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The ICME ejected at 2010 April 3 observed by the STEREO coronagraphs and by the Global Muon Detector Network

C. R. Braga[1], M. Rockenbach[2], A. Dal Lago[1], R. R. S. De Mendonca[1], E. Echer[1], K. Munakata[3], T. Kuwabara[4], C. Kato[3], N. J. Schuch[5], J. Bieber[4] M. L. Duldig[6], J. E. Humble[6], H. K. Al Jassar[7], M. M. Sharma[7], I. Sabbah[8,9]

[1] *National Institute for Space Research, Sao Jose dos Campos, Brazil.*
[2] *Instituto de Pesquisa e Desenvolvimento, Universidade do Vale do Paraiba, Sao Jose dos Campos, Brazil.*
[3] *Department of Physics, Shinshu University, Matsumoto, Japan.*
[4] *Bartol Research Institute and Department of Physics and Astronomy, University of Delaware, Newark, Delaware, USA.*
[5] *Southern Regional Space Research Center CRS/CCR/INPE/MCTI, in collaboration with the Santa Maria Space Science Laboratory LACESM/CT UFSM, Brazil.*
[6] *School of Mathematics and Physics, University of Tasmania, Hobart, Tasmania, Australia.*
[7] *Physics Department, Kuwait University, Kuwait.*
[8] *Department of Natural Sciences, College of Health Sciences, Public Authority of Applied Education and Training, Kuwait City, Kuwait.*
[9] *Department of Physics, Faculty of Science, University of Alexandria, Alexandria, Egypt.*

crbraga@dge.inpe.br

Abstract: The twin Solar TErrestrial RElations Observatory (STEREO) spacecraft provided simultaneous observations of the solar atmosphere from two vantage points, bringing information on the three-dimensional (3D) trajectory of CMEs. The interplanetary counterparts of the CMEs (ICME) modulate the high energy cosmic ray in the heliosphere and, when directed toward the Earth, in the near Earth interplanetary medium. In this way, it is possible to derive the three-dimensional position of the ICME in the near Earth interplanetary medium analyzing the primary cosmic ray distribution. In this work we analyze the CME observed in the solar corona in April 3rd 2010 using observation of STEREO. We derived the speed and direction of propagation of the CME and its interplanetary counterpart (ICME) using triangulation and tie-pointing. For the same period, we analyze the three-dimensional anisotropy of ~50GeV primary cosmic ray intensity as a function of time from observations with 60 directional channels of the Global Muon Detector Network (GMDN). Both results from STEREO and GMDN are compared with each other and also with previous works using in-situ interplanetary data.

Keywords: muon detector, coronal massa ejections, magnetic clouds, cosmic ray density gradient

1 Introduction and objective

In the solar atmosphere, the coronal mass ejections (CME) have been widely observed for more than 40 years using white light using coronagraphs onboard spacecrafts. Currently, these observations are done by the Solar TErrestrial RElations Observatory (STEREO) and Solar and Helispheric Observatory (SOHO). When the CMEs are directed toward the Earth, its corresponding ICMEs are then frequently analysed using in situ data from spacecraft close to the Earth. The ICMEs can also be studied using combined observation of cosmic ray in several detectors in the Earth's surface (see, for example [1]). This technique allows us to derive 3 dimensional information about the interplanetary medium in the Earths vicinity.

A subset of ICME which shows some specific properties is called magnetic clouds. Magnetic clouds are interplanetary structures that, at 1 AU, are identified by its high magnetic field strength (typically higher than 10 nT), low proton temperature and low proton beta parameter (~0.1), a large and smooth rotation in the magnetic fields direction, crossing the spacecraft in about 24 hours ([2]).

The objective of this work is to deduce the 3D propagation direction and speed of a sample coronal mass ejection (CME) on the Sun's atmosphere and its corresponding magnetic cloud in the Earth vicinity. On one hand the CME can the tracked on the solar corona using white-light coronagraph observation and its kinematics properties can be derived. On the Earths vicinity, thanks to its modulation by the stronger magnetic field of the cloud, the high energy galactic cosmic ray can bring us information about its structure.As a case study, we took the magnetic cloud observed at April 5th 2010 reported by [3].In the Lagrangian point L1, the magnetic cloud was observed from 12:00 of April 5th 2010 to 14:00 of April 6th2010 by ACE instrument.

2 Cosmic ray observation by the Global Muon Detector Network (GMDN) and the gradient derival

This work also analyses the cosmic ray modulation during a magnetic cloud observation by analysing the spatial gradient of the high-energy galactic cosmic ray (GCR) density in three dimensions. The gradient gives information on the remote distribution surrounding the detector view. We derive the density gradient from the GCR anisotropy observed with the Global Muon Detector Network (GMDN). The network is composed of detectors located at Nagoya University, Japan; the Australian Antarctic Division, Hobart, Tasmania; the Southern Space Observatory, Sao Martinho da Serra, Brazil; and Kuwait University, Kuwait. Each of these detectors is multi-directional, allowing cosmic ray intensities in 60 viewing directions to be recorded simultaneously. The responses of different surface muon detectors to GCRs have median energies ranging from 50 to 150 GeV [4].

The Larmor radii of the cosmic ray particle, considering an average magnetic field of about 5 nT, is about 0.2 AU [4]. As a magnetic cloud have bigger extensions than the Larmor radii of the particle, cosmic ray are expected to be modulated by magnetic clouds. Moreover, magnetic clouds are frequently accompanied by interplanetary shocks, which also are expected to modulate cosmic rays [5].

The primary cosmic ray omni-directional component of intensity (I) and the three dimensional components of the streaming vector (ξ) are calculated following [6].

Following [7], we assume that enhanced anisotropy perpendicular to the interplanetary magnetic field is predominantly due to **B** x ∇**N** drift flux driven by a gradient of cosmic ray density (**N**). Based upon this assumption, the fractional perpendicular density gradient is given by

$$g_{\perp}(t) = R_L \frac{\nabla_{\perp} N}{N} = -\mathbf{b(t)} \times \xi(t) \qquad (1)$$

where R_L is the effective particle Larmor radius, and **b(t)** is a unit vector in the direction of B.

3 The STEREO spacecraft

The Solar TErrestrial RElations Observatory (STEREO) is a set of two twin spacecrafts launched in October 2006 and provides us with stereoscopic images of the Sun's atmosphere [8]. The two STEREO spacecraft orbit the Sun at approximately 1 AU near the ecliptic plane. Their separation angle increases at a rate of about 45 degrees/year [10]. On April 2010, for instance, the separation was about 138 degrees. One satellite orbits Ahead of the Earth in its orbit around the Sun, and the other Behind (labelled A and B, respectively, hereon). The solar corona, the outermost part of the solar atmosphere can be observed from the stereoscopic while light images obtained by the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) instrument suite [9]. This instrument allows us to make 3-D estimations of the structure and kinematic parameters of CMEs.

4 The case study and results

CMEs are expected to have a travel time from the Sun to the Earth between approximately 1 and 5 days [11]. Even in a period of low solar activity, many CMEs are expected to be observed in a 4-days period and sometimes it is not possible to know exactly which CME caused the magnetic cloud. In order to find the CME which originated the magnetic cloud, first we inspected images of the three coronagraphs (C3 from SOHO and COR 2A and 2B from STEREO) and we made a list of all CMEs ejected in this period. Among the CMEs found, we considered as possible sources of the magnetic clouds only those which were observed as a) west limbo in COR2A; b) east limbo in COR2B and as c) halo or semi-halo in LASCO C3. In the four-day period analysed, only one CME fit the criteria and therefore it was assumed to be the cause of the magnetic cloud. Our result is in agreement with previous work from [3] and [12]. The solar cause of the magnetic cloud was a CME was ejected at 10:24 UT in April 3rd 2010. The CME is seen in LASCO C3 from 11:18 to 15:42 UT as a halo covering a range of about 360 degrees which indicates that the CME is ejected toward the Earth or away from the Earth. By the time of the CME coronagraph observation, the separation of both STEREO spacecraft was 138.8 degrees. On COR2A and COR2B it was observed as a limbo ejected toward the left and right, respectively. The CME boundary in each frame of both COR2A and COR2B were tracked using the CORonograph SEgmentation Technique CORSET. For each frame, this technique is able to compute the CME boundary in a set of frames without direct selection of the CME contours by the user, using texture and level set (1), see [13] for more details. By computing the evolution of the front boundary of the CME as a function of time, one can estimate the sky-plane projected speed of the CME. In the current work case study CME, the sky-plane estimated speed was 826 km/s for COR2A and 898 km/s for COR2B.

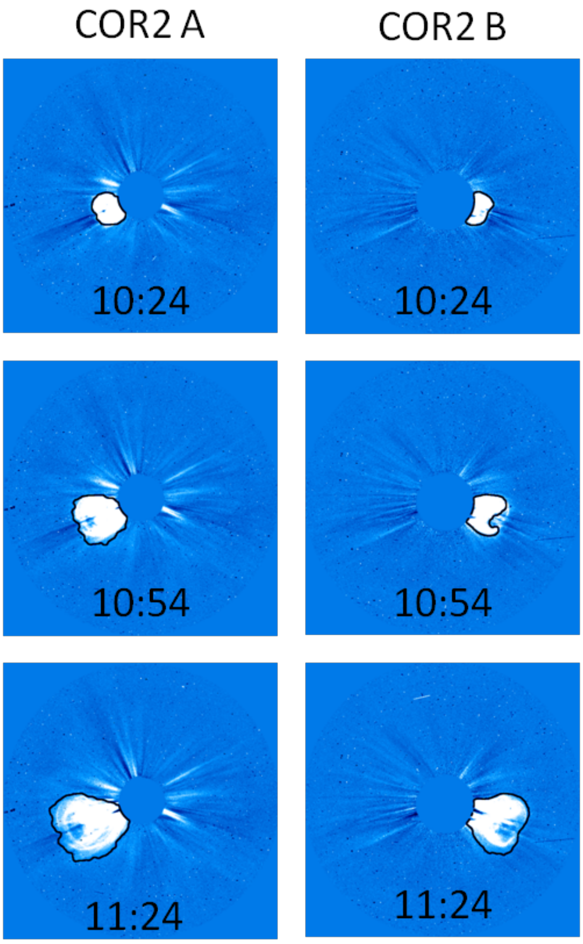

Figure 1: A combination of COR2A and COR2B images observed from 10:24 UT to 11:54 UT of April 3rd 2010. The CME was tracked by CORSET and the boundaries are indicated by the black line.

The next step is combining both images of COR2A and COR2B to derive the three-dimensional properties of the CME, since up to this step the observation gives us only two dimensional information of the CME projected in the sky-plane of each spacecraft. The boundary of the CMEs derived by CORSET for both COR2 and COR2B were used as input to the Sunloop methodology (see details in [14]). This methodology needs input points from corresponding COR2

A and B images to perform tie-pointing and triangulation (see [15] for details). As a result, the three-dimensional position of the CME is determined. Finally, using the boundary found in consecutive frames we derive the average direction of propagation. Due to the time cadence of the CME (which is about 2 images per hour), there are available only four images of the CME in each COR2 coronagraph until it reaches the outside limit. In order to increase the path of the CME tracked, we also included images from the Heliospheric Imager in the analysis.

The trajectory of the front side contour of each frame of stereoscopic images is shown in Figure 2: in the left panel the $x-z$ projection shows that the CME seems to be directed toward the Earth line although the most significant part of the CME is located southward; in the right panel, the $y-z$ projection shows that the CME is almost aligned with the Earthward direction. In Stonyhurst heliographic coordinates (in which the latitude increases toward solar north and the longitude increases toward the solar west limb), we found -24 degrees of latitude and 3 degrees of longitude. We also derived the three-dimensional average speed in the COR2 field of view (from 2.5 to 15 solar radii): 808 km/s. The results found in the current work are in good agreement with previous results from [3] which used geometric triangulation method and estimated the CME ejection direction to be about 10 degrees west of the Sun-Earth line.

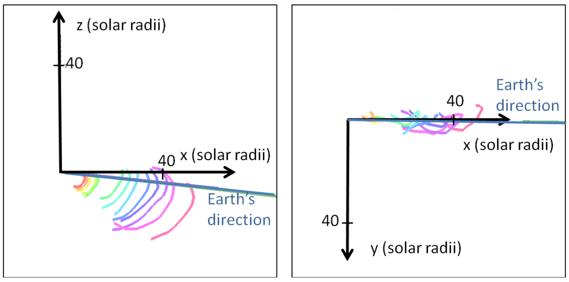

Figure 2: The CME in 3 dimensions Heliospheric Earth Equatorial (HEEQ) coordinates. The left panel shows the $x-z$ projection while the right panel shows the $x-y$. The Earth's direction is indicated by the blue line.

The interplanetary magnetic field data observed by the spacecraft Advanced Composition Explorer (ACE) located on the Lagrangean Point L1 is shown in Figure 3. There is a shock in April 5^{th} 2010 and the peak of the magnetic field intensity is about 20 nT. Inside the magnetic cloud, it is possible to see a quite smooth magnetic field rotation, in agreement with the magnetic clouds description from [2]. Since the travel time of this CME from the Suns corona to the shock observation at 1AU was ~50 hours, the average speed of the CME-magnetic cloud was ~ 803 km/s. This result suggests that the CME average speed in the COR2 field-of-view is kept in the whole path in the interplanetary medium and therefore the CME does not have any significant acceleration or deceleration.

As it is possible to see in the 3^{rd} box of the Figure 3, during the period of the magnetic cloud, the cosmic ray intensity shows a decrease of about 0.5% probably caused by the magnetic cloud and/or interplanetary shock. This decreases last up to a few hours after the end of the magnetic cloud. The x-component of the cosmic ray perpendicular density gradient (given in GSE coordinate system) is almost centred in zero before the shock arrival at ACE and in the first hours of the magnetic cloud observation. During the last hours of the magnetic cloud up to some hours after the end, this gradient component shows a clear and stable negative value which suggests that the cosmic ray density is smaller sunward than away from it. This indicates that the cosmic ray depleted region is predominantly located sunward. The x and y components of the density gradient, on the other hand, change from/to negative and positive values.

5 Summary of results and conclusions

We used coronograph observation from 3 vantage points (2 regarded by the STEREO spacecraft and one by the SOHO) and we could determine that the CME ejected in April 3^{rd} 2010 must to be solar cause of the magnetic cloud observed in April 5^{th} 2010. We CME had a travel time of about 50 hours since the first observation in the solar corona until the shock observation in the Earth's vicinity.

We tracked the CME individually in both COR2 A and B coronagraphs and then we combined both results to derive the CME direction of propagation in three dimensions in the COR2 field-of-view. The CME was found to be ejected approximately toward the Earth. These results are in good agreement with the previous work from [3]. We estimated the CME speed in the COR2 field of view to be 803 km/s and concluded that the average speed in the remaining of the trajectory from the Sun to the Earth is very close to this value.

We also derived the omni-directional component of the cosmic ray intensity and the density gradient by using combined observations from the four multi-directional muon detectors of the Global Muon Detector Network (GMDN). We found an onmi-directional intensity decreases approximately 0.5% during the magnetic cloud observation period. The density gradient was also calculated and the results indicated a cosmic ray depleted region sunward from the Earth.

As a future work, the density gradient of cosmic ray observed by the Global Muon Detector Network will be used to derive the geometry and orientation of the magnetic cloud, in a similar way done by [1] and [16].

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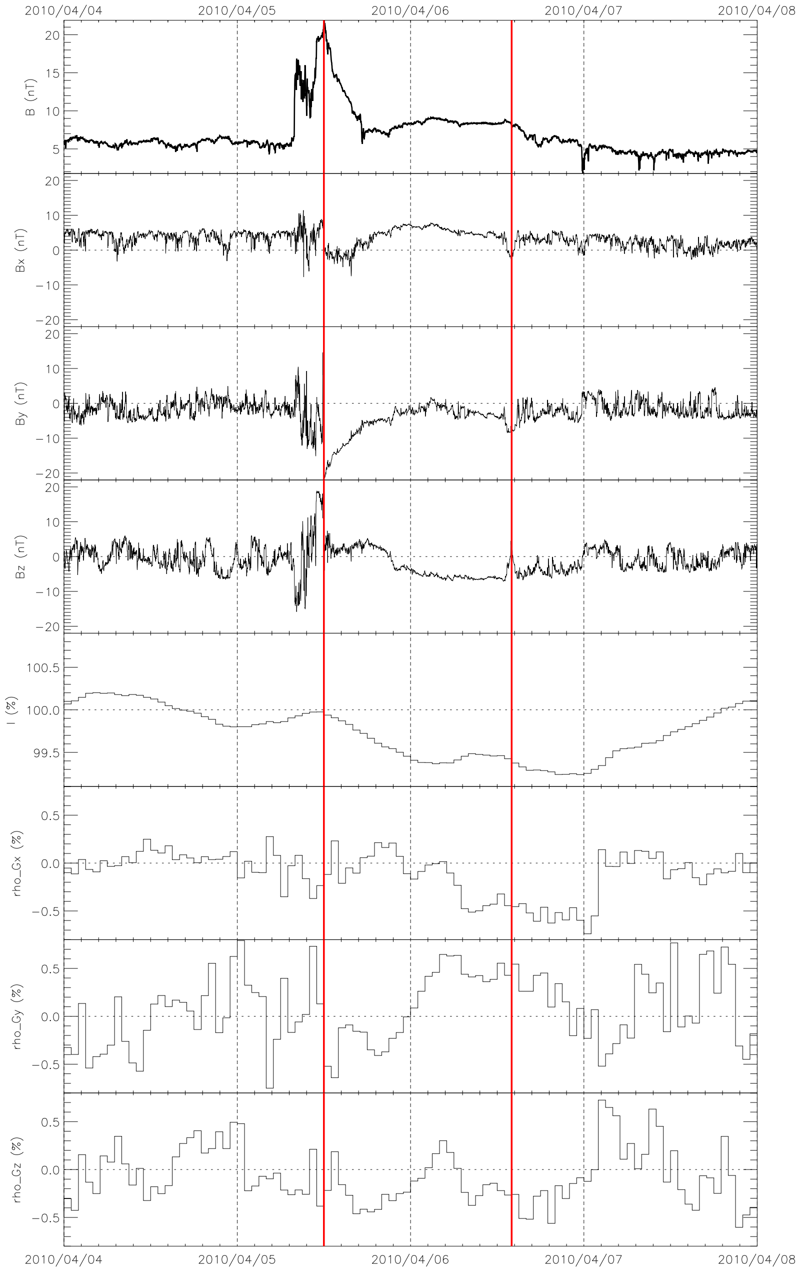

Figure 3: The first panel, from top to bottom, shows the magnitude of the interplanetary magnetic field; the next 3 panels show the components in the GSE coordinate system. The center panel shows the omni directional cosmic ray intensity calculated using the four detector of the Global Muon Detector Network (GMDN). The 3 bottom panels show the GSE components of the cosmic ray perpendicular density gradient. The continuous vertical red lines indicate the period of the magnetic cloud.

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