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A radiation belt disturbance study from the space weather point of view

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ABSTRACT

The radiation belts are a key region located close to the Earth, where the satellites travel. They are located in the centre of the magnetosphere and constitute a region sensitive to the variations of magnetosphere activity. The magnetosphere is in equilibrium in the solar wind. If the solar wind parameters change, then, the magnetospheric balance is upset. Using several processes, particles and energy from the solar wind can enter it, disturbing the magnetosphere and the radiation belts. In this paper, the am index has been used to define a new parameter named Cm, which is indicative of the energy level in the magnetosphere. The impact of CIRs (Corotating Interaction region) and of CMEs (Coronal Mass Ejection) on the magnetosphere has been studied from the Cm point of view, as well as the reaction of the radiation belts to a solar wind disturbance. The results show that the Cm parameter provides a new perspective in space weather studies as it clearly shows that the energy level can be higher for a CIR than for a CME. It also demonstrates that the events with several solar wind structures are much more effective to increase the energy level in the magnetosphere than single ones. Finally, Cm correlates better with the radiation belts fluxes, showing again that Cm is a good indicator of the inner magnetosphere activity. Nevertheless, the energy level in the radiation belts is maximised and the energy level in this population cannot go above a given value which depends on the altitude. The particles coming from the plasmasheet also push the particles from the highest altitudes to the lower ones, allowing the slot filling for $Cm > <Cm>$.

1. Introduction

Space weather is a branch of the magnetospheric physics which started to develop in the 1990s. The purpose is to understand the solar wind variation by observing the Sun and the magnetospheric variation due to the solar wind disturbances. The final objective is to predict the magnetospheric state several days in advance only by observing the Sun. Nowadays, it is quite difficult to predict it as the Sun/solar wind/magnetosphere system is not fully understood [1]. In order to understand the full system, studies are being made about the Sun physics, the solar wind propagation, the impact of the solar wind structures on the magnetosphere and their geoeffectiveness (ability of a structure to destabilise strongly and deeply the magnetosphere).

Being the deepest region of the magnetosphere, the inner magnetosphere is the last region to be impacted when the magnetosphere is disturbed. Usually, the geoeffectiveness of a structure is studied by using the Dst minimum value [2]: a very small Dst means a strong ring current disturbance, i.e. an inner magnetosphere strongly impacted and a very geoeffective structure. The radiation belts are located in the same region.

They are a key population located close to the Earth, where the satellites travel. Numerous studies about the geoeffectiveness of the structures using Dst have been published ([3–6], …). All of them present similar results. Nevertheless, the radiation belts are never accounted for, but satellites data analysis show that, most of the structures, geoeffective ones are inefficient to disturb the radiation belts, whereas little geoefficient structures are very efficient to disturb the radiation belts.

In this paper, the study of the impact of the solar wind structures is presented in a different way. Part II presents a new parameter defined from the magnetic index am, which allows accounting for the energy level in the magnetosphere. In this part, the new parameter is defined, and then examples of solar wind structures impact are shown. The third part is dedicated to the radiation belts relationship study.

2. A new way to estimate magnetic activity

2.1. Definition of Cm

Studies about magnetic activity usually use magnetic

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indices [7,8]. Depending on the phenomenon, global indices (Kp, Ap, Km, am, aa) or local ones (AE for auroral zone, Dst for the ring current one) could be used. Those indices are calculated using ground magnetometers which are located at the feet of magnetic field lines crossing different regions of the magnetosphere. The magnetic indices are calculated by estimating the variation of the magnitude of the horizontal component of the local magnetic field. It also allows estimating the distortion of the field line, which is directly linked to the variation of the current intensity [8] Magnetic indices also provide an indication about the energy entrance in a given current sheet located in a given region and so, about magnetospheric storms. If the outer magnetosphere is easy to disturb, the inner one needs much stronger solar wind disturbance to react. The magnetosphere is also a system which needs some time to come back to equilibrium, and the deeper it is disturbed, the longer it takes to recover. As a consequence, a solar wind structure has to be very geoeffective to really disturb the radiation belts located in the deepest magnetospheric region, and when those are disturbed, they need several days to recover. Several studies using CRRES (Combine Release and Radiation Effects Satellite), SAMPEX (Solar Anomalous and Magnetospheric Particle Explorer), SAC-C (Satélite de Applicaciones Cientificas -C) and DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Region) data show that, above L=2.5 Re, the recovery time for the electrons varies slowly on the energy, and is about 4 days long in for energy range between tens of keV to hundreds of keV [9–11]. So, two identical geoeffective structures impacting the magnetosphere in less than 4 days will impact the radiation belts in a different way than two structures impacting the magnetosphere in a longer period. The energy income from each structure will be the same, but the magnetosphere will react in different ways, as the magnetosphere is "empty" in the first case, but still absorbing the energy of the first structure when the second one arrives in the second case. We can also consider that there is a loading period during which the energy comes from the solar wind into the magnetosphere and an unloading one during which the magnetosphere recovers and absorbs the energy using several processes (waves, aurorae, loss in the ionosphere, …). As a heavy system, the magnetosphere reacts to a solar wind disturbance, with a delay during which the energy is spread within the magnetosphere or absorbed. The magnetic indices do not allow accounting for such an effect as they provide information about the magnetic disturbance and about the energy which is entering the current system.

Am magnetometers includes part of those used to derive Kp and Ap, and are located in the sub auroral region, at the feet of magnetic field lines which apex is located in a 1.42 Re to 3.36 Re L range [7]. This position allows adding the effects of the magnetic activity in the auroral zone to those in the equatorial zone. Am is also a good proxy of the magnetospheric disturbance. Moreover, due to the position of the magnetometers, it allows describing the magnetic field changes in the radiation belts region.

As it has been discussed, the magnetosphere can be described as a loading and unloading system, as well as a capacitor. By analogy, we use am to define a new parameter which will allow accounting for the relaxation time of the system and defined as:

$$cm(t) = \frac{1}{\tau}\int_{o}^{\infty} Am(t-t')\exp^{-t'/\tau}dt'$$

where τ is the relaxation time of the system. The am magnetometers are located in the foot of magnetic filed lines which L is between 1.42 R_e and 3.36 R_e. Moreover, it has been shown that the recovery time for the electrons above 2.5 R_e is about 4 days. As a first approximation, $\tau=4$ days has also been used in this paper, but modifying this value from 3 to 7 days does not change there results of the study. We can also notice that τ may be different depending on the physical process studied or the particle population. This part is out of the scope of this paper and will be part of a future study.

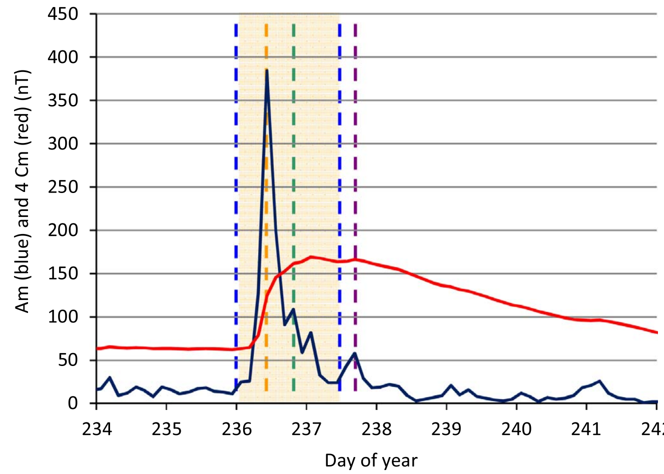

Fig. 1. CME impact on am (in blue) and in 4 Cm (in red) of the 23/24 August 2005.

2.2. Case events

The main solar wind structures are the CIRs (Corotating Interaction Region) and the CMEs (Coronal mass ejections). When they impact the magnetosphere, they are responsible for magnetospheric storms and substorms, which can be more or less intense depending on their structures [12–14]. In this part, three case events are described: a CME impact, a CIR one, and a multiple CME structure.

2.2.1. A CME impact example

Coronal mass ejections (CMEs) occur at the surface of the Sun and then travel in the interplanetary medium. Some of them encounter the magnetosphere [15]. They were shown to be very geoeffective [3,14,16,17]. Fig. 1 presents the evolution of am (in blue) and Cm (in red) during a CME impact. As it is much smaller than am, Cm has been multiplied by 4 to make it easier to compare. This CME has impacted the neck of the magnetosphere on the 23 August 2005 at 21 h UT, leading to a high magnetic activity level (maximum Kp value equals 8 and minimum of the Dst equals −170 nT). In the figure, the CME arrival is indicated by the strong increasing of am (left-blue dashed line). It reaches the maximum value after 12 h (orange dashed line). The very high am value (384 nT) is indicative of a strong magnetic disturbance. The Cm parameter starts to increase at the same time as am, showing that the CME acts as an impulse properly characterised by the am increasing, and a supply of energy within the magnetosphere. The Cm maximum is observed 26 h after the onset and 14 h after the am maximum. The loading phase is also longer than the am disturbance. A second small am maximum is observed 9 h after the end of the first one (green dashed line), due to small variations in the solar wind parameters. It is much smaller than the first one (109 nT). In reaction to this small impulse, the Cm gradient slightly increases, but it does not significantly change the average evolution of Cm.

The CME leaves the Earth environment on the 25 August 2005 at 6 h UT, a few hours after the second am maximum (right blue dashed line, the CME time range being shown by the yellow area), as confirmed by the solar wind data (not shown here). Am reaches a minimum showing the end of the magnetic disturbance, but Cm is still high showing that the energy is still stored in the magnetosphere. The unloading phase starts on the 25 August at