CONTINUOUS INJECTION OF SOLAR COSMIC RAYS IN THE INTERPLANETARY SPACE ALONG THE INTERFACE BETWEEN AMBIENT SOLAR WIND AND THE EJECTED MATTER DURING MAJOR SOLAR FLARES

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ABSTRACT

During the solar cosmic ray events of Mar. and Oct., 1989 and Mar., 1991, following solar optical and X-ray flares, peculiar enhancements in the solar cosmic ray fluxes lasting for hours, in association with Geostationary Magnetopause Crossings (GMCs), were recorded by the particle detectors on board of GOES-7 satellite. On Oct.20, 1989, all three riometers installed at the Brazilian Antarctic Station Comandante Ferraz recorded an additional amount of cosmic noise absorption (CNA) superimposed to the main event, already in progress, caused by the energetic particles injected by the 4B flare of the previous day. Similar solar cosmic ray events were recorded by GOES-7 detectors on Mar. 24, 1991, and another, although of different in nature, on Mar. 13, 1989. These kind of events are interpreted as a result of continuous energetic particles injection at the flare site, which freely propagate along the magnetic field lines of the tangential discontinuity that is built between the solar mass ejecta and the disturbed solar wind. It is suggested that a noticeable "square wave" events can be more clearly observed by space detectors, out of the magnetosphere, during strong solar flares associated to coronal mass ejections.

RESUMO

Durante os eventos de raios cósmicos solares de mar. e out. de 1989 e mar. de 1991, como seguimento de explosões solares no óptico e em raios X, os detetores de partículas do satélite GOES-7 registraram aumentos peculiares no fluxo de raios cósmicos, com várias horas de duração, associados a cruzamentos geoestacionários da magnetopausa (GMC). Em 20 de out. de 1989, os três riômetros instalados na Estação Antártica Comandante Ferraz registraram um aumento adicional na absorção do ruído cósmico (CNA), superposto ao evento principal causado pela injeção de partículas pela explosão

4B do dia anterior. Um evento similar de raios cósmicos solares foi registrado pelo GOES-7 em 24 de mar. de 1991 e um outro, de diferente natureza, em 13 de mar. de 1989. Este tipo de eventos são interpretados como o resultado da injeção contínua de partículas energéticas no lugar da explosão, as quais propagam-se livremente ao longo das linhas de campo magnético da descontinuidade tangencial, que se forma entre a massa solar ejetada e o vento solar perturbado. Sugere-se que eventos de "onda quadrada" bem mais definidos podem ser observados por detectores espaciais, fora da magnetosfera, durante explosões solares de grande magnitude associadas a ejeção de massa coronal.

INTRODUCTION

It is fairly well known the acceleration mechanisms of the so called Energetic Storm Particles, that surround the passage of shock waves, that are often superimposed on the decay phase of the prompt solar proton events (Gosling, 1983 and references therein). However, less is known on this matter of the energetic solar protons that are released in the interplanetary space during the second phase of a flare (de Jager, 1986; Lee and Ryan, 1986). From multiple spacecraft ɔbservations it is known that solar ɜnergetic particles come not only ılong the field lines that map the pacecraft position to the solar flare ɔcation on the solar disc, but also n a wide angular distance on both des of the flare's meridian (Perez-eraza, 1986). It is now a ɔnsensus among the specialists at particles are accelerated first pulsively up to few MeVs and in a cond phase up to hundreds and, rhaps, thousands of MeVs (de ger, 1986; Okudaira, 1989). netheless, the acceleration mechanisms still represent a challenge because any theory should be able to reproduce flare related phenomena, as well as the Coronal Mass Ejection (CME) events during major solar flares.

In this work a case study is presented of three strong inter-planetary events that produced geostationary magnetopause cros-sings at the satellite's position, but from different solar flare charac-teristics releasing energetic solar protons.

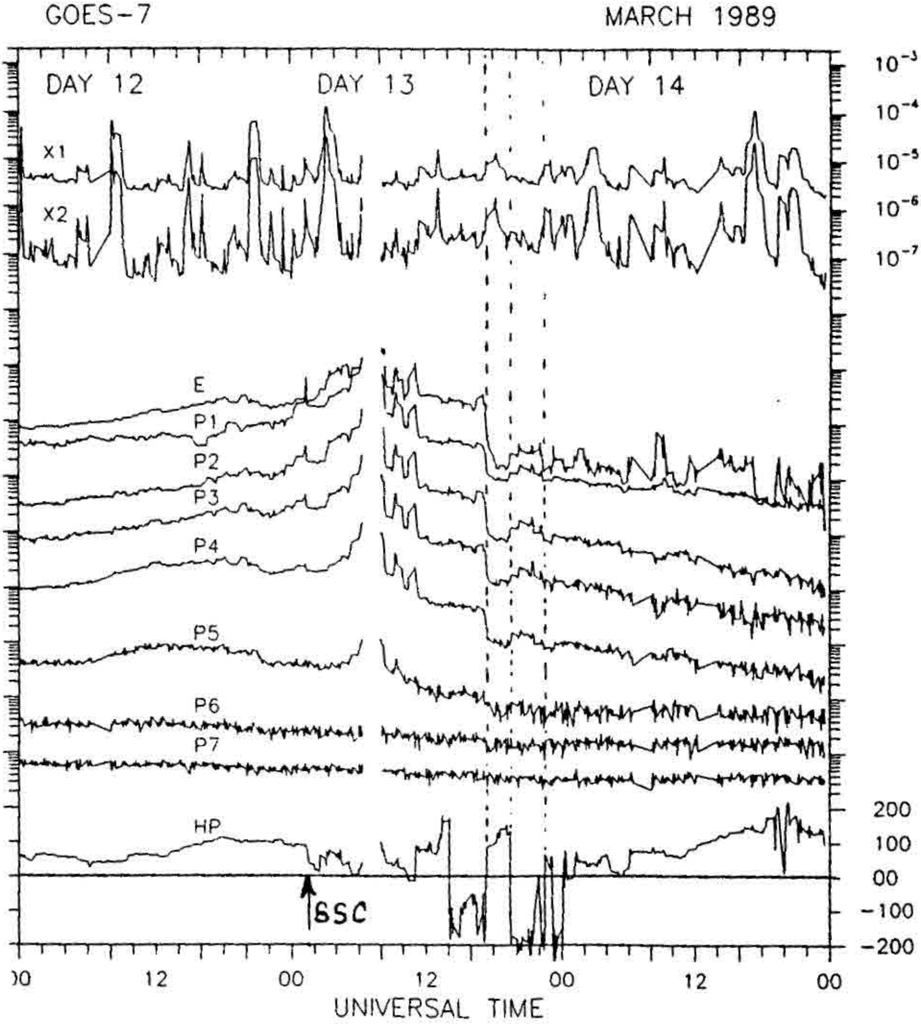
OBSERVATIONS

The data reported in this work correspond to space detectors, on board of GOES-7 geostationary satellite, provided by the National Geophysical Data Center in Boulder, Colorado. Also, for one of the events, useful data from three riometers installed at the Brazilian Antarctic Station Coman-dante Ferraz - EACF (located at -52° magnetic and L ~ 2.25) were available. In all figures, the satellite data consist of X-ray fluxes in two wavelength ranges (X1: 1-8 Å and X2: 0.5-4 Å), electron fluxes (E: ≥2

MeV), proton fluxes in seven energy ranges (P1: 0.6-4.2; P2: 4.2-8.7; P3: 8.7-14.5; P4: 15.0-44.0; P5: 39.0-82.0; P6: 84.0-200.0 and P7: 110-500 MeV), and the northward parallel component (to the Earth's rotation axis) HP of the ambient magnetic field. The riometers at EACF are the standard 30 MHz frequency and use Yagi-Uda directional antennae pointing to the vertical direction and, 40° from zenith, to the south and west with respect do the magnetic pole. The present study concentrates on the arrival of solar energetic particles to the Earth's environment in three solar and interplanetary events.

March, 1989. The series of events during this month was very complex in many aspects. Region 5395 (centered at 35°N. 69°E) on the Sun produced an optical 3B class and a X15 X-ray flare at 1354 UT on Mar. 6. Feynman and Hundhausen (1994) reported a spectacular Coronal Mass Ejection (CME) near this active region at 1415 UT, on the same day. The interesting fact in this event is that, contrary to the expectations, no energetic particles injection, within the ranges of the satellite's detectors, was noticed. On the other hand, two days later, on the morning of Mar. 8, a gradual increase in the low energy channels at a relatively smooth rate was recorded without any significant flare activity. At about 1800 UT a transient on the particle fluxes was noticed, also with no perceptible flare. From then on there was a gradual particle flux increase until Mar. 13. No perceptible influence on the particle fluxes, due to the 4B and impulsive X-ray flare at 1523 UT on Mar. 9 and the 3B X4.5 X-ray flare at 1858 UT on Mar. 10, was noticed either. Feynman and Hundhausen (1994) reported no CME on day 9, but a major and exceptionally bright one was observed on day 10, along with a major X-ray flare, although they cannot precise whether the starting times of both events were coincident or not.

Fig. 1 displays GOES-7 satellite data, with labels as described above, for the days 12, 13 and 14. The interval shown corresponds to the arrival of an interplanetary shock wave signaled by the SSC at 0128 UT on Mar. 13 (Joselyn, 1990). This shock wave most probably was originated by the CME of Mar. 10. On its arrival it compressed the magnetosphere to the extent that the magnetopause passed the satellite's position (nea 0700 LT). This can be seen by th reversal of the parallel componen (Hp) of the magnetic field in Fig. 1 Such rare events are calle Geostationary Magnetopaus Crossings (GMC) and are cause by severe conditions of the sol wind dynamic pressure. Allen et (1989) have estimated that th compression pushed the magne pause, on the side of the subso point, from the stationary 10 R_E 4.7 R_E. In Fig. 1 can be seen t the magnetopause was compressed in four occasions.

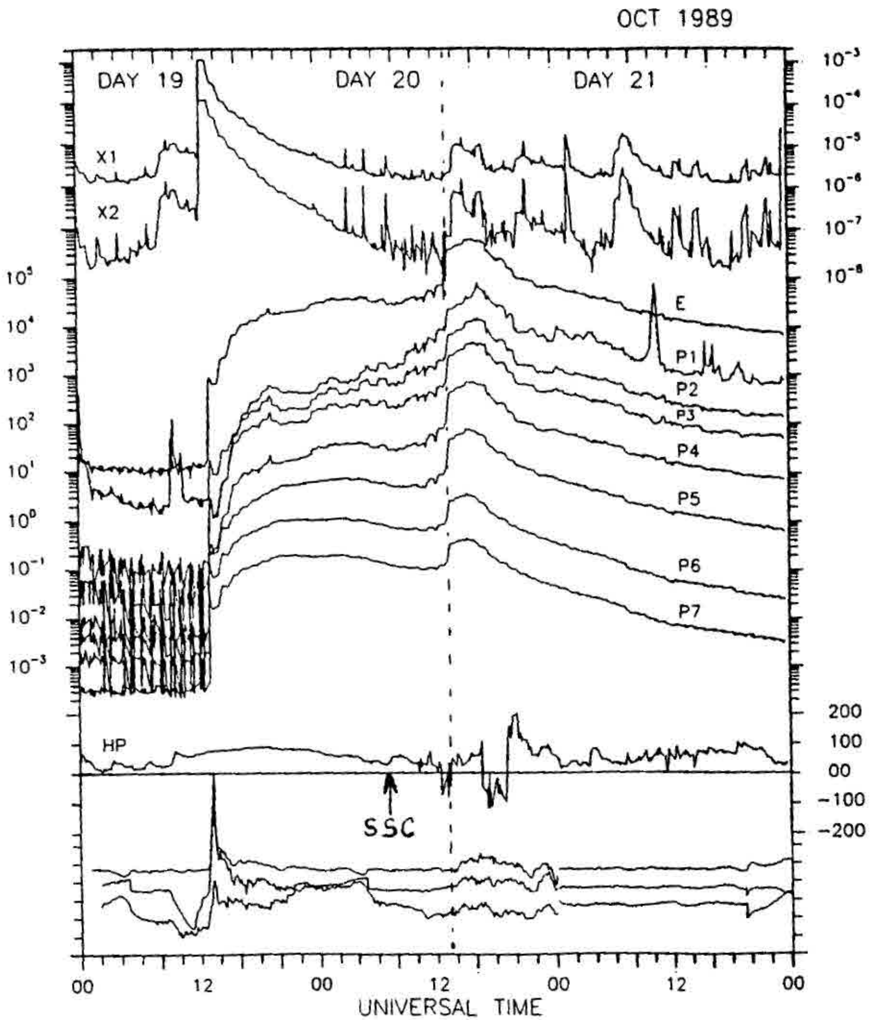


ure 1 - GOES-7 satellite data of Mar. 12, 13 and 14, 1989. X1 and X2 are
ay fluxes in W/m^2; the electrons E and protons P fluxes are in counts/(cm^2
· MeV), and the parallel component of the magnetic field HP is given in

In spite of the intense flare activity and great geomagnetic storm, the solar energetic particles did not show abnormal fluxes, typical for this kind of events. In fact, from GOES-7 data it appears like protons were accelerated only up to energies of less than 80 MeV. In Fig. 1, the sudden decrease in the particle fluxes that coincides with the return to positive values of the Hp component, namely, the first return from compression of the magnetopause, is an indication of the shielding of the geomagnetic field to low energy solar protons. This becomes more evident during the second GMC when the negative values of the Hp component of the magnetic field is anticorrelated with the lower energy particles.

October, 1989. If the March 1989 event was recognized to have reached historic proportions for the intense geomagnetic activity and GMCs, produced by the interaction of the tremendous dynamic pressure of the solar wind on the magnetosphere (Allen et al., 1989), the event of October 1989 can be best characterized by the highly relativistic solar particles arriving at the satellite's location, starting around 1300 UT, on day 19. This event started with a spike of almost two orders of magnitude in the particle fluxes which were most probably released by the 4B flare (located at 27°S 10°E on the solar disk) of Region 5747 at 1229 UT . On Fig. 2 can clearly be noticed that this X-ray flare, identified by the very steep rise in the X-ray fluxes, in fact, could have been responsible for the unusual sudden rise in the energetic particle fluxes. After de initial spike, the particle fluxes are further increased up to three orders of magnitude, from the background, for more than 12 hours in all proton energies and also in the electron flux.

Superimposed on the gross structure of the energetic solar particles fluxes, and when the fluxes being in a decay phase, it is to be noticed a peculiar flux enhancement in all proton energies and electrons. As can be seen in Fig. 2, a sudden enhancement starts around 1320 UT in all particle energies stayinc relatively at the same level fo almost two hours, and thei decreasing smoothly to levels of th main event. Clearly, the initi enhancement is not related to ar solar X-ray activity, since it star several minutes before the close flare. Notice also that, the increa of the particles flux occurs minutes after the GMC; almost the time of the temporary recov of the magnetosphere. Then, wh the second and major GMC st the particle fluxes initiate their de to the main event levels.

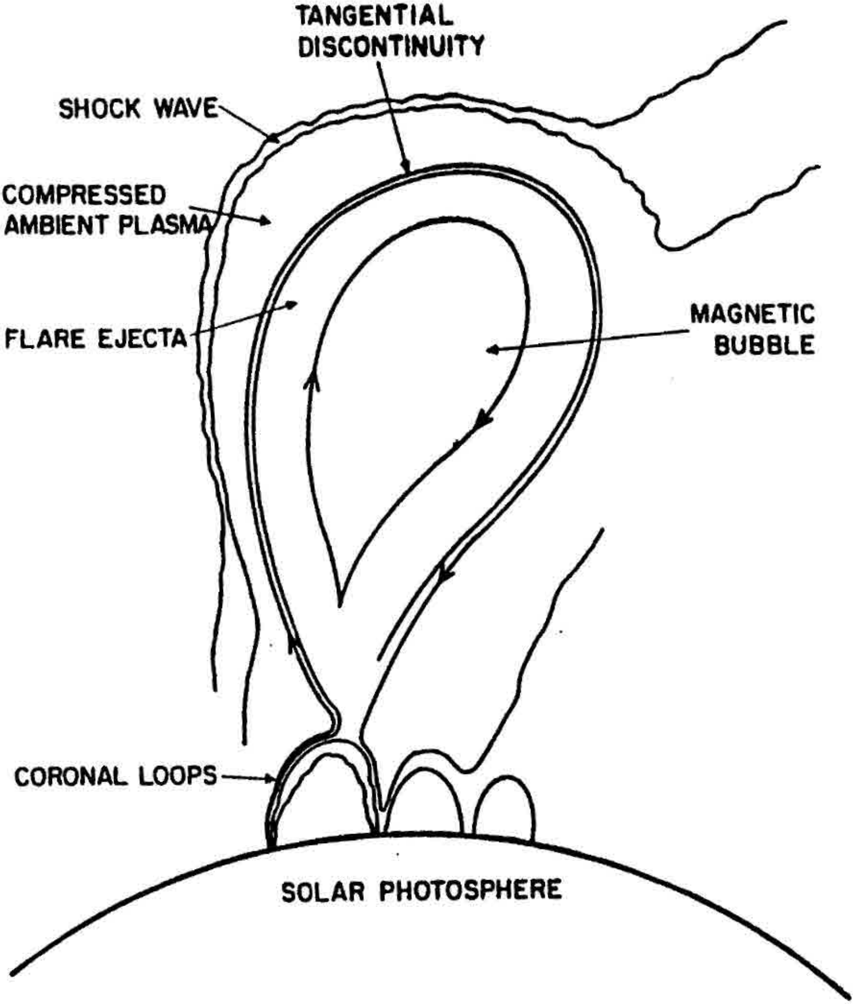


ıre 2 - Same as Fig. 1 for Oct. 1989. At the bottom, cosmic noise spheric absorption of riometers in Antarctica have been added.

This same X-ray flare may have originated the CME at 1245 UT, on the same day, as reported in the Solar Geophysical Data (**548**, Part II, 1990), which was responsible for the interplanetary shock wave that later arrived to the Earth. The arrival of the interplanetary shock was signaled by the SSC at 0730 on day 20, as indicated by the arrow in Fig. 2. Around 1200 UT the pressumed plasma ejecta compressed the magnetosphere, causing a GMC when the position of the satellite was around 0700 LT. After this first GMC, which lasted almost an hour, there was a larger one starting at 1640 UT compressing the magnetosphere for more than two hours. Using criteria and methods of calculations the published in the literature (Sibeck et al. 1991; Petrinec et al. 1991), we estimate that the magnetopause could have receded also down to 4.7 R_E during the first of these GMC and to 6.4 R_E on the second GMC.

On the bottom of Fig. 2, cosmic noise absorption (CNA) corresponding to three riometers installed at the EACF are shown. Unfortunately, at the time of the arrival of the solar energetic particles there was radio interference at the riometers south and west (second and third from top). In spite of this interference, a strong spike in the CNA in as much as 5 dB can be noticed in the vertical and south directions, coincident with the arrival of the solar cosmic ray spike. The CNA in all riometers returned to almost normal levels within an hour, but reached noticeable values shortly after the arrival of the peculiar solar energetic particles, returning to normal conditions after almost ten hours.

March, 1991. This is another event with the occurrence of a GMC, although no clear CME has been reported in the literature. In this case, there was an optical 3B flare, located at 24°S and 11°E in Region 6555 on the solar disk, which started at 0219 UT on day 23, producing the X-ray flare shown on Fig.3. Notice that the flare's development consists of an spike, of several minutes duration, and then a rather gradual enhancement in the X-ray fluxes before reaching the peak of activity one hour later. Solar particle fluxes started to rise almost four hours after de begining of the flare. In spite of the apparent moderate solar activity, the magnetosphere gets compressed beyond the GOES-7 geostationary position (around one hour after the local noon). This GMC is preceded by a SSC 15 hours earlier. In Fig. is again to be noticed an ext enhancement during the decay the particle fluxes starting arou 1930 UT, in close connection w the onset of the GMC (at 2000 U but with duration much longer tl the short incursion of the GMC.



'igure 5 - Artistic conception of the energetic protons model propagation om the storage coronal loops to the interplanetary ›ace.

DISCUSSION AND CONCLUSIONS

From the study of the events shown in Figures 2 and 3 we can draw some conclusions from the identification of common features. Both events, as well as the event of Mar. 1989, had strong interplanetary shock wave interaction with the magnetosphere such as to cause GMCs, preceded by SSCs signaling the arrival of the shocks. During the decay phase of the energetic solar particle fluxes, released in association with the causal solar flares, peculiar enhancements in the particle fluxes, with several hours duration, are noticed in all energy channels in the case of the Oct. 1989 event, and in the lower energies for the Mar. 1991 event. These enhancements are not due to the fact of the satellite being exposed to the environment, outside the magnetosphere, as one can suppose at first, because the extra flux are still present even when the magnetosphere returns to its normal position, as it can be inferred from Figs. 2 and specially in Fig. 3. The event of Mar. 1989 represents the normal case when no extra particle flux, like those pointed out in the other events, is present. In this particular case one can clearly notice, in Fig. 1, the well in the particle fluxes during the interval when the magnetosphere returns to its normal position (around 1720 UT) and when it starts a second GMC around 1945 UT.

Fig. 4 shows two sets of proton energy spectra corresponding to the Oct. 20 event. The first, represented by the continuous lines, corresponds to an interval just before the additional flux enhancement. The second set of spectra (discontinuous lines) was taken from an interval within the enhancement that resembles a deformed square-wave in the higher energies. Notice that both spectra essentially consist of two parts. The first part, up to energies around 7 MeV in the spectra, before the deformed square-wave, and 30 MeV within it. One can notice that the slope of the spectra is nearly the same for both kinds of spectra in the low energy part. However, the slope of the high energy range of the spectra, within the extra enhancement, is larger than the same portion of the spectra before the enhancement. In general, at low energies it is not possible to identify the nature of the solar acceleration mechanism, because of the uncertainties in the propagation and the contribution of the interplanetary shock acceleration. This is typical of events called Energetic Storm Particles (Gosling, 1983), that appear superimposed to the energetic solar particles in Fig. 4, and which are believed to be particles accelerated by interplanetary shock waves via first order Fermi mechanism (Decke and Vlahos, 1986). Due to th steeper slope of the spectra, in th high energy portion of th discontinuous line spectra, one ca clearly identify a different acceleration mechanism, most probably associated with the flare dynamics. For the case of the Mar. 1991 event the energy spectra (not shown) are almost identical to the discontinuous line spectra of Fig. 4, with the same "knee" at 30 MeV.

Similar particle flux enhancement have been noticed by detectors on the Moon when it was outside of the magnetotail (Medrano et al., 1975) and by detectors of other spacecrafts (Venkatesan, 1975) during the well known event of Aug. 4-7, 1972. Medrano et al. (1975) reported a well defined "square-wave" flux of solar protons of energies equal or greater than 50 MeV. Venkatesan et al. (1975) reported that this same enhancement was in aproximate coincidence with a sudden increase and then a sudden decrease in the interplanetary magnetic field lines and alpha particles measured by Explorer 41. Medrano et al. (1976) found that peculiar enhancements, in the solar proton fluxes with few hours duration, follow SSCs with an average delay of 8 hours. Medrano et al., (1975) suggested a direct particle propagation from the flare site along the tangential discontinuity developed between the disturbed solar wind and the piston-driven gas.

A quantitative picture of how harged particles can be ccelerated, from thermal energies ı the chromosphere up to GeV energies, and then be able to escape into the interplanetary space has begun to emerge. In this picture, magnetic relaxation and/or annihilation and reconnection can accelerate and heat electrons and protons up to energies of 10-100 keV, although reconnection can be efective only in low plasma densities because in high densities the magnetic energy can be transformed into Joule heating (de Jager, 1986; Dröge and Schlickeiser, 1986). These pre-accelerated particles can be further stochastically accelerated by moving irregularities (like Alfven waves) with constant speed but random directions; this is called the second order Fermi acceleration mechanism. Particles accelerated in this way can be responsible for type III and V radio emission (Kahler et al., 1984). The rapid heating and/or mass ejection generates a shock wave which spreads out through large portions of the corona at speeds of $\sim 10^3$ to 2×10^3 km/s (Lee and Ryan, 1986). The shock wave thus formed can accelerate charged particles faster than the stochastic process (de Jager, 1986; Okudaira, 1989) through the first order Fermi mechanism up to energies in the range of 100 MeV to GeV values that further are observed in the interplanetary space. Strong support for shock acceleration is provided by type II radio bursts observed in two frequencies apparently corresponding to the fundamental and first harmonic of the local upstream plasma frequency (Lee and Ryan, 1986).

In the light of the experimental observations and what is believed to happen in the lower corona, during solar flares, we can postulate a qualitative model of propagation of the energetic solar protons from the Sun to the Earth's orbit, such as to explain the observations. After the charged particles thus accelerated, by a combination of mechanisms described above, become trapped in magnetic loops of huge field intensity, and can diffuse azimuthally to other solar longitudes (and latitudes) through the interconnecting magnetic tubes in the corona, as it is illustrated in Fig. 5. The azimuthal diffusion can carry particles of higher energies even to the hidden hemisphere of the Sun (Perez-Peraza, 1986). In any case, at the site of the acceleration region it should be expected large quantities of energetic charged particles that remain trapped in the magnetic closed loops, which diffuse perpendicularly to the field lines. The diffused particles progressively reach the field lines that connect to the interplanetary magneitc field which separate the already disturbed ambient plasma from the mass flare ejecta; namely, the field lines that form the tangential discontinuity. The magnetic field of the tangential discontinuity is expected to offer minimum irregularities thus conforming a corridor with higher values of the parallel diffusion coefficient. Due to the minimum perpendicular diffusion of the particles, it should be expected higher particle fluxes along the discontinuity, simply because there is a direct propagation from the flare site.

Of course, this model applies only to events of strong CME associated to major solar flares. Nonetheless, the occurrence of CME may not require an associated flare, and vice-versa, in less energetic events (Feynman, and Hundhausen, 1994). There is the need of a thoroughly analysis of more events of this type, specially the events that were generated by flares located on the eastern side up to, say, 20^{o}, since, according to this model, square-wave fluxes will be more defined when reaching the Earth on the left side of the tongue-shaped tangential discontinuity.

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