Outer radiation belt dropout on September 12, 2014

Livia R. Alves, Ligia A. da Silva, Vitor M. Souza, Paulo R. Jauer, Luis E. A. Vieira, Marcos V. D. Silveira, Marlos Rockenbach, Alisson Dal Lago, Instituto Nacional de Pesquisas Espaciais

Abstract

Solar wind variations and magnetospheric processes result in a dynamic electron population within the outer Van Allen radiation belt, where electron energies range from several 10's to several 1000's KeV. Geomagnetic storms and various solar wind-magnetosphere interaction processes including convection cause either dramatic particle flux increase or decreases. Here we analyze the occurrence of a drop out of ~ 0.04 – 4.5 MeV electron fluxes measured by NASA's Van Allen Probes, during a magnetic cloud-driven geomagnetic storm which started at September 12, 2014. The ~3-day storm left a steady low flux of outer belt energetic electrons that lasted for twelve days. At higher energy levels, electron fluxes decreased by ~1 orders of magnitude throughout the vast region from L* ~3 to 6.6. To describe the physical mechanism associated to the loss observed at L* higher than 4, it was simulated electron trajectory using TS95 and self-consistent BATS-RUS models of magnetic field during the shock, the results are consistent with the magnetopause shadowing.

Introduction

The high energy particles closer to the Earth are trapped by the geomagnetic field in the region known as the radiation belts. Their guiding center motion can be decomposed into three components: gyro-motion around magnetic field lines, bounce-motion between magnetic mirror points located in either hemispheres and azimuthal gradient-curvature drift in the inner magnetosphere around the Earth. These periodic motions are associated to constants of motion, or adiabatic invariants. The regime of validity of the adiabatic invariants is sustained whenever the characteristic times for appreciable variations in either electric or magnetic fields are higher than those of the periodic motions. The first invariant is associated with the particle gyro-motion and conserves the magnetic moment of the particle in the direction perpendicular to the magnetic field. The second invariant is associated with the bounce-motion between the mirror points. Considering the first invariant is also conserved, the relationship between these invariants can also be expressed as the kinetic energy invariant. The third invariant conserves the total magnetic flux enclosed within a drift shell. An adiabatic variation at the radiation belt is observed when changes at magnetospheric physical parameters are observed on a time scale longer than electron bouncing, azimuthal drift or gyro motions. Usually fully adiabatic changes are observed during geomagnetic storms and they are completely reversible when the external forces disappear. The radial diffusion of fixed energy electrons observed during the main and recovery phases is an example of adiabatic motion, and it is known as 'Dst effect'.

The physical mechanism involved in the loss and acceleration processes responsible for the electron high energy outer belt dynamics can be understood as a result from solar wind and magnetospheric coupling. Special conditions of solar wind parameters caused by, e.g. magnetic clouds, fast streams, corotating steraction regions, coronal mass ejection, are responsible for geomagnetic storms observation inside magnetosphere.

Reeves et al. 2003 analyzed the flux variation of relativistic electrons related to more than 250 geomagnetic storms, they verified that only in a quarter of these events the fluxes are decrease, in a way that is not directly related to the strength of the storm.

Solar wind contribution to the loss observed at the outer radiation belt is mostly related to the generation of ULF waves at the magnetosphere (Turner et al., 2012; Kellerman et al., 2012), magnetospheric convection associated with Bz orientation (Baker et al., 2014) and magnetospheric shadowing associated with solar wind dynamic pressure and velocity (Shprits et al., 2012).

In this work, we analyze the occurrence of a drop out of ~ 0.04 – 4.5 MeV electron fluxes measured by NASA's Van Allen Probes, during the geomagnetic storm which started at September 11, 2014. We verified the occurrence of magnetopause shadowing by integrating the Lorentz's force equation for the magnetic field condition generated by self-consistent BATS-R-US observed during the coronal mass ejection shock.

Method

The observational results were obtained using data from the Relativistic Electron-Proton Telescope (REPT), onboard the Van Allen Probes (VAP) A and B, provides particle energy flux measurements at the Van Allen Probes (former known as RBSP) equatorial orbit. Energy data are available from around 1,5 MeV up to 20 MeV with a 25% of energy resolution. Electrons pitch angle information is also provided in detail (Baker et al., 2013). Data from electron flux REPT A and B obtained during September 11-18, 2014 (Figure 1) show high energy electron flux dropout associated with the geomagnetic storm which started at Sep 12 at 1555 UT, when the spacecrafts were at the dusk side.

For investigating the magnetopause shadowing hypothesis one needs to determine the azimuthal drift orbit of an equatorially mirroring electron during the time when the magnetosphere was most compressed due to the arrival of the ICME's shock. We have run the global 3D MHD BATS-R-US (Tóth, 2011; Tóth et al , 2005; . 2012; Gombosi et al., 2001), to obtain a topological configuration of the geomagnetic field during the arrival of the September 12, 2014 event for the most disturbed (dynamic pressure ~14 nPa) condition. The model was stabilized at the steady state (Toth , 2012). The solar wind input parameters were the following: density = 19.92n/ cc, Temperature = 10^5 K, velocity (Vx) = -621.47 km/s, and the magnetic field components (Bx,By,Bz) = (-9.63,13.48,11.20) nT. These configuration was applied to obtain a more realistic configuration of the near-Earth environment. In particular, the IMF value used for running the code was, it was in accordance to the satellites observations. The next step was to integrate the relativistic Lorentz equation

$$\frac{dV}{dt} = -\frac{q_e}{\gamma m_e}\left(\vec{V} \times \vec{B}\right) \qquad (1)$$

for a 90° degrees pitch angle electron with relativistic energy using as input the magnetic field B modeled by BATS-R-US. In equation (1), $\gamma = 1 + E/m_e c^2$ is the Lorentz factor, E is the electron energy chosen to be 2 MeV (lowest energy channel covered by REPT), m_e the electron rest mass, q the electron charge, c the speed of light, and V the electron velocity.

We start the electron's orbit integration at the point (X,Y,Z) GSM = (-8,0,0) Re. Equation (1) is solved by means of a fifth-order Runge-Kutta method. The electron drifts towards the dawnside magnetosphere, as expected. When it reaches the modeled BATS-R-US magnetopause at (X,Y) ~ (-2,-8) Re the electron undergoes a sharp change in its orbit, i.e., its guiding center moves towards increasingly negative values of the Z_GSM coordinate while drifting to the noon-midnight meridian. The electron encounters the southern cusp and escapes to the magnetosheath region. Such a scenario corroborates the idea that relativistic, equatorially mirroring electrons could be lost to the magnetosheath region during periods when the magnetosphere is under major compression, thus validating the magnetopause shadowing hypothesis.

Results and Discussions

According to the REPT data (Figure 1), the dropout started with the first shock registered on September 11, at 2346 UTC with a sudden impulse; a second shock was registered on September 12, around 1555 UTC. We consider the dropout has started just after the first shock observed at Sep 11, when the high energy electron flux decreases. The geomagnetic activity for the first half of the day 12, expressed by Kp, was lowered from 5+ (high magnetospheric convection) to 3 (lower magnetospheric convection), according to Brautigam et al., 2000, this imply in a decrease of two orders of magnitude at the diffusion coefficient, weakening the diffusion performance at the loss process.

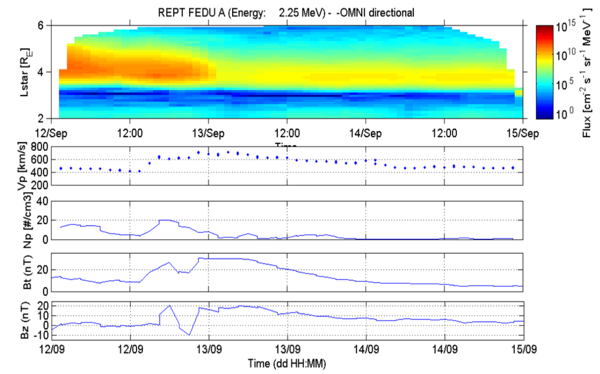

Figure 1: Radiation belt dropout observed from Van Allen Probes data on the top panel, the following panel are the solar wind velocity, density, total magnetic field and north-south component.

The second shock, corresponding to the strongest phase of the dropout, was observed at this second period. Kp was increased from 2- to 6+ the most disturbed period of the event, however, the diffusion coefficient for L between 3 and 4 is around 10-2 – 10-1/day, it means that it will be necessary several days to dropout inner belt adiabatically. The evolution of the geomagnetic index associated to the storm phase is shown in Figure 2.

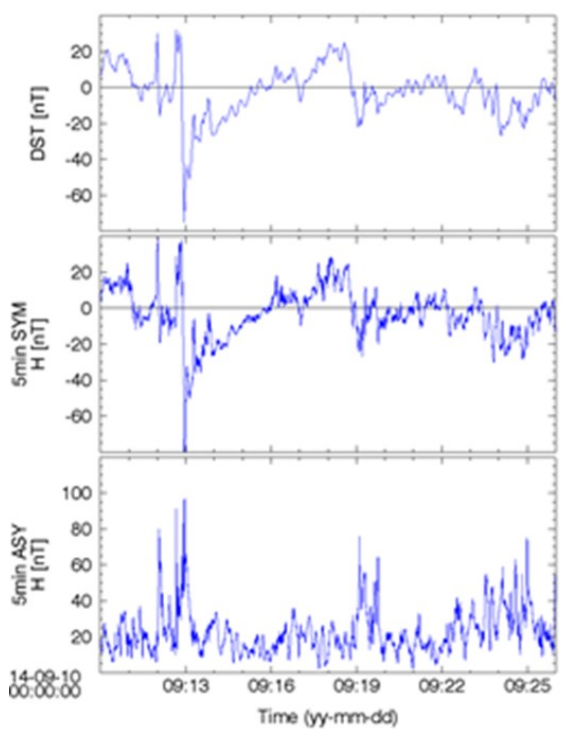

Figure 2: Dst, SYM and ASY index for the complete geomagnetic storm.

The magnetic field observed during the shock associated to the storm was applied to verify the electron loss to the magnetosphere boundary, we start the electron's orbit integration at the point (X,Y,Z) GSM = (-8,0,0) Re.

Equation (1) is solved by means of a fifth-order Runge-Kutta method. The electron drifts towards the dawnside magnetosphere, as expected. When it reaches the modeled BATS-R-US magnetopause at (X,Y) ~ (-2,-8) Re the electron undergoes a sharp change in its orbit, i.e., its guiding center moves towards increasingly negative values of the Z_GSM coordinate while drifting to the noon-midnight meridian. The electron encounters the southern cusp and escapes to the magnetosheath region. Such a scenario (Figure 3) corroborates the idea that relativistic, equatorially mirroring electrons could be lost to the magnetosheath region during periods when the magnetosphere is under major compression, thus validating the magnetopause shadowing hypothesis.

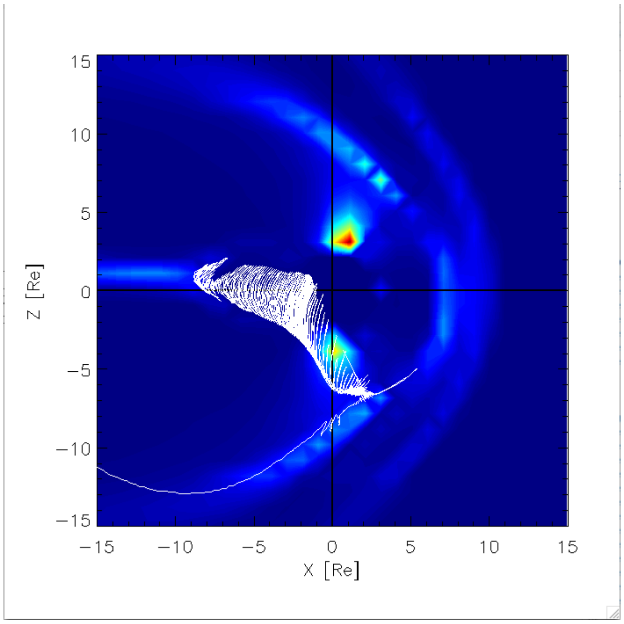

Figure 3: Magnetic field intensity at the magnetosphere for the shock condition, superposed to the electron trajectory coming from midnight to noon.

Conclusions

This results is first one of a series from the simulation associated to the observed electron flux variation by Van Allen Probes can be associated to the magnetopause shadowing phenomena described as been one of the mechanisms for the electron loss at the outer radiation belt. Another simulation run is in progresses taking to account the different pitch angles observed at the electrons distributions, besides the particles local time and geomagnetic storm phase. The test with these other particles parameter will enable us to quantify the loss due to magnetopause shadowing and the changes associated to the magnetic field intensity, particle position and local time on the particles trajectory at the radiation belt.

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