sim 8^\circ$) electrons. Consideration of low pitch angle electrons has two distinct effects on the results of the comparison. The first one is the reduction of the difference in flux intensity measured by the two instruments at all energy levels and at all L values. Such a reduction in flux intensity is also observed for the integral flux, but equatorial low pitch angle fluxes remain one order of magnitude higher than those at low altitude in the outer belt. The second effect is the reduction of the number of vertical structures associated with dropout events, showing that they are more alike than for spin-averaged data. However, during more intense storms like the ones of February, the flux decrease

remains more important at low altitude. An other important result of this comparison is the evolution of the correlation in the outer belt and the effect of the pitch angle on it. For spin-averaged data, between January and March, the correlation between the integral flux of the two instruments is above 0.8 in the inner region of the outer belt and then decreases for higher values of L . It is clear that when considering low pitch angle electrons, the correlation in the outer region of the outer belt is significantly improved. The results obtained here ($\text{corr} > 0.8$ for all L) are comparable to the results of the comparison of the measurements of MagEIS and Arase which have a similar orbit to the Van Allen probes [Szabó-Roberts et al., 2021]. Eventhough the correlation is found to be high in the outer belt for the period between January and March, such results were not found for the observation between October and December. In this case, the correlation is lower ($\text{corr} < 0.8$) at every L values and a major decrease is found at $L \sim 4$. This decrease in the correlation is most likely due the magnetic activity difference between the two periods considered. However, the comparison of low pitch angle electrons ($\sim 24^\circ$) leads to an improvement of the correlation at high L values. Largest error on the slope of the regression line and generally poorer correlation were found for $\text{pa} \sim 8^\circ$ due to a larger number of missing data for this low value of the pitch angle during this time period.

Chapter 4

Conclusions and perspectives

High resolution and high fidelity observations of the terrestrial radiation belts are performed by science class spectrometers, which purpose is to measure the flux of energetic particles present in the belts. Those instruments are carried by satellites whose orbit can be very different while still being able to probe a large fraction of the belts. In this framework, measurements from the Energetic Particle Telescope (EPT) onboard the PROBA-V satellite were used to study the dynamics of the radiation belts at an altitude of 820 km throughout the year 2014. This year was particular for the EPT because of the unexplained issue that occurred on one of its sensors in June, resulting in a lack of observations for several months. As of mid September, recordings of electron and proton fluxes can again be used for the purpose of this work.

The main features of the radiation belts and the events leading to the perturbation of this system are discussed in chapter 2. Moreover, observations performed at low altitude are directly compared to NASA AE8/AP8 model of the radiation belts. High electron fluxes are measured in the polar horns, corresponding to the penetration of the outer belt at low altitude, as well as in the South Atlantic Anomaly (SAA). Flux intensity in the SAA is lower than in the horns, but is much more stable in time. The variation of electron flux in the outer belt is strongly dependent on the magnetic activity, which can be characterized by the Dst index. Dropout events, i.e. very fast and intense decrease of electron fluxes are frequently observed at high L values, near the outer edge of the outer belt. Depending on the strength of the storm, dropouts can occur at L values as low as $L \sim 4$. For intense storms, like the one of February 19, injection of electrons in the slot region are observed. Fluxes in the inner belt only increase during extreme events, when injection of electrons are able to reach this region, which did not occur in 2014.

Opposite to electrons, protons are not found in the outer belt during quiet periods of time. However, when Solar Energetic Particle events take place, injection of energetic protons from high L values to low ones are observed. Such events were observed in January 2014. EPT measurements during this period show that proton fluxes in the SAA remained constant during this event.

A direct comparison between the integral fluxes calculated from EPT measurements averaged on longitude-latitude bins and the NASA model was also conducted. This was done for both protons and electrons observations. It is clear that the model captures

well the main features of the belts as they are observed at low altitude. However, it also appears clearly that this model cannot reproduce flux variations observed during geomagnetic storms or SEP events. Simulated electron flux intensity is in general slightly higher than measured ones in the horns and more than one order of magnitude in the SAA. Flux intensity is better simulated for protons, given the very stable nature of this population in the inner belt. The main difference between the model and measurements of the EPT are caused by a difference in the shape and position of the horns and of the SAA.

Observations of electrons flux provided by the Magnetic Ion Spectrometer (MagEIS) in the outer belt during 2014 were used to perform a comparison with the measurements of the EPT at low altitude. Unlike the PROBA-V satellite, the two Van Allen Probes which carry the MagEIS instrument are on an elliptical orbit near the magnetic equator. However, even if the two instruments are far away from each other, they are able to probe electron fluxes on the same magnetic shells. A comparison of the observations from both instruments were conducted on three months periods for various electron energies, locations in the outer belt and for several value of the pitch angle (for MagEIS measurements). As expected due to trapped particle trajectories, flux intensity in the outer belt is found to be higher near the magnetic equator than at low altitude, even when considering low pitch angle electrons only. However, the difference in intensity is smaller for electrons that have a pitch angle of $\sim 8^\circ$ than for spin-averaged measurements. Moreover, both instruments show a decrease of the flux intensity as the energy becomes larger. This decrease appears to be much faster for the EPT than for MagEIS, leading to a larger difference in the differential flux intensity in the channels of higher energy. The comparison also shows that the variation range of the flux is larger near the equator than at low altitude (slope of the regression line < 1), except during dropout events. For higher L values (mostly at $L \sim 6$ but also at $L \sim 5$) and for level 2 data of MagEIS, the drop in the flux is much more important and more frequent for the EPT. This difference in the observations leads to characteristic vertical structures in the flux-flux plots presented in chapter 3. However, for low pitch angle electron fluxes at the equator, observations of dropouts are more similar to ones seen by the EPT, except during the intense storms of February for which significant deviations between the two instruments remain. The Pearson correlation coefficient was computed as a function of L and for different value of the pitch angle. For the data taken between January and March, it is clear that the correlation is improved by considering low pitch angle electron fluxes with MagEIS. The increase in the correlation is higher at larger L values and is maximum for the lowest value of the pitch angle ($\sim 8^\circ$). In the latter case, the correlation between the two instruments is high (> 0.8) for all L. For the data taken from October to December, the correlation is found to be smaller through the outer belt, even for low pitch angle values. A very important drop in the correlation is noticed at $L \sim 4$, which is mostly likely due to the magnetic activity of this time period rather than an impact of the issue of the EPT. Nonetheless, an increase of the correlation is still observed at high L when taking low pitch angle fluxes into account.

The two time periods that were used in this work to perform the comparison between the instruments feature a very different magnetic activity and were taken prior and after

the issue of the EPT. In order to evaluate the impact that this incident had on the measurements of the EPT, it is necessary to find time periods that have a similar magnetic activity before and after the incident. This was not possible to do for the year 2014. However, it might be possible to find such time intervals by considering other years of simultaneous observations by the EPT and MagEIS. Moreover, considering longer periods of time would increase the number of points available for the comparison. Indeed, with the time period considered in this work, the number of points available for the lowest values of the pitch angle was relatively low, especially in December. This could also contribute to a reduction of the error on the slope of the linear regressions.

A similar comparison to the one presented in this work can be done in the inner belt, however, additional pre-processing of the data must be performed. Because the EPT is only able to record fluxes in the SAA, much longer time periods are needed to conduct this comparison. Nonetheless, the advantage of a comparison in the inner belt is that the instruments are physically closer from each other, and should measure fluxes in a similar region of space. This could give additional insight on the calibration of the instruments and on the potential effect of the issue of the EPT on the data.

The amount of simultaneous observations of the radiation belts by the EPT and MagEIS gives the opportunity to pursue this investigation in greater details which could lead at the same time to a better understanding of the very complex magnetic environment of the Earth.

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