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Analysis and study of the *in situ* observation of the June 1st 2008 CME by STEREO

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In this work we present a combined study of the counterpart of the coronal mass ejection (CME) of June 1st of 2008 in the interplanetary medium. This event has been largely studied because of its peculiar initiation and its possible forecasting consequences for space weather. We show an *in situ* analysis (on days June 6th–7th of 2008) of the CME in the interplanetary medium in order to shed some light on the propagation and evolution mechanisms of the interplanetary CME (ICME). The goals of this work are twofold: gathering the whole *in situ* data from PLASTIC and IMPACT onboard STEREO B in order to provide a complete characterization of the ICME, and to present a model where the thermal plasma pressure is included. The isolated ICME features show a clear forward shock which we identify as an oblique forward fast shock accelerating ions to a few-hundred keV during its passage. Following the shock, a flux rope is easily defined as a magnetic cloud (MC) by the magnetic field components and magnitude, and the low proton plasma-β. During the spacecraft passage through the MC, the energetic ion intensity shows a pronounced decrease, suggesting a closed magnetic topology, and the suprathermal electron population shows a density and temperature increase, demonstrating the importance of the electrons in the MC description. The *in situ* evidence suggests that there is no direct magnetic connection between the forward shock and the MC, and the characteristics of the reverse shock determined suggest that the shock pair is a consequence of the propagation of the ICME in the interplanetary medium. The energetic ions measured by the SEPT instrument suggest that their enhancement is not related to any solar event, but is solely due to the interplanetary shock consistent with the fact that no flares are observed on the Sun. The changes in the polarity of the interplanetary magnetic field in the vicinity of the ICME observed by electron PADs from SWEA are in accordance with the idea that the CME originated along a neutral line over the quiet Sun.

The magnetic cloud model presented in this work provides the plasma pressure as a new factor to consider in the study of the expansion and evolution of CMEs in the interplanetary medium. This model could provide a new understanding of the Sun–Earth connection because of the important role that the plasma plays in the eruption of the CME in the solar corona and the reconnection process carried out with the Earth's magnetosphere.

1. Introduction

Coronal mass ejections (CMEs) are violent manifestations of the solar activity where the stored energy is released through the plasma and magnetic field ejection (Hundhausen, 1988; Kahler et al., 1988). Interplanetary coronal mass ejections (ICMEs) are the total effects that the CMEs display in the interplanetary medium (Gosling et al., 1990; Zurbuchen and Richardson, 2006). An overview of the ICME signatures is given by Jian et al. (2006), based on the pattern of changes in the properties of the magnetized plasma but, as pointed out in their work, none of these features are unique or are enough by themselves to identify an ICME. Some of these manifestations are intrinsically related with their counterpart (i.e., CME) on the Sun, but others are a consequence of their interaction and evolution throughout the interplanetary medium. For instance, statistical analysis has shown that around one-third of the ICMEs have associated magnetic clouds (MCs)

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(Gosling et al., 1990) whose magnetic field configuration is close to that derived by CME configuration models. Many studies have discussed the possibility that the flux rope structure has not been identified at 1 AU due to ICME distortion and large impact parameter (Marubashi, 1997; Huttunen et al., 2005; Jian et al., 2006). Magnetic clouds *in situ* features are elevation in the magnetic field magnitude, rotation in at least one component of the magnetic field, and low proton-β plasma (Burlaga et al., 1981). Studies of energetic particles, associated with ICMEs, suggest that the observed decrease in the cosmic rays is due to the closed magnetic field topology (Richardson, 1997) in the cool plasma regime. The appearance of solar energetic particles (SEPs) and their acceleration mechanisms are related with the solar flares, which sometimes appear with the CMEs and/or the associated shocks (Reames, 1999). The shock could be a consequence of the interplanetary propagation because, even though the place of its formation is still unclear (Gopalswamy et al., 2010), it is caused by the interaction of the CME with the outward ambient plasma flow. ICMEs also typically have low Mach numbers, which property has a significant impact on their geo-effectiveness and general solar wind–magnetosphere coupling (Lavraud and Borovsky, 2008).

Other ICME features have been the focus of several works (Jian et al., 2006 and references therein). These features have been related to the role that the electrons play in the ICME thermodynamics and evolution, and they could provide information about the physical process on the Sun. Specifically in MCs the importance of the suprathermal electrons inside the MC has been discussed by Nieves-Chinchilla and Viñas (2008) and references therein. Previous works (Osherovich et al., 1993; Dasso et al., 2003) have shown that the temperature of the electrons could be significantly greater than that of the protons ($T_e > T_p$). Additionally, the electron temperature anisotropy ($T_\parallel > T_\perp$) inside the MCs can have indirect effects associated with the excitation of electromagnetic ion-cyclotron waves (Dasso et al., 2003). Although, we do not have direct measurements of the plasma in the corona, it has been shown that reconnection processes seem to be the trigger of the CMEs (e.g. Vršnak, 2008; Pick et al., 2005), and they could play an important role in the evolution and propagation of the ICMEs, at least in the first stages. In addition, the bidirectional strahl electron signatures could provide important information about the topology of the magnetic field lines, indicating whether they are connected or not to the Sun (Gosling et al., 1987).

The ICME subsets called magnetic clouds (MCs) are the easiest structures to model because of their magnetic field characteristics (see Lepping et al., 1995). Some of the models developed are based on a flux rope concept with a force-free configuration (Lepping et al., 1990), which only takes into consideration a subset of the characteristics of magnetic clouds as defined by Burlaga et al. (1981). Other models relax the force-free condition (Owens, 2006), whereas others (Hidalgo et al., 2002a, 2002b; Cid et al., 2002) attempt to describe them in their full context with a minimum set of assumptions. However, comparing these models it is fair to say that they all describe a limited subset of the properties of the MCs. Recently, the technique developed by Hu and Sonnerup (2001) to resolve numerically the Grad–Shafranov equation for the MC (Hu and Sonnerup, 2002) has provided a new step in the comprehension of this interplanetary event. No force-free assumption is included and their numerical results provide a cross section reconstruction which shows that they are far from being circular (Möstl et al., 2008).

Isolating some of those ICME features (i.e., shock, magnetic cloud, energetic particles, etc.) in the magnetized plasma (as described above) from the others is appropriate in a first instance for carrying out a study and analysis. However, by combining all the *in situ* observations of the magnetic field, electron and ion plasma properties, energetic particle measurements and wave characteristics with MC models we would be able to have a robust and more global understanding of the dynamical behavior of ICMEs and their Sun–Earth relationship.

Fortunately or unfortunately, the extended current long solar minimum has provided just a few events to analyze, but the advantage is that all of them have been the focus of a number of papers. The June 1st and 2nd of 2008 event has been one of those events that has produced an extensive amount of research papers (Robbrecht et al., 2009; Möstl et al., 2009; Kramar et al., 2009; Wood et al., 2010; Bisi et al., 2010; Lynch et al., 2010). This event has two main characteristics: one is that the source is not well defined and it is not associated with flares, not even with long duration flares, disappearance of filaments or EUV dimming associated with CMEs (Thompson et al., 1998). It means that the lack of signatures on-disk could have been a reason to catalogue this event as a backside CME according to standard criteria used. So this event is referred as 'storm problem' (Robbrecht et al., 2009 and references therein), because it could be of the 20% group of geoeffective ICMEs reported by Schwenn et al. (2005), which were not preceded by an identifiable frontside halo CME. The second characteristic is the particular configuration of the CME with the twin STEREO spacecraft. In this case, the remote sensing analysis has been possible and has allowed tracking the evolution and expansion of the ICME (Möstl et al., 2009).

Prior to the initiation event of 1st and 2nd of June 2008, the COR1 and COR2 images from STEREO mission are total brightness images. Following a streamer the CME entered the COR2A telescope field of view of STEREO A and a faint partial halo on COR2B. The streamer swelling and its partial disappearance after the CME erupted, and the slow evolution of the CME with flux-rope structure identify this event as a streamer-blow-out CME (Vourlidas et al., 2002). However, this event is not associated with any signature on the disk, i.e., the EUV and Hα imaging do not show any feature on the lower corona, which means that a clear source region has not been observed (Robbrecht et al., 2009). The initiation and the influence of this event on the ambient corona have been the issue of others papers (Kramar et al., 2009). On the other hand, the *in situ* data from STEREO B on the days June 6th and 7th show the typical signatures of ICMEs (Möstl et al., 2009). In addition, the angle separation (53°), as well as the absence of equatorial coronal holes, allows the interpretation of the HI1 images by STEREO A. Through this analysis, with the technique developed by Davis et al. (2009), it has been possible to provide information about the measurement of the edge and core distances during the ICME trip in the interplanetary medium (Möstl et al., 2009). This kind of analysis has allowed us to link the remote imagery to the *in situ* signatures, thanks to the set of instruments onboard the STEREO mission and has provided information about the characteristics of the propagation of CMEs through the heliosphere.

In this paper we combine data from different instruments such as PLASTIC and IMPACT onboard STEREO B in order to provide the overall picture of this ICME to complete the remote sensing analysis done with SECCHI onboard STEREO A. Within this context, we present a comprehensive physical model, where the inclusion of the plasma is taken into account in order to understand and characterize the magnetic field and plasma parameters.

2. *In situ* observations

As a consequence of the CME observed by STEREO from June 1st to 2nd of 2008, the *in situ* data from STEREO B show the typical signatures of an ICME in the magnetic field and plasma data. Magnetic field data, in RTN coordinates were obtained from IMPACT-MAG (Acuña et al., 2008; Luhmann et al., 2008) and