Characterization of Alfvén fluctuations in the solar wind near Earth

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Resumen / El medio Sol-Tierra presenta un comportamiento complejo, dominado por interacciones no lineales y recorriendo estados fuera del equilibrio. Específicamente, la magnetosfera terrestre es un sistema altamente dinámico que continuamente intercambia energía y cantidad de movimiento con el viento solar, principalmente mediante procesos de reconexión magnética, causando tormentas y subtormentas geomagnéticas. Sin embargo, el entendimiento de la respuesta magnetosférica a las variaciones en el viento solar continúa siendo un problema abierto dada la amplia variedad de mecanismos involucrados. En particular, diversos estudios sugieren que la turbulencia Alfvénica podría tener un rol importante en el nivel de acoplamiento entre el viento solar y la magnetosfera. En este trabajo se analizarán datos interplanetarios del plasma y del campo magnético, medidos por instrumentos a bordo del satélite ACE (Advanced Composition Explorer), que se encuentra en el punto Lagrangiano L1. Se presentará un análisis de la turbulencia magnetohidrodinámica y su carácter Alfvénico para diferentes regímenes del medio interplanetario en las cercanías del entorno terrestre.

Abstract / The Sun-Earth medium presents a complex behavior, dominated by non-linear interactions and going through states out of equilibrium. Specifically, the terrestrial magnetosphere is a system highly dynamic which continuously interchange energy and momentum with the solar wind, mainly through magnetic reconnection processes, causing geomagnetic storms and substorms. However, understanding the magnetospheric response to the solar wind variations remains an open problem given the wide variety of mechanisms involved. In particular, diverse studies suggest that Alfvenic turbulence could play an important role in the amount of coupling between the solar wind and the magnetosphere. In this work, interplanetary plasma and magnetic field data will be analyzed, measured by instruments aboard the ACE (Advanced Composition Explorer) satellite, which is located at the L1 Lagrange point. A study of the magnetohydrodynamic turbulence and its Alfvenic character will be presented for different regimes of the interplanetary medium in the proximity of the terrestrial medium.

Keywords / solar wind — solar–terrestrial relations — magnetic reconnection — magnetohydrodynamics (MHD) — turbulence

1. Introduction

Turbulence is an ubiquitous phenomenon. Whenever fluids characterized by a high Reynolds number are set in motion, turbulence tends to develop (Biskamp, 2003). Particularly, when a fluid is electrically conductive, turbulent movements are accompanied by magnetic field fluctuations.

In this context, the Alfvén effect describes small-scale turbulent fluctuations as Alfvén waves weakly interacting and propagating along the large-scale field. The strong Alfvenic nature of the magnetohydrodynamic (MHD) turbulence is due to the fact that this mode has a greater presence than other magnetohydrodynamic modes.

Our main motivation to study the activity of Alfvén waves lies in recent published results suggesting that Alfvenic turbulence could be playing an important role in the coupling between the solar wind and the magnetosphere (D'Amicis et al., 2007). This is due to the fact that important variations of the geomagnetic field have been observed in the absence of intense disturbances in the solar wind like interplanetary coronal mass ejections (ICMEs) and co-rotating interaction regions (CIRs).

Through this research, we aim to bring forward the magnetohydrodynamic turbulence and Alfvenic activity, by means of the characterization of Alfvén fluctuations in the solar wind near Earth, at 1 au.

2. Theoretical framework and data

2.1. MHD turbulence

By solving the MHD equations for an homogeneous plasma, described by a state of equilibrium with pressure p_0 and density ρ_0, embedded in an homogeneous magnetic field $\mathbf{B}_0$, where fluctuations are small enough, three modes are obtained: fast magnetoacoustic waves, slow magnetoacoustic waves, and Alfvén waves.

Focusing on the last mode mentioned, an important property is the correlation among velocity and magnetic

Poster contribution

field fluctuations, which fulfills:

$$\mathbf{v} = \pm \frac{\mathbf{b}}{\sqrt{4\pi\rho_0}}, \tag{1}$$

where $\mathbf{v}$ and $\mathbf{b}$ are the velocity and magnetic field fluctuations, respectively, and ρ_0 is the mean mass density.

The fundamental effect of the Alfvén waves in magnetohydrodynamics is manifested more clearly by reformulating the MHD equations in terms of the Elsässer fields (named as $\mathbf{z}^{\pm}$):

$$\mathbf{z}^{\pm} = \mathbf{v} \pm \frac{\mathbf{b}}{\sqrt{4\pi\rho_0}}. \tag{2}$$

Assuming incompressibility, linearizing the MHD equations for small fluctuations over $\mathbf{B}_0$ and neglecting dissipation, a reduced version of these equations is obtained:

$$\frac{\partial \mathbf{z}^{\pm}}{\partial t} \mp \mathbf{B}_0 \cdot \nabla \mathbf{z}^{\pm} = 0. \tag{3}$$

In Eq. 2, $\mathbf{z}^{\pm}$ represents the two possible Alfvén wave modes, one propagating parallel to $\mathbf{B}_0$, and the other mode, propagating anti-parallel. Due to that, when Alfvén waves are present they travel away from the Sun, for a $\mathbf{B}_0$ outward from the Sun, the present mode corresponds to $\mathbf{z}^{-}$, denoting a parallel propagation with respect to $\mathbf{B}_0$. By contrast, for a $\mathbf{B}_0$ inward to the Sun, $\mathbf{z}^{+}$ results in the present mode, which implies an anti-parallel propagation with respect to $\mathbf{B}_0$.

The energy related to $\mathbf{z}^{+}$ and $\mathbf{z}^{-}$ modes is given by (e.g., Bruno & Carbone, 2013):

$$e^{\pm} = \frac{1}{2}\langle (z^{\pm})^2 \rangle. \tag{4}$$

By means of the normalized difference of the energy between the two modes, called normalized cross-helicity, the relative weight of each Elsässer field can be analyzed and therefore the state of turbulence:

$$\sigma_c = \frac{e^{+} - e^{-}}{e^{+} + e^{-}}. \tag{5}$$

For a pure Alfvén wave oriented in an outward or inward direction, that is to say, aligned with the background interplanetary magnetic field, the values σ_c=±1 are expected. While for fully developed turbulence $\sigma_c \sim 0$ is expected.

2.2. Data

To perform this work, interplanetary data from the Advanced Composition Explorer (ACE) satellite, which is located at the Lagrange point L1, is analyzed. Plasma measurements (solar wind speed and proton density) are obtained from the Solar Wind Electron Proton Alpha Monitor (SWEPAM) instrument, while magnetic field measurements are obtained from the Magnetometer instrument (MAG). Both the solar wind speed and the magnetic field are in GSE (Geocentric Solar Ecliptic) coordinates.

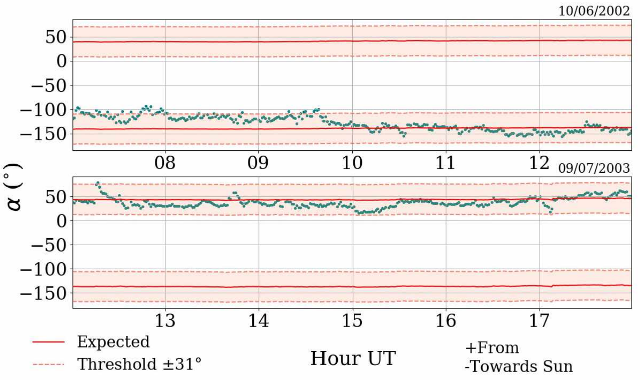

Figure 1: Characterization of the IMF through the angle resulting from the IMF projection in the ecliptic plane and the Sun-Earth line, named α. In the *upper panel*, an IMF directed towards the Sun, and, in the *lower panel*, an IMF directed towards the Earth, both cases defined by the Parker spiral. Green dots represent observed α values.

With the purpose of studying the two possible Alfvén modes, two distinct cases are selected, one where the background interplanetary magnetic field (IMF) $\mathbf{B}_0$ is directed towards the Sun, and the other where $\mathbf{B}_0$ is directed towards the Earth. Both cases have a period of 6 hours with a temporal cadence of 64 seconds, one on June 10, 2002, from 7 to 12 UT, and the other on July 9, 2003, from 12 to 18 UT, respectively. It is important to emphasize the absence of interplanetary structures, such as ICMEs or CIRs, during the aforementioned periods.

3. Methodology

According to theory, Alvenic fluctuations are perpendicular to $\mathbf{B}_0$, hence, the two case studies selected are characterized by the Parker spiral with the purpose of analyzing these fluctuations, some of which are expected to be found along the $\hat{z}$ component. Although fluctuations can also occur in other components, in order to simplify the study, it was decided to focus on the $\hat{z}$ component.

Fig. 1 shows the tool used to identify the two Parker-characterized periods, which was generated in a previous study (Dorsch et al., 2021). The tool presents the α angle, which is formed by the IMF projection in the ecliptic plane and the Sun-Earth line, where the solid lines point out the two expected angles according to Parker spiral and the dotted line, which stands at ± 31° of the expected value, denotes the threshold up to which a Parkerian behavior is still considered (indicated by the shaded region). If the data is within the threshold associated with positive values, which occurs in the interval during July 9, 2003, then $\mathbf{B}_0$ is directed towards the Earth. On the other hand, if it is within the threshold associated with negative values, which occurs in the interval during June 10, 2002, then $\mathbf{B}_0$ is directed towards the Sun.

Once the periods are selected, the Elsässer fields are calculated, using Eq. 2, in order to analyze the corre-

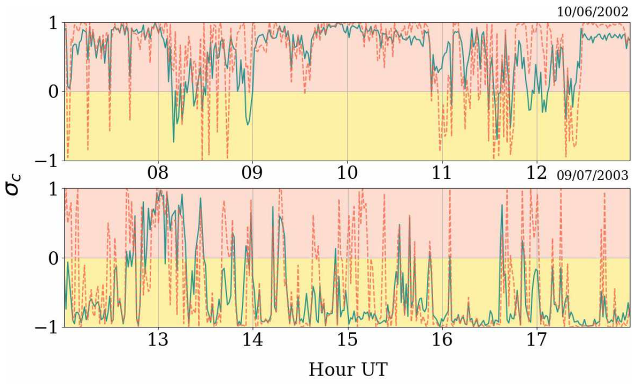

Figure 2: Normalized cross-helicity for a period with an IMF towards the Sun, in the *upper panel*, and for a period with an IMF towards the Earth, in the *lower panel*. Indicated in solid lines, the σ_c resulting from considering all the Elsässer field components, while in dotted lines considering only $\hat{z}$ component.

lation between $\mathbf{v}$ and $\mathbf{b}$. Then, throughout Eq. 4 the energy associated with the $\mathbf{z}^+$ and $\mathbf{z}^-$ modes is calculated. Lastly, using the normalized cross-helicity defined by Eq. 5, the state of Alfvenicity/turbulence is determined by relating the energy resulting from the $\mathbf{z}^+$ and $\mathbf{z}^-$ modes. In addition to the total σ_c, the σ_c associated with the $\hat{z}$ component of $z^{\pm}$ is calculated with the purpose of identifying and analyzing the energy related to the polarization of the fluctuations in $\hat{z}$.

4. Results

The resulting normalized cross-helicity for the two periods is shown in Fig. 2.The upper panel shows the period where $\mathbf{B}_0$ is towards the Sun, during June 10, while the bottom panel shows the period where $\mathbf{B}_0$ is towards the Earth, during July 9. For both cases, the solid line indicates the total σ_c while the dotted line indicates the σ_c associated with $z^{\pm}$ $\hat{z}$ energy.

It is apparent the tendency of σ_c towards positive values for the case where $\mathbf{B}_0$ is in the direction of the Sun, and towards negative values for the case where $\mathbf{B}_0$ is in the direction of the Earth. In the first case, this indicates that the energy associated with the $\mathbf{z}^+$ mode prevails over that associated with the $\mathbf{z}^-$ mode. On the contrary, in the second case, the tendency to negative values denotes a predominance of $\mathbf{z}^-$ energy over $\mathbf{z}^+$ energy.

In both periods, and mainly in the one with $\mathbf{B}_0$ towards the Sun, the occurrence of Alfvenic fluctuations can be observed, where the value of σ_c approaches ± 1. For the case of June 10, Alfvenic fluctuations are observed over the second half of 7 UT, between 9 UT and 11 UT, and over the second half of 12 UT. For the case of July 9, although the Alfvenic fluctuations are not as present as during the aforementioned case, these are observed principally over the first half of 16 UT and most part of 17 UT.

On the other hand, intervals in which σ_c approaches to 0 indicate turbulence in process or already developed, where the Alfvenic character vanishes since non-linear modes start to acquire relevance.

Comparing the energy of the $\hat{z}$ component with the total energy of the Elsässer fields, for the intervals with Alfvenic fluctuations, it can be noticed the resemblance. This result indicates that in $\hat{z}$, which corresponds to a component perpendicular to $\mathbf{B}_0$, z^+ or z^- dominates, depending on the orientation of the IMF. The slight deviation of the total σ_c is due to the fact that it also includes parallel fluctuations.

5. Conclusion and future work

In this work, two Alfvén waves modes were identified, which allowed us to prove that such waves propagate in an outward direction from the Sun.

The similitude between the normalized cross-helicity associated with $\mathbf{z}^{\pm}$ and with $z^{\pm}$ $\hat{z}$ denotes that the polarization of the Alfvén fluctuations is in the direction of this component, which is perpendicular to $\mathbf{B}_0$ direction and the Alfvén wave propagation.

Therefore, we were able to characterize the Alfvén waves propagation and the polarization of their fluctuations. Moreover, we observed the presence of Alfvenic fluctuations in the interplanetary medium of the terrestrial environment.

This work presents the foundations and motivates the future investigation of the impact of Alfvén MHD turbulence in solar-terrestrial coupling and its effects on geomagnetic activity.

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References

Biskamp D., 2003, *Magnetohydrodynamic Turbulence*, Magnetohydrodynamic Turbulence, Cambridge University Press

Bruno R., Carbone V., 2013, Living Rev. Sol. Phys., 10, 2

D'Amicis R., Bruno R., Bavassano B., 2007, Geophys. Res. Lett., 34, L05108

Dorsch B.D., et al., 2021, BAAA, 62, 10