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Study of local regularities in solar wind data and ground magnetograms

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A B S T R A C T

Interplanetary coronal mass ejections (ICMEs) can reach the Earth's magnetosphere causing magnetic disturbances. For monitoring purposes, some satellites measure the interplanetary parameters which are related to energy transfer from solar wind into magnetosphere, while ground-based magnetometers measure the geomagnetic disturbance effects. Data from the ACE satellite and from some representative magnetometers were examined here via discrete wavelet transform (DWT). The increase in the amplitude of wavelet coefficients of solar wind parameters and geomagnetic field data is well-correlated with the arrival of the shock and sheath regions, and the sudden storm commencement and main phase, respectively. As an auxiliary tool to verify the disturbed magnetic fields identified by the DWT, we developed a new approach called effectiveness wavelet coefficient (EWC) methodology. The first interpretation of the results suggests that DWT and EWC can be effectively used to characterize the fluctuations on the solar wind parameters and their contributions to the geomagnetic field. Further, this kind of technique could be implemented in quasi real-time to facilitate the identification of the shock and the passage of the sheath region which sometimes can be followed by geoeffective magnetic clouds. Also, the technique shows to be very useful for the identification of time intervals in the dataset during geomagnetic storms which are associated to interplanetary parameters under very well defined conditions. It allows selecting ideal events for investigation of magnetic reconnection in order to highlight in a more precise manner the mechanisms existing in the electrodynamical coupling between the solar wind and the magnetosphere.

1. Introduction

An important kind of solar phenomenon is the coronal mass ejection (CME) because it can cause geomagnetic storms. This event can easily reach space regions close to 1 AU and it can be designated as an interplanetary coronal mass ejection (ICME). The term magnetic cloud (MC) is used to characterize an ICME having a specific configuration such as an enhanced magnetic field strength, a smooth rotation of the magnetic field vector and low proton temperature and plasma density (e.g., Burlaga et al., 1981; Klein and Burlaga, 1982; Gosling, 1990).

Near 1 AU, MCs have approximately 0.25 AU radial sizes with an average duration of 27 h, an average peak magnetic field strength of 18 nT, and an average solar wind speed of about 420 km/s (e.g., Klein and Burlaga, 1982; Goldstein, 1983; Lepping and Berdichevsky, 2000). Inside ICMEs, the measured plasma velocity has typically a linear variation along the spacecraft trajectory. However, a much higher velocity is present in the front of the MC than in its rear which indicates expansion (Démoulin and Dasso, 2009). Burlaga and Behannon (1982) found consistency between the expansion speed estimated from in situ observations and the increase of their typical size obtained from measurements with different spacecraft located between 2 and 4 AU. The MCs

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closer than 1 AU to the Sun presented higher plasma densities than the surrounding solar wind. Thus, the density inside the flux tubes has a rapid decrease with the increasing distance from the Sun where the cloud undergoes a radial expansion.

When the MC is moving faster than the surrounding solar wind (SW), plasma and magnetic field accumulate, in principle, in front of it, forming a disturbed region called sheath region. The studies on the dynamics of those kinds of electrodynamic structures are among the current concerns of the space community (Bothmer and Schwenn, 1994; Ojeda et al., 2005, 2013; Chian and Muñoz, 2011). Many studies about the characteristics of MCs have been carried out over the last three decades (e.g., Klein and Burlaga, 1982; Lepping et al., 1990; Dasso et al., 2005; Ojeda et al., 2013). Many authors summarized the occurrence of interplanetary coronal mass ejection (ICME) in the near-Earth solar wind (Bothmer and Rust, 1997; Bothmer and Schwenn, 1998; Mulligan et al., 1998; Lynch et al., 2003; Wu et al., 2003; Huttunen et al., 2005; Nieves-Chinchilla et al., 2005; Cane and Richardson, 2003; Richardson and Cane, 2010). In this paper, we analyze solar plasma records concerning to the occurrence of ICMEs using an alternative wavelet technique algorithm developed by Mendes et al. (2005) and applied in Mendes da Costa et al. (2011) to study the geomagnetic storm behavior. Motivated by these earlier works, we deal with time variations of solar wind parameters due to solar events to verify their behaviors immediately before reaching the Earth, the "cause", and the "effect" of the solar wind–magnetosphere interaction, the geomagnetic storm, in ground magnetograms.

According to Farrugia et al. (1993), MCs can be used for the study of the solar wind energy input to the magnetosphere since the interplanetary magnetic field (IMF) components vary smoothly with time and retain the polarity for relatively long intervals. This is the main purpose of this work which provides an assessment to the electrodynamical coupling by investigating the level of regularity in "source" signal and "effect" signals. The efforts intend to verify the increase of wavelet coefficient amplitudes in signals associated to ICMEs propagation and to relate the effectiveness of this period of non-regularity with the development of geomagnetic storms. The proposed approach can be an auxiliary tool in the future for the investigation of solar wind energy transfers to the magnetosphere in periods of well-identified behavior. Thus, here, the discrete wavelet transform (DWT) has been applied to detect small (and nonlinear) transients in solar parameters and geomagnetic data. In order to develop this study, one year of data was investigated. The period of April 2001 which corresponds to the events during the solar maximum of the 23rd solar cycle was analyzed and presented as an example. Most of these magnetic storms in April 2001 were associated with MCs occurrence although shocks have also been observed.

The content of the paper is organized as follows. Section 2 is devoted to give a brief introduction on geomagnetic storms, showing an example of solar-interplanetary-magnetosphere coupling. Section 3 presents the data and the analyzed period, and the methodology implemented. Section 4 gives the results and a discussion on them. Finally, Section 5 brings the conclusion of this work.

2. Geomagnetic storm

The primary causes of geomagnetic storms are supposed to be strong dawn-to-dusk electric fields associated with the passage of southward directed interplanetary magnetic fields, B_s, passing the Earth for sufficiently long time intervals. The solar wind energy transfer mechanism is the magnetic reconnection between the IMF and the Earth's magnetic field (Dungey, 1961; Gonzalez et al., 1994). The most commonly used coupling function for the solar wind–magnetosphere interaction related to electric field is $E_y = VB_s$, see Gonzalez et al. (1994) for more details.

As a consequence, the level of magnetosphere activity varies widely. Geomagnetic activity is classified by intensity and usually described by the variation of indices to distinguish between a quiet and a disturbed day (occurrence of storms or substorms). The index mostly used in order to quantify the effects on low latitudes is the Dst index (Sugiura and Kamei, 1986), and more recently, Sym-H (Iyemori, 1990). Dst represents the variations of the H component due to changes of the ring current. The Sym-H is essentially a 1-min version of the traditional hourly Dst index. The main characteristic of the 1 min time resolution Sym-H index is that the effects of solar wind dynamic pressure variation are more clearly seen than in indices with lower time resolution (Wanliss and Showalter, 2006). Its calculation is based on magnetic data provided by eleven stations on low and medium latitudes. Each month only six stations are used for its calculation, some stations can be replaced by others depending on data conditions (Iyemori, 1990).

The principal defining property of a magnetic storm is the enhancement of the ring current due to the increase of the trapped magnetospheric particle population. These particles present a drift due to magnetic field curvature and gradient which leads the ions to move from midnight to dusk and electrons from midnight toward dawn surrounding the Earth close to the dip equator (Gonzalez et al., 1994).

The geomagnetic storms consist of four phases: sudden commencement, initial phase, main phase and recovery phase (Gonzalez et al., 1994). The characteristic signature of a magnetic storm is a depression in the horizontal component of the Earth's magnetic field (H) which is used to calculate the Dst index. In general, geomagnetic storms begin with a sudden impulse due to the arrival of the interplanetary shock structure (Sudden Storm Commencement – SSC) what generally coincides with the increased ram pressure and, consequently, an increase of the Dst values (initial phase) followed by a "negative excursion" in the Dst index which indicates sustained southward interplanetary fields (main phase) and the return to normal conditions (recovery phase) as discussed in Gonzalez et al. (1994).

3. Dataset and analysis methodology

In this section, we present the ACE satellite data used to characterize the variations of solar parameters due to ICMEs propagation. We will also present the data used to analyze the effects of the magnetospheric activity identified on the ground. Our study consists in verifying the magnetic events that occurred in April 2001. These solar events occurred during the solar maximum of the 23th solar cycle. The method used here is based on the Discrete Wavelet Transform (DWT) to verify the increase of wavelet coefficient amplitudes in the signals associated to the ICMEs propagation and to relate the effectiveness of this period of non-regularity to the development of geomagnetic storms.

3.1. ACE satellite data

In this paper, the effects of the solar activity upon the Earth and the space close to it were studied using ACE satellite data and the Sym-H index. Both of these datasets are available at the NOAA web site (SPIDR, 2008). The data for ground behavior analysis will be presented in the next section.

Our interest is to characterize the variations on the solar parameters related to the ICMEs propagation. For that reason, we selected the IMF components (Bx, By, Bz in GSE coordinate),