Is Solar Wind Turbulence a Driver of Geomagnetic Activity at Mid-Low Latitudes?

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Research Article

Abstract: The coupling of solar wind to the magnetosphere is one of the widely studied dynamical processes that characterize the Sun-Earth coupled system. In this work, the effects of solar wind magnetohydrodynamic (MHD) turbulence on geomagnetic field at the mid-low latitudes during the year 2009 when the Sun nearly plunged into the Maunder minimum was studied statistically. We characterized the MHD Alfvénic turbulence by means of 2-D histograms and related these histograms to the behaviour of geomagnetic activity at mid-low latitudes as measured by ASY-D, ASY-H, SYM-D, and SYM-H indices. We discovered that geomagnetic activity at mid-low latitudes is not driven by solar wind Alfvénic turbulence during period of low solar activity.

Keywords: Alfvén waves, cross-helicity, geomagnetic field, mid-low latitudes, residual energy, solar wind.

1. Introduction

Solar wind is a magnetofluid, a quasi-neutral fluid that fluctuates over a wide range of scales as it travels away from the solar corona into the interplanetary medium. The very high temperature of the sun enables the solar wind to escape the gravity of the sun and expand into the interplanetary medium; being modified by the effects of dynamics in the process. Also, the gain in kinetic energy of the energized and charged particle constituents of the solar wind as the wind expands contributes to its ability to escape the very high gravity of the sun. Solar wind could be seen as a mixture of magnetohydrodynamic (MHD) Alfvénic fluctuations [4, 12]. Large scale, quasi-steady geomagnetic perturbations are controlled by interplanetary magnetic field and solar wind parametes. Badruddin and Singh [1] observed a coupling in the plasma density/pressure on solar wind and fluctuations in geomagnetic fields, hours before the onset of storm activity and suggested a link to the enhancement of solar wind – magnetosphere coupling efficiency. Smith [11] established a link between magnetic flux and solar wind mass flux in the heliosphere. Incompressive quasi 2-D fluctuations are the predominant component of turbulence in solar wind, hence non-compressive MHD could be used to model turbulence in solar wind both in collisional and collisionless state [5]. MHD turbulence with negligible cross-helicity is supported by theoretical studies of Goldreich and Sridhar [8], and numerical simulations of Choi and Vishniac [6], and Müller and Biskamp [10].

2. Materials and Method

One year (2009) solar wind 1-minute data were got from OMNI website (http://omniweb.gsfc.nasa.gov/ow.html) from solar wind plasma and magnetic field experiments, and geomagnetic activity indices (ASY-D, ASY-H, SYM-D, and SYM-H) 1-minute data of corresponding period were downloaded from the World Data Center, C2, Kyoto, Japan. Solar wind consists of isotropic Alfvén wave packets that interact weakly and non-linearly with one another only when they propagate in opposite directions in a plasma rest frame (Iroshnikov, 1963 and Kraichnan, 1965 as in Chandran, [5]. Alfvén waves travelling away from the sun do not interact with one another, but interact with Alfvén waves travelling towards the sun. Turbulence plays a major role in the study of solar wind-magnetosphere interaction as both solar wind and magnetosphere are characterized by high Reynold's number [3, 9]. The continual vibrations of the open magnetic field lines by convective motions in the photosphere can launch Alfvén waves. A mix of the outward-propagating Alfvén waves and inward-propagating Alfvén waves are needed to generate the Alfvén energy cascade. In this study, we analyzed the role played by Alfvén wave turbulence in solar wind as represented by cross-helicity and residual energy. A measure of the outward-propagating Alfvén waves over inward-propagating Alfvén waves is called cross-helicity or it is the correlation between velocity and magnetic field vectors in a turbulent flow. Tu and Marsch [12] defined the normalized cross-helicity,σ_C as:

$\sigma_C = e^+ - e^- / e^+ + e^-$ (2.1)

where e^+ is the energy per unit mass associated with the z+ mode and e^- is the energy per unit mass associated with the z^- mode. The $z^\pm$ the Elsässer variable that refers to a positive (negative) correlation/mode. A positive mode travels away from the sun while a negative mode travels towards the sun. Elsässer (1950) as in [12] defined the variables as:

$z^{\pm} = v \pm b$ (2.2)

where v is the velocity of the solar wind and **b** is the magnetic field expressed in Alfvén speed units. In other words, $b = B/\sqrt{4\pi\rho}$ where B is the magnetic field in nT and ρ is the proton density in n/cc.

The residual energy measures the energy per unit mass between kinetic energy, e^{v} and magnetic energy, e^{b}. Tu and Marsch [12] defined the normalized residual energy, σ_R as:

$\sigma_R = e^{v} - e^{b}/e^{v} + e^{b}$ (2.3)

where $e^{v} = {}^{1}/_{2}(v^2)$ and $e^{b} = {}^{1}/_{2}(b^2)$. Both σ_C and σ_R are in Alfvén units. For Alfvénic fluctuations, $\sigma_C = \pm 1$ and $\sigma_R = 0$. Equipartition means $\sigma_R = 0$. Absolute values of σ_C less than 1 means that non- Alfvénic fluctuations exist in the solar wind parameters.

The z components of the interplanetary magnetic field and velocity (b_z *and* v_z respectively) were selected from OMNI website as they are more Alfvénic than the x and y components [12] but this choice does not completely eliminate other turbulences that are not Alfvénic in nature. The magnetic field line directions were then evaluated using **sign** $B(t).\langle B \rangle$, where $B(t)$ is the hourly magnetic field line time series and $\langle B \rangle$ is the 12 hour average of the magnetic field which is the best scale to describe large-scale turbulence like solar wind [12]. The normalized cross-helicity and normalized residual energy were calculated at 1 hour scale using (2.1) and (2.3) respectively as solar wind shows more Alfvénicity at this scale [1]. 2-D histograms of $\Delta\sigma_2 - \Delta\sigma_R$ were then plotted to determine if there were Alfvénicity or not. Then we calculated one hour average values of ASY-D, ASY-H, SYM-D, and SYM-H in each square bin of $\Delta\sigma_C - \Delta\sigma_R$ to reveal any statistical relationship between solar wind and geomagnetic activity.

3. Observations and Results

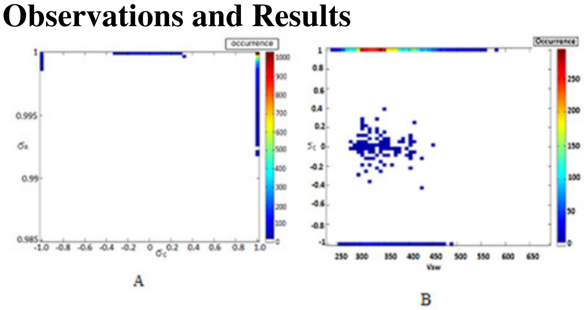

Figure 3.1: 2-D histograms showing the distributions of σ_R and σ_C (A), and solar wind speed, V_{SW} respectively.

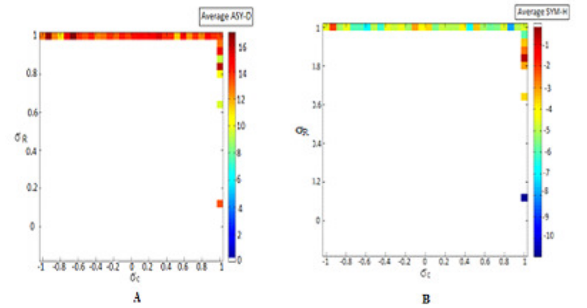

Figure 3.2: Average values of ASY-D (A) and ASY-H (B) in every square bin of $\Delta\sigma_C - \Delta\sigma_R$.

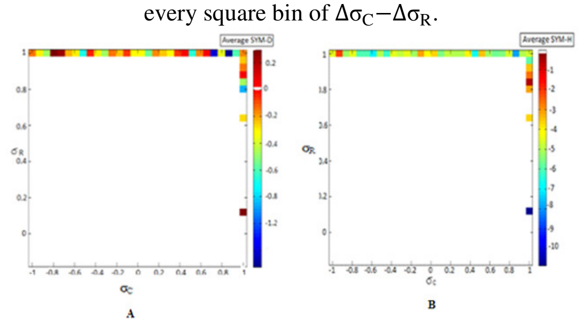

Figure 3.3: Average values of SYM-D (A) and SYM-H (B) in every square bin of $\Delta\sigma_C - \Delta\sigma_R$

Figure 3.1 (A) represents the distribution of σ_C and σ_R in a 2-D histograms showing peaks corresponding to $\sigma_C = 1$, and $\sigma_R = 1$ and the solar wind speed is generally low, $v_{SW} < 400\text{k m}^{-1}$ (fig. 3.1B). Figures 3.2 and 3.3 are the 2-D histograms of the mean peak values of the geomagnetic indices (ASY-D, ASYH-H, SYM-D, and SYM-H respectively). The peak values are scattered over two quadrants of the histograms. The residual energy, $\sigma_R = +1$ and cross-helicity, $\sigma_C = \pm 1$.

4. Discussion

Results from fig.3.1A suggest high Alfvénic turbulence that are carried outwards by slow wind, $v_{SW} < 400\text{k m}^{-1}$ (fig. 3.1B) with the predominance of kinetic energy structures over magnetic energy structures, $\sigma_R = +1$. Bavassano et al., (1998); Bruno and Carbone, (2005), and D'Amicis et al., [7] got similar results but with the predominance of magnetic energy over kinetic energy, (σ_R ~ -1) during periods of solar minimum. D'Amicis et al. [7] had earlier found out that at solar minimum magnetic structures were negligible with respect to Alfvénic fluctuations while at solar maximum, Alfvénic fluctuations were not prominently localized. This is in agreement with our results. Figures 3.2 and 3.3 show that the averaged peak values of the geomagnetic indices are not localized at a particular region of the histograms and those peaks corresponding to regions of Alfvénic fluctuations are generally low. However, the predominance of kinetic energy structures over magnetic energy structures is again very obvious and these kinetic energy structures propagate ouwards, $\sigma_R = +1$. Wanliss and Weygand (2007) in D'Amicis et al., [7] showed that the properties of SYM-H are not directly related to the scale-free properties of solar wind but to the properties of the magnetosphere. Thus, any correspondence of mean peak values of the indices and solar wind fluctuations are mere coincidence. Past workers attributed this result to the different current systems involved in storms and substorms dynamics. The ring current located in the inner magnetosphere is enhanced during storms and is greatly influenced by the intrinsic dynamics of the magnetosphere rather than by the system's driver i.e. the solar wind [7].

5. Conclusion

Based on the results of our analysis, we conclude that solar wind turbulence is an imbalanced MHD turbulence ($\square_{\square} \neq 0$), with the outward propagating Alfvén waves predominating over the inward propagating Alfvén waves. We also conclude that solar wind does not drive geomagnetic activity at the mid-low latitudes. Kinetic energy structures predominate over magnetic energy structures in Alfvén waves.

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