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# Cosmic ray decreases caused by interplanetary shocks observed by the muon telescope at Sao Martinho da Serra, Southern Brazil

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**Abstract:** The space between the planets in the Solar System is continuously permeated by a supermagnetosonic, magnetized plasma, the solar wind. This is the outward expansion of the Suns atmosphere. Furthermore, the Suns sporadically emits huge coronal mass ejections (CMEs) that disturb the solar wind. When the interplanetary remnants of these CMEs are faster enough, shock waves are driven. These shock waves are observed as abrupt variations in solar wind plasma ad magnetic field parameters. As one consequence, when these shock waves pass by Earth, cosmic ray decreases are observed by ground based detectors. It is the aim of this work to study interplanetary shock waves effects on cosmic rays measured at ground level. Interplanetary shocks are identified and their parameters determined using the Advanced Composition Explorer (ACE) plasma and magnetic field instruments. Cosmic rays decreases are studied using the Muon Detector Multidirectional telescope MDM, installed at the Southern Space Observatory - OES/CRS/CCR/INPE-MCTI, in So Martinho da Serra-RS, Brazil. The period of analysis is from January 2006 to July 2011. The amplitude of cosmic ray decreases is correlated to the shock strength, as measured by density and magnetic field plasma compressions. The results are compared with previous published works.

**Keywords:** cosmic ray, fast forward, fast shocks, muons.

## 1 Introduction

The interplanetary medium is permeated by the continuous expansion of the solar corona, the solar wind, which carries outward the solar magnetic field. As the solar wind is very rarefied, ordinary collisions are replaced by long-range Coulombian forces in terms of particle interactions. Thus the solar wind is a colissionless magnetized plasma where the steepening of nonlinear waves can occur and generate shocks. In the case of interplanetary plasma the mean free path in the Earth's orbit is around the Earth-Sun distance (1 astronomical unit, $1.49598 \times 10^8$km).

Interplanetary shocks can be classified according to their propagation relative to the Sun: if its propagation is toward the Sun, its called a reverse shock, if its propagation is away from the Sun it is called a forward shock[8] ;[3];[9];[7]. Furthermore, they can also be classified according to the wave mode: if the solar wind relative velocity is higher than the magnetossonics fast mode wave, characteristic velocity of the medium, its considered fast shock and if it is greater than the slow mode of the magnetossonics wave the shock is considered slow. [2];[7]. As the shock waves have a larger spatial extension than the interplanetary structure that generates them, it is common for a spacecraft near the Earth's orbit to observe just the shock, but not the ejecta that drives or induces it[6]. Figure 1 illustrates the plasma parameters behavior with the arrival of a fast forward shock (F). Geomagnetic storms occur due to strong disturbances in the Earths magnetosphere, usually caused by coronal mass ejections (CMEs). The main feature of a storm is a decrease in the H (horizontal) component of the geomagnetic field during some tens of hours [9]. Due to its magnetic field, CMEs block the passage of charged particles such as galactic cosmic rays (primary), usually causing a decrease in the count of particles on the surface of the Earth. Muons are the result of the decay of the primary cosmic rays due to interaction with the constituents of the atmosphere and they strikee the earth isotropically. Generally when a geomagnetic storm occurs a decrease in the count of these particles can be observed and it is called Forbush decrease ([1]; [5]).

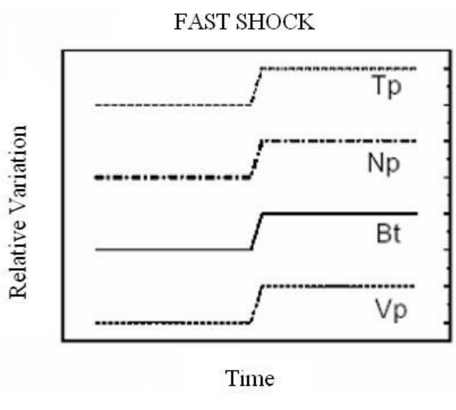


**Figure 1**: Diagram illustrating a fast forward shock, with corresponding variations in plasma parameters and interplanetary magnetic field magntitude. [3].

## 2 Methodology

In this work we analyzed 29 F type (Fast Forward) shocks, that occurred between January, 2006 and July, 2011. We used data from ACE satellite (Advanced Composition Explorer), designed by NASA (National Aeronautics and Space Administration) and launched on August 25, 1997 from Kennedy Space Center, in Florida [8].

The ACE spacecraft is 1.6 meters long and 1 meter high, not including the 4 solar panels and the magnetometer antenna. The satellite is about 1.5 million kilometer from Earth, orbiting the inner Lagrangian point L1, which is the gravitational equilibrium point between the Sun and Earth (see Figure 2).

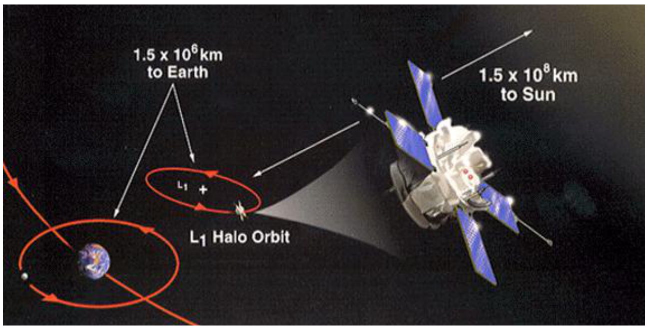


**Figure 2**: Illustration representing the ACE satellite orbit. Source: *http* : //*www.srl.caltech.edu*/*ACE*/*ace*$_m$*ission.html*.

It was used data from SWEPAM and MAG instruments that are on board of ACE satellite. The SWEPAM instrument measures the flow of particles, electrons and ions in the solar wind as a function of his position and energy, and gives the basic moments of solar wind plasma: speed, density and temperature. The MAG instrument provides interplanetary magnetic field data. Thereby, we obtain data of parameters such as speed, temperature, solar wind density and interplanetary magnetic field intensity, providing the study of the internal conditions of the solar wind plasma. The SWEPAM and MAG instruments data are available on the ACE mission website (http://www.srl.caltech.edu/ACE).

In order to study cosmic ray decreases, we used used data from the Multidirectional Muon Detector (MMD) that is operating in the Southern Space Observatory (SSO / CRS / INPE - MCTI) in So Martinho da Serra, RS, Brazil (Latitude 29  26 '24" S, Longitude 53 , 48', 38 " W, 492m above sea level) since 2001 [10]. The SMS detector is part of the Global Muon Detector Network (GMDN), which is composed by four telescopes located in Nagoya (Japan), Hobart (Australia), Kuwait (Kuwait) and So Martinho da Serra (Brazil),. Figure 3 shows the coverage area of the GMDNand the asymptotic directions of view for each directional channel of each detector.

The values of the cosmic ray intensity were analyzed in terms of the relative deviation in relation to the annual average. Only the vertical channel of DMM in So Martinho da Serra, RS, Brazil , corrected by the atmospheric pressure, was used. The relative variation was determined using the expression:

$$muons\Delta = \frac{(particlecount - average)}{(average)} \times 100 \qquad (1)$$

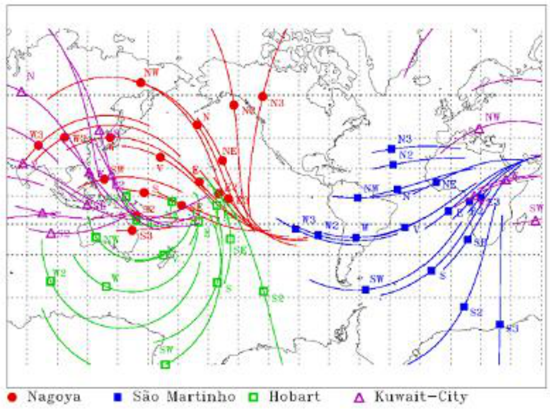


**Figure 3**: Diagram showing the coverage area of GMDN and the asymptotic directions of view of each detector.[10].

**Figure 4**: Figure 4  Picture of the Multidirectional Muon Detector Telescope installed on SSO / CRS / INPE - MCT, in August 2012

We can identify the occurrence of shock by the analysis of the interplanetary plasma and magnetic field parameters (as shown in Figure 1).

## 3 Preliminary Results

The shock arrival at ACE is indicated in Figures 5, 6 and 7 by a red line.

The speed changes abruptly from 500 km/s to approximately 700 km/s, and the density increases in the shock region, confirming that there was a plasma compression caused by the shock. It is also possible to see an increase in the value of magnetic field intensity from 5nT to 12nT. Figure 5 is an example of a fast forward shock, moving away from the Sun, with a relative velocity greater than the solar wind and the magnetossonic wave.

Figure 6 is another case, of a fast forward shock, observed by ACE on day 034 2009. The magnetic field jumps from  5 to 8 nT, and the density from 10N($1/cm^3$) to 25N($1/cm^3$). It is possible observe a relatively large decrease during the shock passage, which starts several hours before.

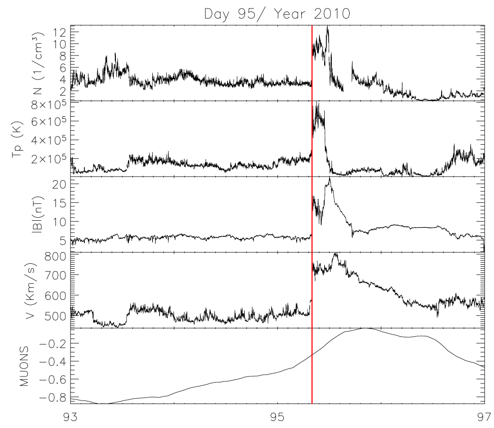


**Figure 5**: Wide figure example. Conference webpage header.

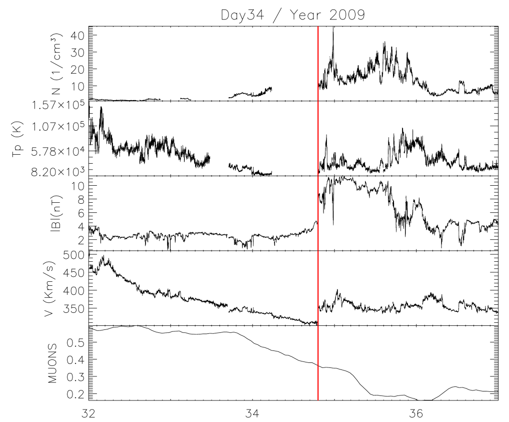


**Figure 6**: Wide figure example. Conference webpage header.

## 4 Future work

We have showed some examples of cosmic ray decreases observed by the So Martinho da Serra, RS, Brazil muon telescope due to the arrival of interplanetary fast forward shocks. The next steps in this study are to calculate the shock strength, i.e, the magnetic field and plasma density compression ratio across the shocks, to calculate the cosmic ray decrease due to the shock only, and correlate them.

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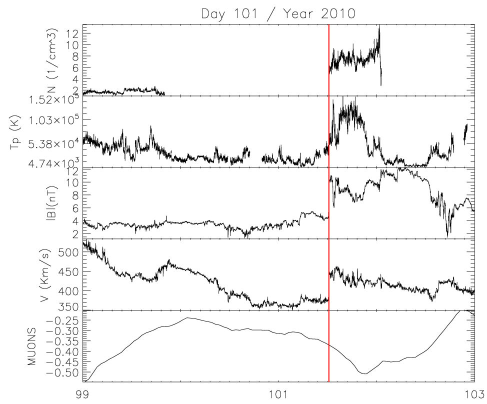


**Figure 7**: Wide figure example. Conference webpage header.

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