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Analysis of behavior of solar wind parameters under different IMF conditions using nonlinear dynamics techniques

Arian Ojeda*, Alexander Calzadilla, Bienvenido Lazo, Katy Alazo, Siomel Savio

Department of Space Geophysics, Institute of Geophysics and Astronomy, Havana City, Cuba

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Abstract

We select time windows in time series of solar wind for a group of magnetic clouds and plasmoids to analyze the dynamical behavior of the IMF B_z component and the V_x flux velocity component. Besides, we select time windows before the occurrence of magnetic clouds to analyze the solar wind behavior under "normal" conditions. These physical variables are characterized applying two techniques adopted from the nonlinear dynamics theory, the spatio-temporal entropy (STE) and the correlation time (τ). They were calculated for each time window using the chaos data analyzer (CDA) and visual recurrence analysis (VRA) software. The obtained results show that under magnetic cloud conditions, the IMF B_z has the tendency to longer correlation times and lower values of STE. Besides the V_x component of the solar wind flux has a complex behavior in all studied cases.

Keywords: Solar wind–magnetosphere coupling; Magnetic clouds; Plasmoids; Signal processing; Spatio-temporal entropy; Correlation time

1. Introduction

Since the last decades of the past century, modern methods for the nonlinear analysis of time series have been developed and systematized, as show in the excellent book of Kantz and Schreiber (1997). These modern methods of nonlinear analysis are very useful for studying complex phenomena of different nature. They contribute to improve our understanding of diverse physical, chemical, biological, economic or social processes; beside, they provide a better modeling capacity and forecasting.

A lot of work has been carried out to characterize the dynamics of the solar wind–magnetosphere coupling system (Vassiliadis et al., 1991; Shan et al., 1991a, b; Baker et al., 1990, 1991; Klimas et al., 1996, 2000; Calzadilla and Lazo, July 2001). In general, these studies have been devoted to analyze time series of some geomagnetic index (AE, AL and Dst) and physical parameters of the solar wind like the components of the interplanetary magnetic field, the speed and density of the solar plasma.

In the context of space weather studies, it is very important to investigate and understand the solar mass ejections to the interplanetary media; in particular those classified as magnetic clouds. The term "magnetic clouds" was introduced to describe particular phenomena with the following properties according with Burlaga's work (Burlaga et al., 1981, 1982; Schwenn and Marsch, 1991):

- The magnetic field direction rotates smoothly through a large angle during a time interval of the order of 1 day.
- The magnetic field strength is higher than average.
- The temperature is lower than average.

*Corresponding author. Tel.: +53 537 2714331; fax: +53 537 2739497.
E-mail address: arian@iga.cu (A. Ojeda).

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All the last conditions must be satisfied at the same time if an event is to be identified as a magnetic cloud. Any one of the aforementioned criteria can be observed in the absence of a magnetic cloud. A practical criterion to detect magnetic cloud is characteristically low β plasma, since the plasma pressure is lower than the magnetic pressure in a magnetic cloud event by definition.

These types of phenomena travel in the interplanetary media; when arriving to the terrestrial orbit, they may affect the geomagnetic activity to a greater or lesser degree. Using the information on physical parameters of the solar wind reported by orbiting spacecraft (WIND) with a time resolution of 1 min, we can apply the techniques of nonlinear dynamics to study the evolution of magnetic clouds.

From the total energy transported by the solar wind, just a small fraction of ~5% is able to penetrate the magnetopause or reach the terrestrial magnetosphere. These energy transfers occur by two fundamental physical processes, the magnetic reconnection and the viscous type interaction: The magnetic reconnection implies an interaction between the interplanetary magnetic field and the terrestrial magnetic field in the diurnal side of the magnetosphere (Dungey, 1961), as well as in other regions (Song et al., 2000).

Non-magnetic mechanisms of coupling or transport are usually referred to as interaction of viscous type. They imply a transfer of tangential momentum through the magnetopause by means of some type of viscous drag generated by macro or micro instabilities in the plasma (Axford and Hines, 1961).

The viscous-type interactions include two fundamental physical mechanisms:

- The diffusion of particles through the magnetopause by means of the stochastic dispersion of resonant waves (Tsurutani and Thorne, 1982).
- The Kelvin–Helmholtz instability at the flanks of the magnetopause which typically occurs during the evolution toward a nonlinear regime.

This paper is a contribution to contemporary space weather studies. Using two nonlinear dynamics techniques, we compare the results obtained from the study of magnetic clouds and plasmoids that reach the earth magnetosphere. We use the D_{st} index as a measure of the geomagnetic field perturbation at low latitudes and time series of the solar wind parameters to estimate the correlation and the entropy of solar wind–magnetosphere coupling dynamics.

2. Data

We have analyzed time series of 20 magnetic cloud events (with the best temporal continuity) selected from the group of 58 events reported on the NASA web site: http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_table.html.

The studied time series represent physical parameters of the solar wind (interplanetary magnetic field and velocity components in the plasma flow) recorded by the WIND satellite with the time resolution of 1 min. To characterize the level of disturbance in the geomagnetic field at the global scale during the passage of magnetic clouds or plasmoids, we take the lowest value of the geomagnetic D_{st} index reached at every time window selected. (The Dst index is available at the NOAA web site http://spidr.ngdc.noaa.gov/index.html). The dates of the plasmoids and time intervals of quiet solar wind parameters analyzed in our work are shown in Tables 1 and 2 (magnetic clouds occur approximately 48 h after the quiet solar wind window in every case analyzed).

All the analyzed data (58 time series) have some gaps. We selected the best time series, just 20 of the total with a few temporal gaps. To fill these gaps, we used a routine written in Borland Delphi 6 for linear interpolation according to the method proposed by Price et al. (1994). This method is applicable due to the fact that the characteristic times involved in the dynamics of the behavior of studied time series are much longer than the interpolated intervals. Under this condition, one can assume that no extra noise is introduced in the time series due to the interpolation.

3. Used methods

We used the CDA software (Chaos Data Analyzer, 1995, http://sprott.physics.wisc.edu) to obtain the correlation time (τ) from the correlation function. The correlation function Eq. (1) is obtained by multiplying each data point represented for $X(t)$ (where "t" is the positional order in the time series) by $X(t–\tau)$ and summing the result over all the data points. The parameter τ or time delay (Takens, 1981), is the number of data points that varies starting from a particular data point under analyzes.

$$F(\tau) = \frac{\sum_{i=1}^{N} X(t_i) + N\sum_{i=\tau+1}^{N} X(t_i)X(t_i-\tau)}{F(0)}; \quad \tau = 0, 1, \ldots, N-1. \tag{1}$$

The sum is then plotted as a function of τ. This gives a measure of how dependent data points are on their temporal neighbors. The value of τ at which the correlation function first falls to $1/e$ is taken here to be the correlation time of the time windows selected. Highly random data have no correlation, and their correlation function drops abruptly to zero implying small correlation time. Highly correlated data like the output of a sine wave generator will have a correlation function that varies with τ but whose amplitude decreases slowly.