DYNAMIC MODELING OF THE HIGH ENERGY PROTON BELT

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ABSTRACT

Protons in the 10 MeV – 100 MeV range are normally very stable in the radiation belt. Such high energy particles are trapped in the belt for years. Nevertheless, during intense storm periods, their populations are modified. First they decrease at the outer edge of the belt, due to the magnetospheric modifications which correspond to the important changes in the magnetic field itself. They are lost in the interplanetary medium. On the contrary, in the case of a Solar Proton Event (SPE) associated with the arrival of a Coronal Mass Ejection (CME), solar high energy protons can be transported deeply in the magnetosphere, giving rise to a second belt in the 30 MeV range. That was seen on board CRRES (Combined Release and Radiation Satellite), not only during the March 1991 event, but also during smaller events (Ref. 1). Results of modeling these physical processes using the Salammbô code will be shown in this study.

1. INTRODUCTION

Charged protons in the magnetosphere are from different origins (see figure 1). First, the very low energy population

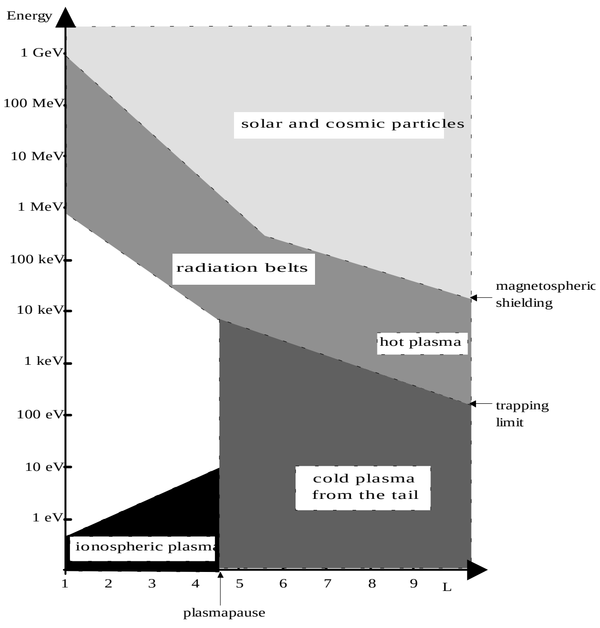

Figure 1. *Proton energy related to the McIlwain parameter in the inner magnetosphere.*

comes from the ionosphere and is confined into the plasmasphere. Second, cold and hot plasma in the plasmasheet for example are solar wind plasmas which have penetrated the magnetosphere maybe during reconnection events. These plasmas are accelerated in the inner magnetosphere, giving rise to the ring current and the low energy proton belt. Third, high energy protons have their origin in the Cosmic Ray Albedo Neutron Decay phenomenon (CRAND). Finally, very high energy protons can directly penetrate the magnetosphere, due to their very large Larmor radius. The boundaries between all these populations are subject to fluctuations, in particular during magnetic storms. At low energy (Ref. 2, 3), the boundary is related to the electric fields either convective or induced. This boundary, the plasmapause, can be pushed into the L = 2 region during intense activity period. This partially explains the rise of the ring current, which results in magnetic field modifications. At higher energy, changes in the boundary is related to those of the magnetic field itself. As a result for example, the magnetospheric shielding is reduced and very high energy solar protons can penetrate deeply in the magnetosphere. At the opposite, belt particles cannot be trapped anymore during magnetic activity periods, due to the opening of drift shells to the interplanetary medium (Ref. 4).

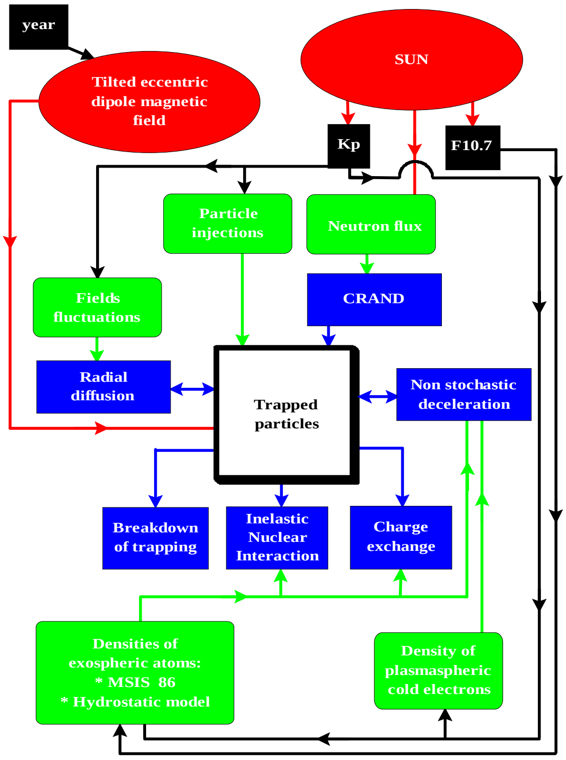

Figure 2. *Equatorial proton model : Salammbô 2D.*

All these processes, affecting the proton population, must be modeled in order to understand the dynamics of protons in the inner magnetosphere. Attempt to model some of these phenomena with simple parameters is explained here. First, we will show how the opening of drift shell to the interplanetary medium can flush all high energy protons from the belt. Second, we will see the consequences of solar protons penetration deeply in the magnetosphere. These processes have been modeled using the Salammbô 2D code, the two dimensions being the relativistic magnetic moment M and the McIlwain parameter L. This code has been already developed to explain low energy belt variations, using a Kp dependence of the radial diffusion coefficients (Ref. 2, 3). It solves the diffusion equation for equatorial protons from 1 keV to 300 MeV and from L equal to 1 to L equal to 7 in Earth radii (Re). This code takes into account the following physical phenomena (see figure 2). First, as sources, we have modeled the CRAND phenomenon and the low energy proton injections from the night side of the magnetosphere during magnetic storms and substorms. Radial transport, frictions (with neutral atoms of the exosphere and cold electrons of the ionosphere), inelastic nuclear interactions (with exosphere particles : H, He, Ar, N, N_2, O, O_2) are also introduced. Finally, we take direct losses by charge exchange with Hydrogen atoms of the exosphere and proton precipitation on the Earth at all latitudes. In this study, we tried to add in this code losses due to the opening of drift shells, magnetospheric shielding, and SPEs effects on the high energy proton belt.

2. LOSS PROCESSES MODELING

During high activity periods, the magnetic field can be intensively modified. Then high L shells can open to the interplanetary medium and particles trapped on those shells can be lost from the belt point of view essentially on the magnetopause (Ref. 4). We tried to model this effect using simple parameters from ground base measurements and the interplanetary medium.

To model this effect, a simple particle code was built, using different magnetic field models. Starting with a particle located near the magnetopause at noon, this code follows the particle along its trajectory (its drift shell). Then it is easy to calculate if the trajectory is closed or not. The first closed trajectory when the starting point is moved from outside the magnetopause to inside determines the limit between opened and closed drift shells. Then the magnetic flux inside the first closed drift shell can be calculated and the third adiabatic invariant (L) evaluated. Using an Olson Pfitzer dynamic model, the magnetosphere and the magnetopause depends on two different parameters (Ref. 5) : the solar wind pressure (SWP) and the magnetic index Dst. Then it was possible to calculate the L value of the first closed drift shell Llos depending on these two parameters.

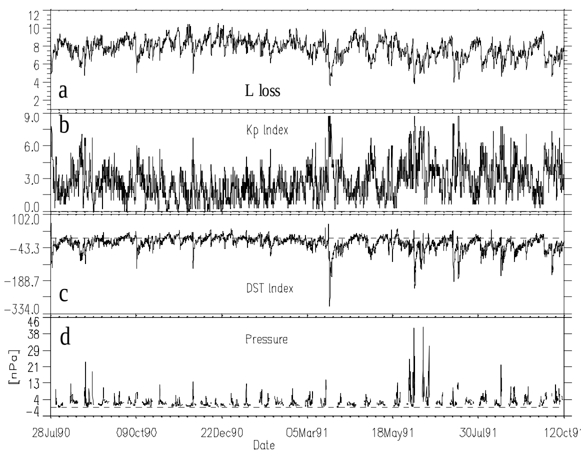

Figure 3. *Modeled losses (a), Kp (b) and Dst (c) geomagnetic indexes, and SWP (d) during the CRRES period.*

That was made for different magnetic fields, and the results are shown on figure 3. As our calculation depends not only on the solar wind pressure and Dst, but also on the magnetic index Kp, these three parameters were plotted on the figure 3 during all the CRRES live from OMNIWEB data. On this figure, the March, 1991 event is quite visible as the minimum Dst value (around Dst = -300 nT) and a big Kp value (around Kp = 9). Other magnetic activity periods are also seen on this figure, in May and June, 1991. The calculated Llos during all the period is plotted on the same figure. As the magnetic activity increases, Llos is decreasing, going from a mean value of nearly 8 down to L = 4 in the case of a big storm. In fact, on the OMNIWEB measurements, due to the orbital motion and problems on instruments, a lot of data are missing, which cannot permit to calculate the solar wind pressure. In these cases, Llos is certainly too high (in case of missing solar wind data, the pressure was fixed at 2.6 nPa which corresponds to mean values of 8 particles/cm^3 for the solar wind ion density and 450 km/s for the solar wind velocity). For example, during the March, 1991 event, the solar wind pressure is missing. If it was measured, the Llos would decrease below L = 4. In fact, looking closely at the measurements, it seems during this event that particles are lost down to around L = 2.7. It means that during intense periods, a big part of the belt is flushed (from L = 2.7 to L > 7) and new protons replace (at low energy) the old population during the same event. But what about high energies? In fact, this loss process does not depend on energy, the lost closed drift being the same for all the particles. Nevertheless, the drift period of low energy particles is much longer that those of high energy at the same L. It means that high energy particles can have enough time to be lost, while part of low energy particles are still trapped when the disturbance is finished. But if the magnetic field is disturbed for hours, particles are all lost. In particular, very high energies can be lost at the outer edge of the radiation belt during very intense storms. That was measured on board

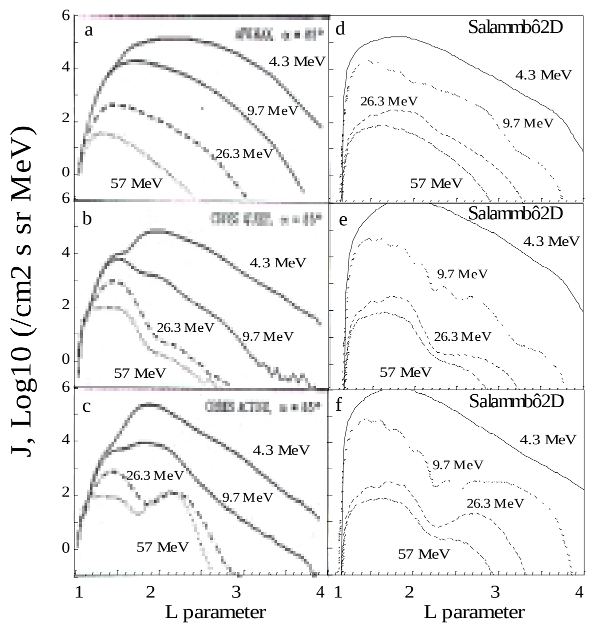

Figure 4. *AP8MAX model (a); CRRES quiet (b) and active (c) measurements (Ref. 8); Salammbô 2D results for a static state (d), for the CRRES quiet period (e) and for the CRRES active period (f) for 4.3, 9.7, 26.3 and 57 MeV equatorial protons.*

different satellites for protons in the 30 MeV range, like DMSP during the February, 1986 event (Ref. 9, near L = 2.2), Relay 1 during the September, 1963 event (Ref. 11), or Explorer 26 during the April, 1965 event (Ref. 10). But at these very high energies, magnetospheric shielding variations can be the cause of the outer belt depletion. But then, if you look at CRRES quiet period (Ref. 8, figure 4b) again, you will find that maybe all the L > 2 particles were removed from the belt during an intense event (and new population replace the old one for E < 30 MeV). In fact, this was possible during the March, 1989 event with the lowest Dst event recorded of around -600 nT (this can be confirmed with NOAA/TIROS data). Then in the code, starting from a stationary state (see figure 4d) closed to the AP8MAX model (see figure 4a), after the Llos placed at L = 2 in March, 1989, we run Salammbo 2D to the March, 1991 event. Just before this event, we plot the results (see figure 4e) and compare them to the CRRES quiet model (Ref. 8, see figure 4b). At very high energies (26.3 and 57 MeV), the CRAND phenomena has replenished the outer part of the belt, giving a shape for that high energies not too far from the measurements.

The figure 5 give a summary of all the processes which can influence the outer part of the proton belt. In this figure, trapped particles are inside the white region (notified 1). At low energies (low relativistic moments), particles are continuously injected from the night side of the magnetosphere, with the help of the electric field (region 2). At higher energies, particles are lost (especially during intense activity periods) at the same Llos value (region 3) as higher L shells are opened to the interplanetary medium through the magnetopause. Then, at very high levels (region 4), particles can be lost directly to the interplanetary medium (magnetospheric shielding). All the limits between these regions are varying with magnetic activity, and their modeling is difficult. Nevertheless, it will be possible with the help of good in-flight measurements.

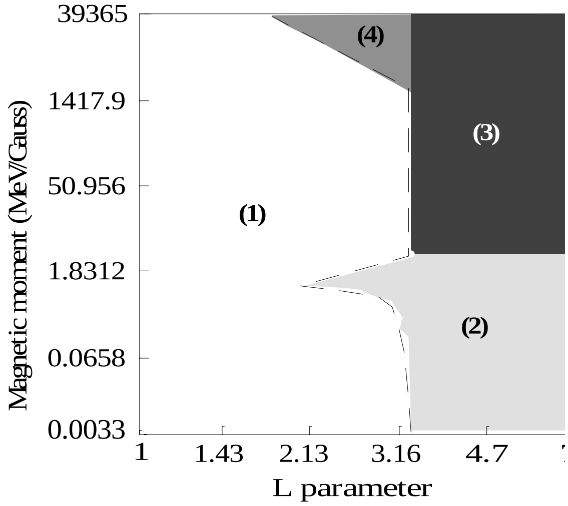

Figure 5. *Physical phenomena distribution in the calculating code domain : trapped particles (1), continuously injected particles (2), lost particles by magnetopause modifications (3), lost particles by magnetospheric shielding modifications (4).*

To conclude, proton radiation belt is depleted during magnetic storms in the outer region. But what process can inject new populations in this region, in order to obtain a mean radiation belt which looks like AP8 measurements?

3. SOLAR PROTON EVENTS (SPEs) MODELING

The Sun emits waves, magnetic fields and particles which interfere with the Earth and can give rise to perturbations. The variability of those emissions is related to the solar spots, active magnetic centers, that can induce eruptions. The sun spot number follows 11 year cycles. The spots are more numerous during solar maximum (5 years period) and less numerous during solar minimum. During eruptions, very high energy particles of several hundreds of MeV can be ejected to form SPEs. The particles can reach the Earth in one day or less, and strongly modify the most energetic population (Ref. 1, 8, 9). But these modifications can be observed during several days or months. The high energy particles issue from SPEs can enter directly in the magnetosphere and they normally just cross it (that is the same physical phenomena which was taken as magnetospheric shielding). But during very active periods, protons from eruptions can penetrate the magnetosphere where they are accelerated. If the eruption is related to a storm, caused by a CME for example, a second proton belt can be created (Ref. 15). That has been seen onboard CRRES after the March, 1991 storm for instance (see figure 4c), or even on smaller events (Ref. 1).

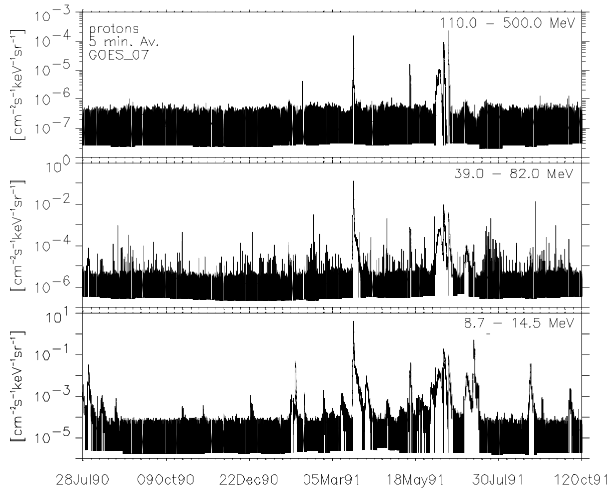

Figure 6. *GOES proton measurements during the CRRES period.*

We have tried to model those events always with the same code. First, SPEs can be seen on geostationary satellites like the GOES ones (see figure 6). Those measurements of high energy protons at geostationary altitudes (r = 6.6 Re) have been used in the code to change boundary conditions and take SPEs into account. Those particles are then transported from the interplanetary medium to the inner magnetosphere (see dotted black line on figure 5) with conservation of their energy and their flux. With such a model, we have tried to reproduce the March, 1991 SPE effect on the high energy proton belt. Starting from the state obtained for the CRRES quiet period (see figure 4e), we have first manually (because of SWP data missing) set loss near L = 2, then we have modulated code boundary conditions at L = 7 in agreement with the given GOES satellites high energy solar proton spectrums. At the end of the CRRES period, we obtain with the code a second proton belt on the 30 MeV range for equatorial particles (see figure 4f). We can see on this figure a bump on the 26.3 MeV particles, which looks like the one measured on board CRRES (Ref. 8). Those results are quite satisfying in the sense of physical phenomena understanding, even if flux levels have to be performed. Deficiencies on second proton belt building are certainly related to magnetospheric shielding modifications, and to the great importance of the time synchronization of all those different processes (losses and injection of SPE particles).

4. CONCLUSION AND PROSPECTIVE

Two big perturbations can seriously modify the charged particle populations around the Earth : magnetic storm and SPEs. Those two phenomena can be considered independently. Storms can happen during solar minimum without registered SPE, like during the February, 1986 storm for example. Solar protons issue from SPEs can reach the Earth before the associated storm commencement, like for the March, 1991 storm for example. SPE can be also related to a CME, like for the March, 1991 storm for example.

In this study, the main effects on the high energy proton belt of those two phenomena have been isolated. Storms are provoking particle losses affecting all energies at the same L value, and magnetospheric shielding modifications depending on particle energy. The parameterization of those effects still presents some deficiencies due to data missing, but the origin and the running of those physical effects are well understood and can be easily modeled by the code. A better data base will allow us to perform the model towards a quite good prevision of high energy proton losses for a given storm. On the opposite, SPEs can increase the high energy proton population. The code is able to take SPE effects into account, and to give realistic results. The main progress of this study is the selection of all important phenomena to model the dynamics of the high proton belt. Here is the first step reached in this study. Induced results can be observed in onboard measurements. The principal advantage is the use of a code available from 1 keV to 300 MeV equatorial protons in which we can introduce easily new understood physical phenomena. Actually, since the static Salammbô proton code development began in 1990 (Ref. 12), it has been introduced a Kp dependent radial diffusion for low energy proton dynamic modeling (Ref. 2, 3), and now we have introduced ring current modifications and SPEs effects for dynamic modeling of higher energies. This code, concerning storm short time dynamics, has to be related to the long term variation proton code (Ref. 13) that takes into account solar cycle variations of the high energy proton belt at low altitude (Ref. 14). This solar cycle dependent code is also the same code, taking into account yearly modifications of solar cycle dependent parameters (and not storm dependent ones) that influence solar cycle variations of the high energy proton belt. It permits to give a static state related to the solar cycle period which is more precise than the AP8 MAX and MIN models. Added to the dynamic model studied here, it will permit to define worst case effects on the entire proton belt. An application to the latitude dependent Salammbô 3D code has to be done now, in order to palliate static results of the AP8 models from NASA.

5. REFERENCES

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