In-situ OBSERVATION OF ALFVÉN WAVES IN ICME SHOCK-SHEATH INDICATES EXISTENCE OF ALFVÉNIC TURBULENCE

A PREPRINT

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ABSTRACT

The dynamic evolution of coronal mass ejection (CME) in interplanetary space generates highly turbulent, compressed, and heated shock-sheath. This region furnishes a unique environment to study the turbulent fluctuations at the small scales and serve an opportunity for unfolding the physical mechanisms by which the turbulence is dissipated and plasma is heated. How does the turbulence in the magnetized plasma control the energy transport process in space and astrophysical plasmas is an attractive and challenging open problem of the 21st century. For this, the literature discusses three types of magnetohydrodynamics (MHD) waves/ fluctuations in magnetized plasma as the magnetosonic (fast), Alfvénic (intermediate), and sonic (slow). The magnetosonic type is most common in the interplanetary medium. However, Alfvénic waves/fluctuations have not been identified to date in the ICME sheath. The steepening of the Alfvén wave can form a rotational discontinuity that leads to an Alfvénic shock. But, the questions were raised on their existence based on the theoretical ground. Here, we demonstrate the observable in-situ evidence of Alfvén waves inside turbulent shock-sheath at 1 AU using three different methods descirbed in the literature. We also estimate Elsässer variables, normalized cross helicity, normalized residual energy and which indicate outward flow of Alfvén waves. Power spectrum analysis of IMF indicates the existence of Alfvénic turbulence in ICME shock-sheath. The study has strong implications in the domain of interplanetary space plasma, its interaction with planetary plasma, and astrophysical plasma.

1 INTRODUCTION

Coronal mass ejection (CME) is a huge cloud of solar plasma (mass $\sim 3.2 \times 10^{14}$ g, kinetic energy $\sim 2.0 \times 10^{29}$ erg) submersed in magnetic field lines that are blown away from the Sun which propagates and expands into the interplanetary medium [Vourlidas et al., 2010, Howard, 2011]. Their studies are of paramount importance given their natural hazardous effects on humans and the technology in space and ground [Schrijver and Siscoe, 2010, Moldwin, 2008, Schwenn, 2006]. The propagation speed of CMEs is often higher than the ambient solar wind which causes the formation of fast, collision-less shocks ahead of CMEs [Kennel et al., 1985]. These shocks cause heating and compression of the upstream (anti-sunward side) slow solar wind plasma, forming turbulent sheaths between the shocks and the leading edge of the CMEs [Sonett and Abrams, 1963, Kennel et al., 1985, Zurbuchen and Richardson, 2006, Jian et al., 2006, Echer et al., 2011, Richardson and Cane, 2011, Kilpua et al., 2017].

The shock and sheath are responsible mostly for (i) acceleration of solar energetic particles [Tsurutani and Lin, 1985, Manchester IV et al., 2005, Gosling, 1983, Giacalone et al., 1994, Zank et al., 2000, Verkhoglyadova et al., 2015, Zank et al., 2007, Li et al., 2003], (ii) significant geomagnetic activity [Tsurutani et al., 1988, Shen et al., 2018, Oliveira and Raeder, 2014, 2015, Lugaz et al., 2016], (iii) Forbush decrease phenomena [Raghav et al., 2014, 2017, 2020, Bhaskar et al., 2016, Shaikh et al., 2017, 2018, 2020a], (iv) accelerate pickup ions [Giacalone and Jokipii, 1995, Gloeckler et al., 1994, Zank et al., 1996], and (v) auroral lightning [Baker and Lanzerotti, 2016] etc. Besides this, the shock initiates a magnetosonic wave in the magnetosphere and associated electric field accelerates electrons to MeV energies [Foster et al., 2015, Kanekal et al., 2016].

Recent theoretical [Zank et al., 2014, 2015, Li et al., 2003, Le Roux et al., 2015, 2016, le Roux et al., 2018] and observational [Khabarova et al., 2015, 2016, 2017, Zhao et al., 2018, 2019, Shaikh et al., 2018, 2019, 2020a,b, Raghav and Shaikh, 2020] studies clearly indicate the local generation of quasi-2D structure [Zank et al., 2017, Adhikari et al., 2017], flux ropes [Shaikh et al., 2017] or magnetic islands in sheath region, and they may responsible for the acceleration of charged particles. Recently, the loss of electron flux from the radiation belt has been observed during the shock-sheath encounter with Earth's magnetosphere [Hietala et al., 2014, Kilpua et al., 2015a, 2017]. This may be caused due to an increase in ultra-low frequency (ULF) wave power and dynamic pressure which is further responsible for pitch angle scattering and radial diffusion of the electron flux. The precipitated high energy electron flux from the radiation belt is used as a key parameter in climate models and the understanding of atmospheric chemistry and associated climatological effects [Verronen et al., 2011, Andersson et al., 2014, Mironova et al., 2015]. In addition to this, the other planets and their atmospheres are highly affected by the shock-sheath of CME, for example, in the case of Mars, loss of the ions flux ($>\ 9\ amu$) is observed which might be caused by its high dynamic pressure [Jakosky et al., 2015].

CME induced shock-sheath provides a unique opportunity to investigate the nature of plasma turbulence, plasma energy/fluctuation-dissipation, and plasma heating process. The plasma turbulence demonstrates the features such as Alfvén waves, Whistler waves, ion cyclotron waves, or ion Bernstein waves, etc [Krishan and Mahajan, 2004, Gary and Smith, 2009, Schekochihin et al., 2009, Shaikh, 2010, He et al., 2011, Sahraoui et al., 2012, Salem et al., 2012]. In fact, sometimes plasma fluctuations do not exhibit any wave-like configuration at all but resemble nonlinear structures such as current sheets [Sundkvist et al., 2007, Osman et al., 2010]. Various studies related to the nature of turbulence and generation of waves in the shock-sheath region have reported in the recent past. Liu et al. [2006] observed the mirror mode wave within the shock-sheath region. Kilpua et al. [2013] observed that the power of ultra-low frequency fluctuations (in the dynamic pressure and magnetic field) peaks close to the shock-front and sheath-magnetic cloud boundary. Furthermore, a large-amplitude magnetic field fluctuation, as well as intense irregular ULF fluctuations and regular high-frequency wave activity is also observed in the downstream of CME shocks [Kataoka et al., 2005, Kajdič et al., 2012, Goncharov et al., 2014]. Moreover, Whistler waves associated with weak interplanetary shocks are also observed [Ramírez Vélez et al., 2012].

The solar wind is predominantly associated with turbulent plasma [Bruno and Carbone, 2005, 2013], which contributes in acceleration of the solar wind [Verdini et al., 2009, Lionello et al., 2014], solar wind heating [Freeman, 1988, Usmanov et al., 2011, Adhikari et al., 2015], and the scattering of the solar energetic particles [Li et al., 2003, Zank et al., 2007]. The turbulence of the solar wind plasma increases due to interplanetary shock [Burlaga, 1971, Richter et al., 1985, Jian et al., 2011]. The particle acceleration rate is controlled by the shock strength, the turbulence level, the magnetic field strength, and the shock obliquity [Zank et al., 2000, 2006]. It has been noted that the turbulence behind quasi-perpendicular shocks is more sporadic than that behind quasi-parallel shocks [Macek et al., 2015]. Note that, for quasi-perpendicular shocks, the cross-field currents are strong, produces significant levels of downstream plasma wave turbulence. Also, the shock steepening and the structure of shocks highly depends on the properties of the associated turbulence [Adhikari et al., 2016]. Moreover, Zank et al. [2015] demonstrated that the shock downstream turbulent, including vortical turbulence and Alfvénic like fluctuations is generated by the impact of upstream Alfvénic fluctuation disturbances. Recently, Zank et al. [2018] and Adhikari et al. [2016] studied the interaction between turbulence and termination shock and showed that quasi-two-dimensional turbulence dominates and slab-like turbulence plays a secondary role in the downstream of the shock wave.

Besides this, various studies investigated Alfvénic fluctuations and Alfvén waves inside an ICME from $1\ AU$ to $5.4\ AU$ [Li et al., 2017, Marsch et al., 2009, Yao et al., 2010, Haoming et al., 2012, LI et al., 2013, Li et al., 2016a, Gosling et al., 2010, Raghav and Kule, 2018a] and calculated their contribution to local plasma heating[Li et al., 2017]. ICME driven shocks are faster, stronger and show a larger distribution of shock parameters as compare to stream interaction shock [Kilpua et al., 2015b]. Therefore, sheath plasma is expected to be highly compressed, hence pure Alfvén wave is not at all expected. Moreover, the turbulent nature of the sheath suggests the existence of Alfvénic fluctuations [Kataoka et al., 2005] but explicitly not found to date. Besides, the literature indicates a theoretical debate on the existence of Alfvénic shock existence [Wu, 1987, Kunkel, 1966, Taniuti and Jeffrey, 1964] which may be expected during the steepening of Alfvén waves. Therefore, it is necessary to study the characteristics of Alfvén wave/fluctuations inside the highly turbulent sheath. Here we demonstrate the unambiguous in-situ evidence of Alfvén wave suggests nature of Alfvénic turbulence within the shock-sheath region of CME.

2 Event details

The shock-sheath under investigation is engendered by a CME which crossed the WIND and ACE spacecraft on 06^{th} November 2000. Figure 1 demonstrates the temporal variations of various in-situ plasma parameters and the interplanetary magnetic field (IMF) measured by the Wind spacecraft (The ACE spacecraft measurements are also studied, however not presented here). The commencement of the shock at spacecraft is identified as a sudden enhancement in the total IMF (B_{mag}), plasma beta (β), plasma density (N_p), plasma temperature (T_p), and plasma speed (V_p), it is indicated by the first vertical black dashed line. In general, Rankine-Hugoniot condition is used to confirm the shock. The same condition is employed to the shock events observed by Wind spacecraft and its characteristics are given online at `https://www.cfa.harvard.edu/shocks/ac_master_data/00076/ac_master_00076.html`. The shock is followed by large fluctuations in IMF (See δB variations in the fifth panel of Figure 1) with enhanced magnetic field strength; high N_p, & T_p which is manifested as a shock-sheath region. The second shaded region shows the least fluctuations in B_{mag} and its components, the slow variation in θ and ϕ, the slow steady trend in V_p, and low β. This indicates the presence of a ICME magnetic cloud region [Zurbuchen and Richardson, 2006]. The studied event is also listed in ICME catalogs available on-line e.g., `https://wind.nasa.gov/list_plot_Wind/20001106_311_wind.png`, `http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm`, and `http://space.ustc.edu.cn/dreams/wind_icmes/web/png/WIND_20001106_223050_20001107_174216.png`.

3 Alfvén wave identification

In literature, an Alfvén velocity is defined as:

$$V_A = \frac{B}{\sqrt{\mu_0 \rho}} \tag{1}$$

where B is a magnetic field and ρ is proton density. A typical Walén test is employed to confirm the presence of the Alfvén wave in the solar wind. The Walén relation is described as [Walén, 1944, Hudson, 1971, Yang and Chao, 2013, Yang et al., 2016, Raghav and Kule, 2018a,b]:

$$\Delta V = R_w \Delta V_A \tag{2}$$

where, R_w is the Walén slope, ΔV and ΔV_A are the fluctuations in solar wind speed and fluctuations in Alfvén speed (magnetic field) respectively. The presence of Alfvén wave/ variations in the solar wind is suggested by a high correlation between the corresponding components of ΔV and ΔV_A as well as $R_w = \pm 1$. The estimation of the correct background magnetic field and solar wind speed is essential to deduce fluctuations in their respective components. In this study, we confirmed the presence of Alfvén waves /fluctuations in the sheath region using three different methods as follow;

3.1 Method 1

In the first method, for the shock sheath region, the average values are estimated for each component of the magnetic field and solar wind vector respectively. We obtain ΔB by subtracting a mean value of the corresponding B component from each measurement. As a result, the Alfvén velocity fluctuation is given as:

$$\Delta V_A = \frac{\Delta B}{\sqrt{\mu_0 \rho}} \tag{3}$$

Similarly, we calculate ΔV by subtracting averaged proton flow velocity from measured values of each component respectively. In Figure 5 top three panels represents comparisons of x, y, and z of components of ΔV_A and ΔV respectively. It clearly shows correlated variations between their respective components within the shock-sheath region and indicates the possibility of an Alfvén wave. Their correlation and regression analysis is depicted in Figure 2. The Pearson correlation coefficients (R) of each x, y, and z components are –0.83,–0.44, and –0.75 and the corresponding regression slopes are –0.90, –1.1, and –0.78. (For ACE spacecraft data with 64 sec time resolution, the correlation coefficients are –0.80, –0.92 and –0.91 and the corresponding regression slopes are –0.50, –0.72, and –0.68 respectively. It should be noted that the corresponding figures are not displayed here. The Anti-Sunward Alfvén wave is confirmed by the significant negative correlation and regression coefficient ≈ -1 confirms the presence of Anti-Sunward Alfvén wave in the shock-sheath region of the examined CME [Gosling et al., 2010, Raghav and Kule, 2018a].

3.2 Method 2

In general, the mean values for selected regions or the average value of de Hoffmann-Teller (HT) frame are utilized as background quantities [Raghav and Kule, 2018a, Raghav et al., 2018, Raghav and Kule, 2018b, Yang and Chao,

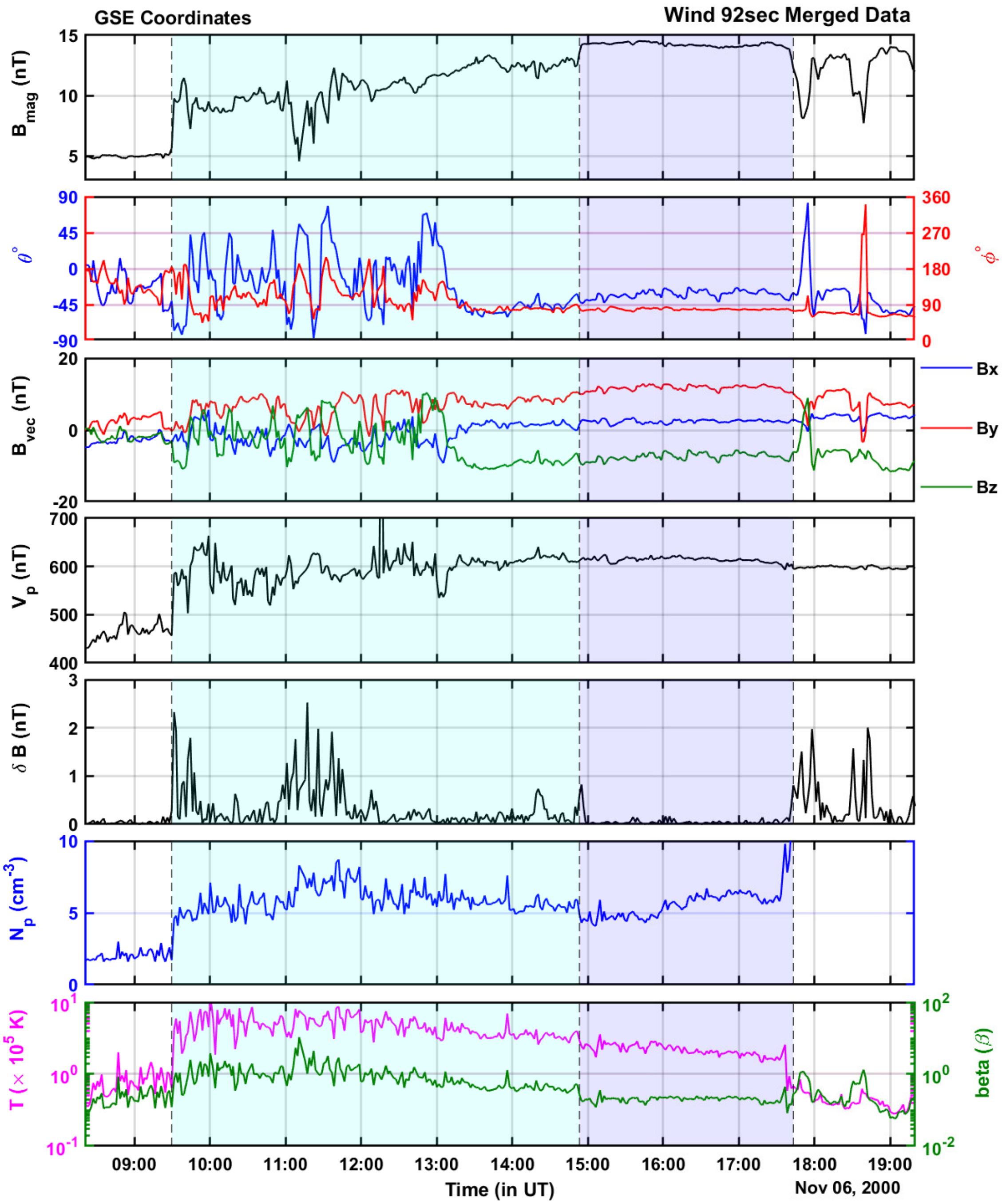

Figure 1: The CME observed by the Wind spacecraft on $06^{th}\ November,\ 2000$ with time cadence of 92 sec. The top to bottom panels represents different interplanetary parameters such as: total interplanetary field strength IMF B_{mag},elevation ($\theta^{\circ} = \arccos(\frac{-B_z}{B}) - 90^{\circ}$) & azimuth ($\phi^{\circ} = \arctan(\frac{-B_y}{-B_x}) + 180^{\circ}$) angle, IMF vectors i.e. B_{vec}, Plasma velocity (V_p), absolute value of IMF fluctuation i.e. $\delta B_i = \frac{B_{i+1} - B_{i-1}}{2}$, Proton density ($N_p$), and Temperature ($T_p$) & plasma beta ($\beta$) respectively. The shaded regions represents the shock-sheath of CME (cyan) and its magnetic cloud (purple). All observations are in GSE coordinate system.

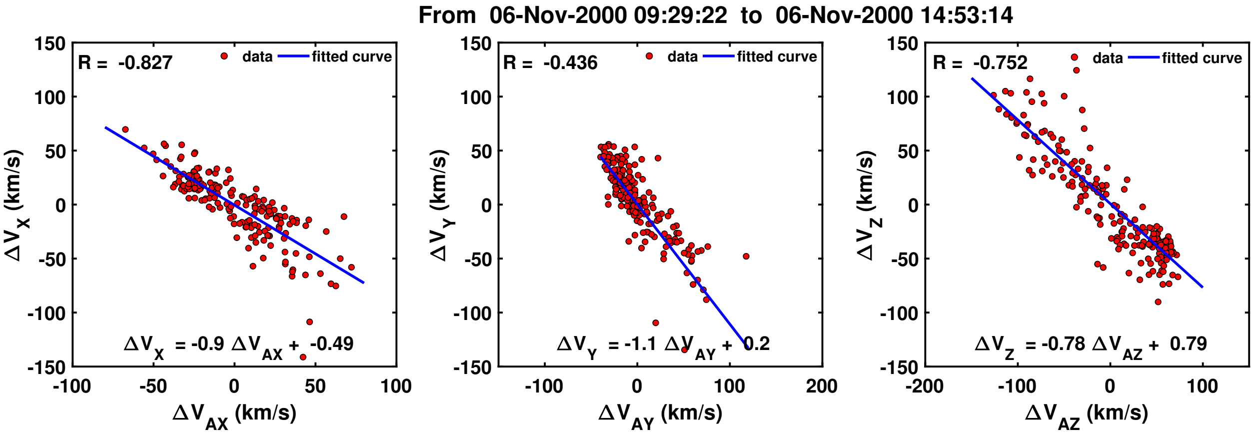

Figure 2: The correlation and regression analysis between the respective ΔV and ΔV_A components. The scattered black circle with filled red color represent observations from Wind spacecraft with time cadence of $92\ s$. The R is the coefficient of correlation. The equation in each panel indicate the linear fit relation between respective components of ΔV and ΔV_A.

2013, Gosling et al., 2010]. However, Gosling et al. [2009] and Li et al. [2016b] suggested that the HT frame can change in high-speed solar wind streams and the solar wind fluctuations are pertinent to a slow varying base value of the magnetic field. In order to reduce the uncertainty in Alfvén wave identification, the fourth-order Butterworth bandpass-filters are applied to each component of plasma velocity and magnetic field data. The equally spaced 10 logarithmic frequency bands are selected. The applied filters are 10s-15s, 15s-25s, 25s-40s, 40s-60s, 60s-100s, 100s-160s, 160s-250s, 250s-400s, 400s-630s, and 630s-1000s. The Walén relation for each band-passed signal is analyzed as follows:

$$V_i = \pm R_w V_{Ai} \tag{4}$$

The band-passed V and V_A components with the i^{th} filter are represented here by V_i and V_{Ai}. The value of the correlation coefficient between the respective components of V_i and V_{Ai} for each frequency band-passed signal confirms the presence of Alfvén waves or Alfvénic oscillations in the region under study. A similar approach is used by Li et al. [2016b]. The complete region under study is separated with 15 minutes of time window into the sub-regions. The frequency-time distribution contour map with a 15-minute bin size is displayed in Figure 3. The value of the correlation coefficient for each sub-region is shown as a colour map on the contour plot. Dark blue shed shows negative correlation, while dark red shed shows a significant positive correlation. As a result, the presence of dominating Alfvénic flow along the x, y, and z components are shown in Figure 3 contour map by the dark color-strips, particularly inside the sheath region.

Very recently, [Chen and Boldyrev, 2017] utilized a wavelet coherence test to study the nature of plasma turbulence at kinetic Alfvén scales in the Earth's magnetosheath. The wavelet coherence test is generally employed to identify regions in time-frequency space where the two-time series co-vary (but does not necessarily have high power). We have also used this test to double-check the existence of Alfvénic fluctuations/waves in the ICME sheath region. Figure 4 demonstrate the magnitude squared wavelet coherence (γ), between V_{Ax} & V_x (top panel), V_{Ay} & V_y (middle panel), and V_{Az} & V_z (bottom panel) and the phase lag ψ (black arrow) for $\gamma > 0.75$ (i.e. for highly significant correlated values), measured by Wind spacecraft. We observed a strong anti-correlation in all the components of V_A & V within the spacecraft frame frequencies range $0.25\ mHz < f_{sc} < 64\ mHz$. This significant anti-correlation (see the direction of the black arrow in Figure 4) clearly indicates that the shock-sheath region is dominated by the Anti-sunward deviation from anti-correlation is also visible for some frequency regions, especially towards the higher frequency side. Kindly note that for a certain interval of time (see middle and trailing edge of the sheath region), we observed the absence of Alfveńic fluctuations for certain frequency bands (for consistency, see Figure 3 and 4).

4 Properties of Alfvén wave

Here, we opine that the Walén test and definition of Alfvénicity are based to a large extent, on the approximate incompressibility of the background. The top three panels of figure 5 make it very evident how closely correlated the components of ΔV and ΔV_A are to one another.

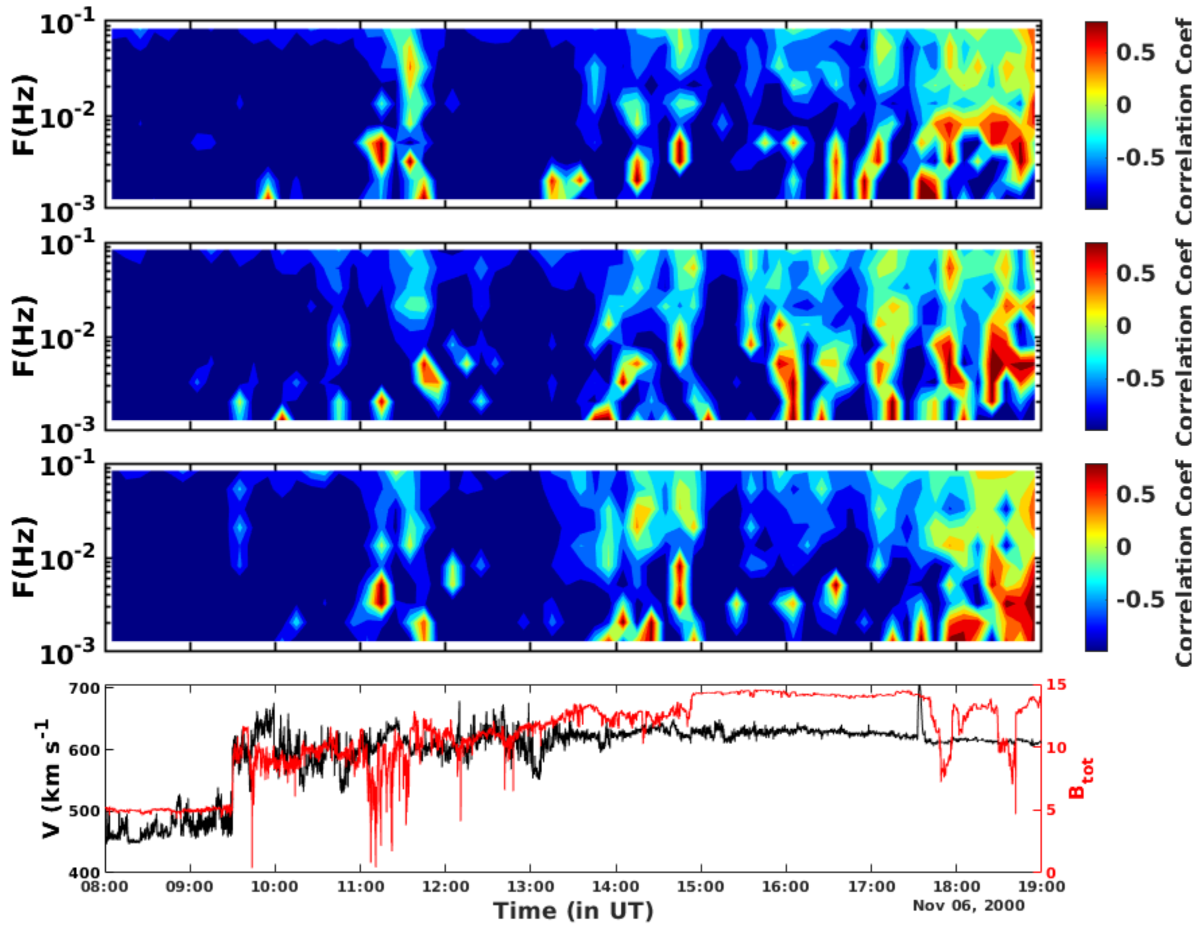

Figure 3: *Time-frequency distribution of correlation coefficient between V_{Ai} and V_i for complete event. Solar wind speed and magnetic field are shown in last panel. Wind satellite $3s$ observations are utilized for the analysis.*

Presence of Alfvénic fluctuation within the solar wind (especially in corotating high velocity streams) demands to use Els$\ddot{a}$sser variables to separate out the contribution of "outward" and "inward" to the turbulence. Els$\ddot{a}$sser variables are used in the theoretical studies [Elsasser, 1950, Dobrowolny et al., 1980a,b, Veltri et al., 1982, Marsch and Mangeney, 1987, Zhou and Matthaeus, 1989] as well as for the first time in interplanetary space (data analysis) by Grappin et al. [1990], Tu et al. [1989], Tu and Marsch [1990]. The Els$\ddot{a}$sser variables are defined as:

$$\vec{Z}^{\pm} = \vec{V} \pm \frac{\vec{B}}{\sqrt{4\pi\rho}}, \tag{5}$$

here, $\vec{V}$ and $\vec{B}$ are proton velocity and magnetic field fluctuation, measured in the GSE co-ordinate system. The $\pm$ sign in front of $\vec{B}$ depends on the sign of $[-k \cdot B_0]$. The Els$\ddot{a}$sser variables are defined in such a way that $\vec{Z}^{+}$ and $\vec{Z}^{-}$ always refers to the waves propagating outward and inward direction [Roberts et al., 1987a,b]. θ_{VB} is estimated as

$$\theta_{VB} = cos^{-1}(\frac{-B_x}{B_{mag}}) \tag{6}$$

The equation 5 get modified for $\theta_{VB} \leq 90°$ as $\vec{z^{+}} = \vec{V} - \vec{V}_A$ and $\vec{z^{-}} = \vec{V} + \vec{V}_A$, for $\theta_{VB} > 90°$ the equation will remains the same. The energy associated with z^{+} and z^{-} is defined as:

$$e^{\pm} = \frac{1}{2}\langle(z^{\pm})^2\rangle, \tag{7}$$

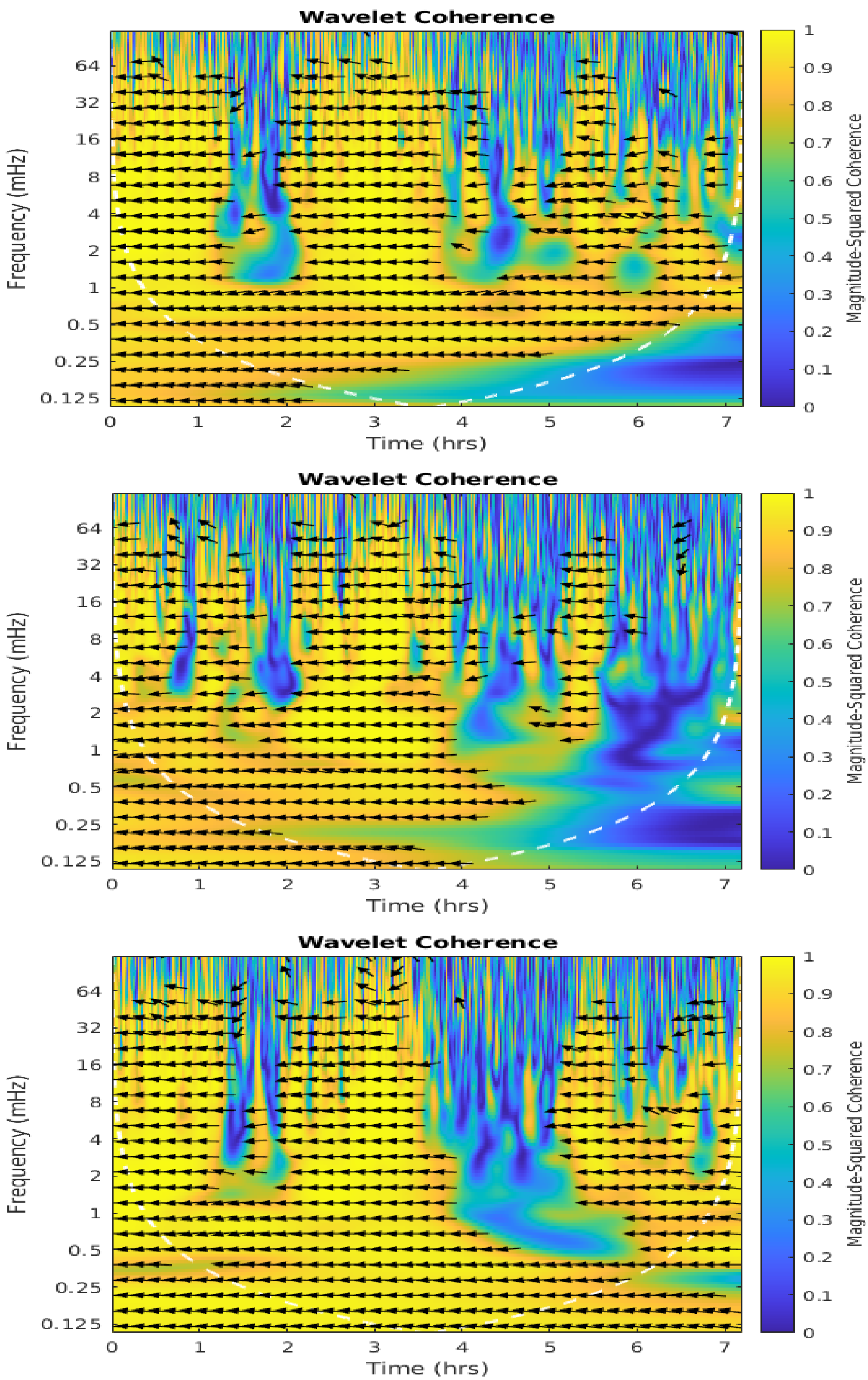

Figure 4: *Wavelet coherence analysis between solar wind velocity and magnetic field components during ICME sheath and MC transit. The color bar represents magnitude-squared coherence and angle of black arrows from the x + direction gives phase ψ angle between the two signals. The cone of influence is represented by the white dashed line marks. The onset of shock is treated as $0\ hours$, the front edge of MC is $\approx\ 5.5\ hours$*

Moreover, the normalized cross helicity is estimated as

$$\sigma_c = \frac{e^+ - e^-}{e^+ + e^-}, \tag{8}$$

also, the normalized residual energy defined as

$$\sigma_R = \frac{e^v - e^b}{e^v + e^b} \tag{9}$$

where e^v & e^b is kinetic and magnetic energy respectively. σ_R is measure of the excess magnetic field energy with respect to kinetic energy or vice versa Bruno and Carbone [2013]. Where, $e^v = 0.5 < v^2 >$ and $e^b = 0.5 < b^2 >$ are kinetic and magnetic energy associated with Elsässer variables ($z^\pm$). Here, $v = 0.5(z^+ + z^-)$ and $b = 0.5(z^+ - z^-)$ respectively.

Here, the $\sigma_c > 0$ & $\sigma_R < 0$ indicates dominant flow of outward propagating waves [Matthaeus and Goldstein, 1982, Tu et al., 1989]. In our study, we got highly positive value of normalized cross helicity in the shock-sheath region indicates dominance of outward Alfvénic turbulence.

The Figure 6 demonstrate scattered plot of the normalized residual energy (σ_R) Vs normalized cross helicity (σ_c). These defined parameters are valid only if $\sigma_R^2 + \sigma_c^2 \leq 1$ *i.e.*, the data points should lie within the circle [Bavassano et al., 1998]. Note that most of the observed data points has positive σ_c. This implies that identified Alfvén wave within the ICME sheath region dominantly propagating towards the earth.

5 PSD Analysis

We performed a power spectral density (PSD) analysis to study the characterization of the multi-scale nature of shock-sheath turbulences/fluctuations. Figure 7 represents the spectral output for the B_x, B_y and B_z components of the IMF. The common feature of the incompressible MHD plasma turbulence i.e. Kolmogorov-like turbulence is observed in the intermediate frequency range which is consistent with $\sim f^{-1.66}$ [Bruno and Carbone, 2005]. We believed that the entire turbulent interactions within these regimes are governed by the Alfvénic cascade.

We estimate cyclotron frequencies for proton and alpha particle for the observed magnetic field of $5 - 12\ nT$ range, which turn out to be $0.47\ Hz - 1.10\ Hz$ for proton and $0.24\ Hz - 0.55\ Hz$ for alpha. The various studies reveal that at length-scales beyond the MHD regime, the power spectrum shows spectral break which halts the Alfvénic cascade [Goldstein et al., 1994, Leamon et al., 1999, Bale et al., 2005, Alexandrova et al., 2008, Sahraoui et al., 2009, Shaikh and Shukla, 2009]. At $\sim 0.5 - 0.6$ Hz, the PSD spectrum "breaks" from a $\sim f^{-1.6}$ power-law inertial range to a $\sim f^{-3.1}$ dissipation range (see Figure 7). However, Perri et al. [2010] suggest that the spectral break in the solar wind is independent of the distance from the Sun and that of both the ion-cyclotron frequency and the proton gyro-radius. Therefore, it is also possible that the observed high-frequency break in our study is caused by a combination of different physical processes as a result of high compression within the shock-sheath region. The other possible mechanism for the spectral break may result from energy transfer processes related to; 1) kinetic Alfvén wave (KAW) [Hasegawa and Chen, 1976], 2) electromagnetic ion-cyclotron-Alfvén (EMICA) waves [Wu and Yoon, 2007, Gary et al., 2008], or the fluctuation associated with the Hall magnetohydrodynamics (HMHD) plasma model [Alexandrova et al., 2007, 2008].

At higher frequencies, the spectrum of the magnetic field fluctuations has power-law dependence as $\sim f^{-\alpha}$, where, the value of α may range from 2 to 4. The average value of the α is close to 7/3 [Leamon et al., 1998, Smith et al., 2006, Alexandrova et al., 2008]. In our study, it is about ~ -3.1. These higher frequency part of the spectrum may be associated either with a dissipative range [Leamon et al., 1998, Smith et al., 2006] or with a different turbulent energy cascade caused by dispersive effects [Stasiewicz et al., 2000, Sahraoui et al., 2006, Galtier and Buchlin, 2007, Alexandrova et al., 2008, Sahraoui et al., 2009, Li et al., 2016b]. Stawicki et al. [2001] proposed that suppression of the Alfvénic fluctuations are due to the ion cyclotron damping at intermediate wave frequency (wavenumber), hence the observed power spectra are weakly damped dispersive magnetosonic and/or whistler waves (unlike Alfvén waves). The presence of the whistler wave mode in the high-frequency regime was proposed by the [Beinroth and Neubauer, 1981]. Goldstein et al. [1994] found out the existence of multi-scale waves (Alfvénic, whistlers, and cyclotron waves) with a single polarization in the dissipation regime of the spectrum. Observation of the obliquely propagating KAWs (in the $\omega < \omega_{ci}$ regime or Alfvénic regime) puts a question about the spectral breakpoint due to damping of ion cyclotron waves [Howes et al., 2008]. The Kinetic [Howes et al., 2008] and Fluid [Shaikh and Shukla, 2009] simulations show that the ion inertial length-scale is comparable to that of the spectral breakpoint near the characteristic turbulent length-scales. For the length-scales larger than the ion inertial length-scales, the simulations demonstrate Kolmogorov-like spectra. Moreover, for smaller ion inertial length-scales, they observed the steeper spectrum that is close to $f^{-7/3}$.

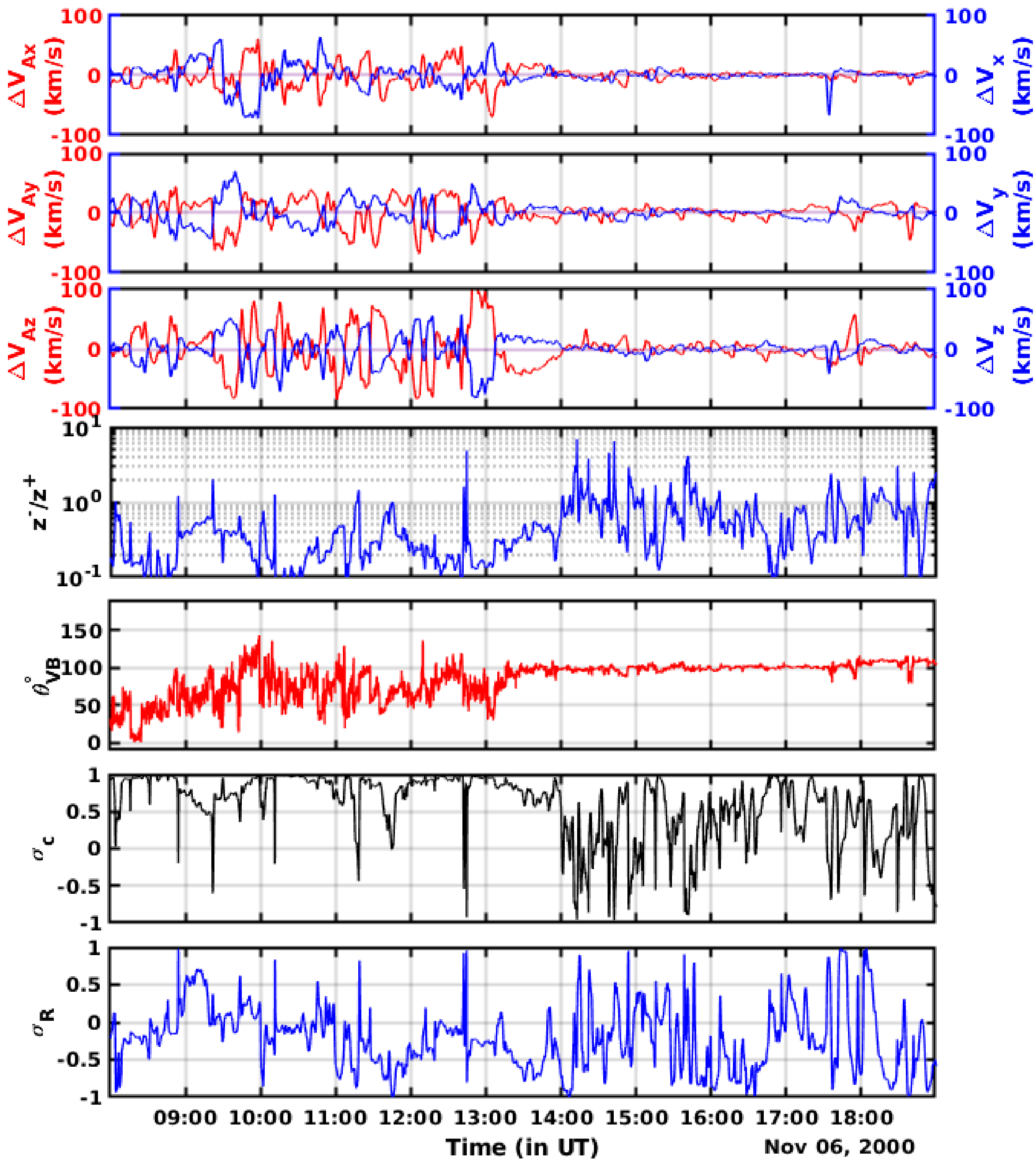

Figure 5: Top three panels demonstrate the temporal variation of Alfvén velocity fluctuation vector ΔV_A (red) and that of the proton flow velocity fluctuation vector ΔV (blue). It demonstrates Alfvénic and shock-sheath characteristic of the studied region of an ICME. The fourth panel represents the ratio of inward to outward Elässer variable. The fifth panel gives appearance of the angle between solar wind velocity and magnetic field. The Sixth panel and seventh panels represents the temporal variation of the normalized cross helicity (σ_c) and normalized residual energy (σ_R) respectively. The analysis is performed using wind spacecraft data with time cadence of 3 sec.

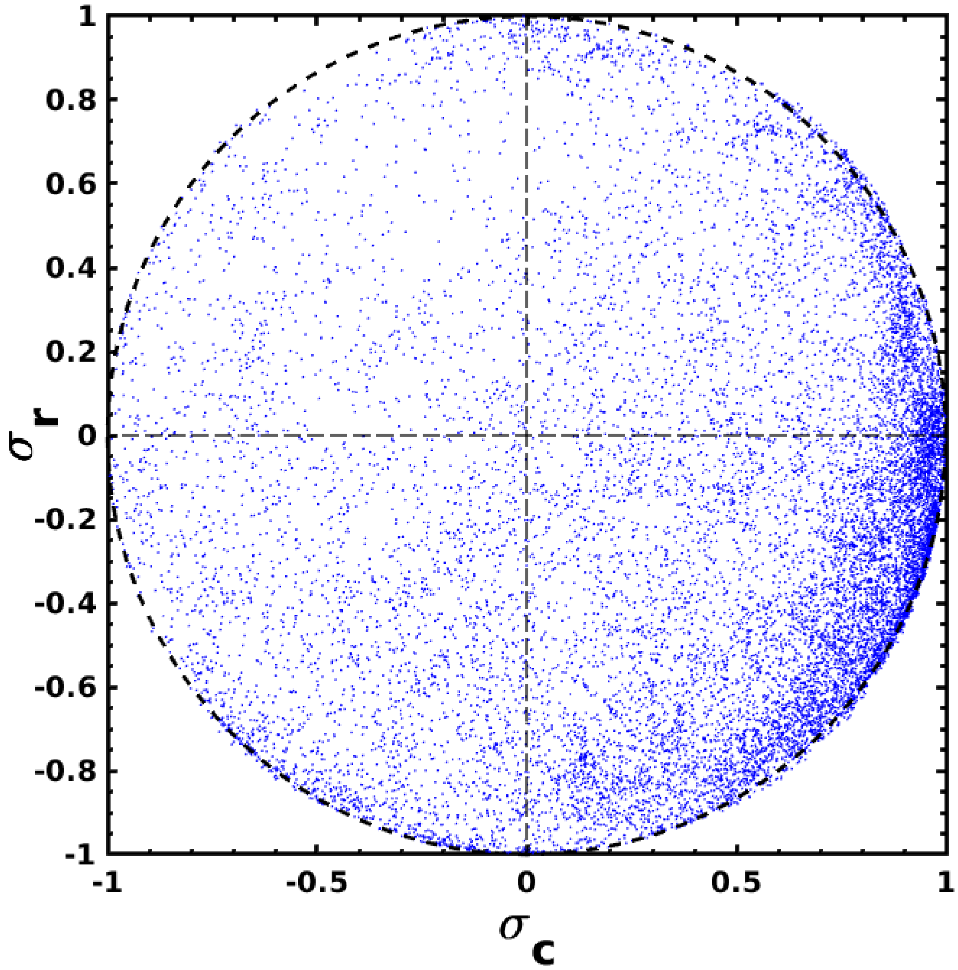

Figure 6: The scatter plot of normalized residual energy (σ_r) and normalized cross helicity (σ_c) , estimated by Wind spacecraft data of 2000 November 06.

6 Discussion

Using three distinct techniques, we found a substantial correlation between the variations in the magnetic field and velocity vectors. This suggests that the magnetic field and fluid velocity are oscillating simultaneously and propagating in the same direction as the magnetic tension force. The various plasma features (see Figure 2, 3,4,5) confirms the presence of Alfvén wave in shock-sheath region. Similar analysis has been performed for various ICME-sheath regions observed by Wind spacecraft and listed in `https://wind.nasa.gov/ICMEindex.php`. It is important to note that Alfvén waves/fluctuations have not been found in all the studied ICME-sheath events. Moreover, only following events shows inward or outward flow of Alfvén waves/fluctuations out of studied events; e.g Very soon we will analysed all the events listed in aforementioned catalogue to study their possible origin, propagation and dissipation in sheath plasma.

The overall distinguishable features of Alfvén waves during the shock sheath strongly support dominant Alfvénic turbulence. Moreover, the Alfvén waves are pervasive in the solar wind, and it is important to note that the method 2 (section 3.2, Figure 3) shows the presence of Alfvén wave in up-stream of shock. However, their transmission in shock-sheath is questionable. The solar wind at 1 AU is overwhelmingly Alfvénic, therefore it is possible that the same Alfvénic background is present in the ICME shock-sheath region too and a significant compressible component is just superposed on that [Chen et al., 2013].

The Alfvén waves lead to non-linear interactions [Dobrowolny et al., 1980a] which are crucial for the dynamical evolution of a Kolmogorov-like MHD spectrum [Bruno and Carbone, 2013]. We have also performed a power spectral

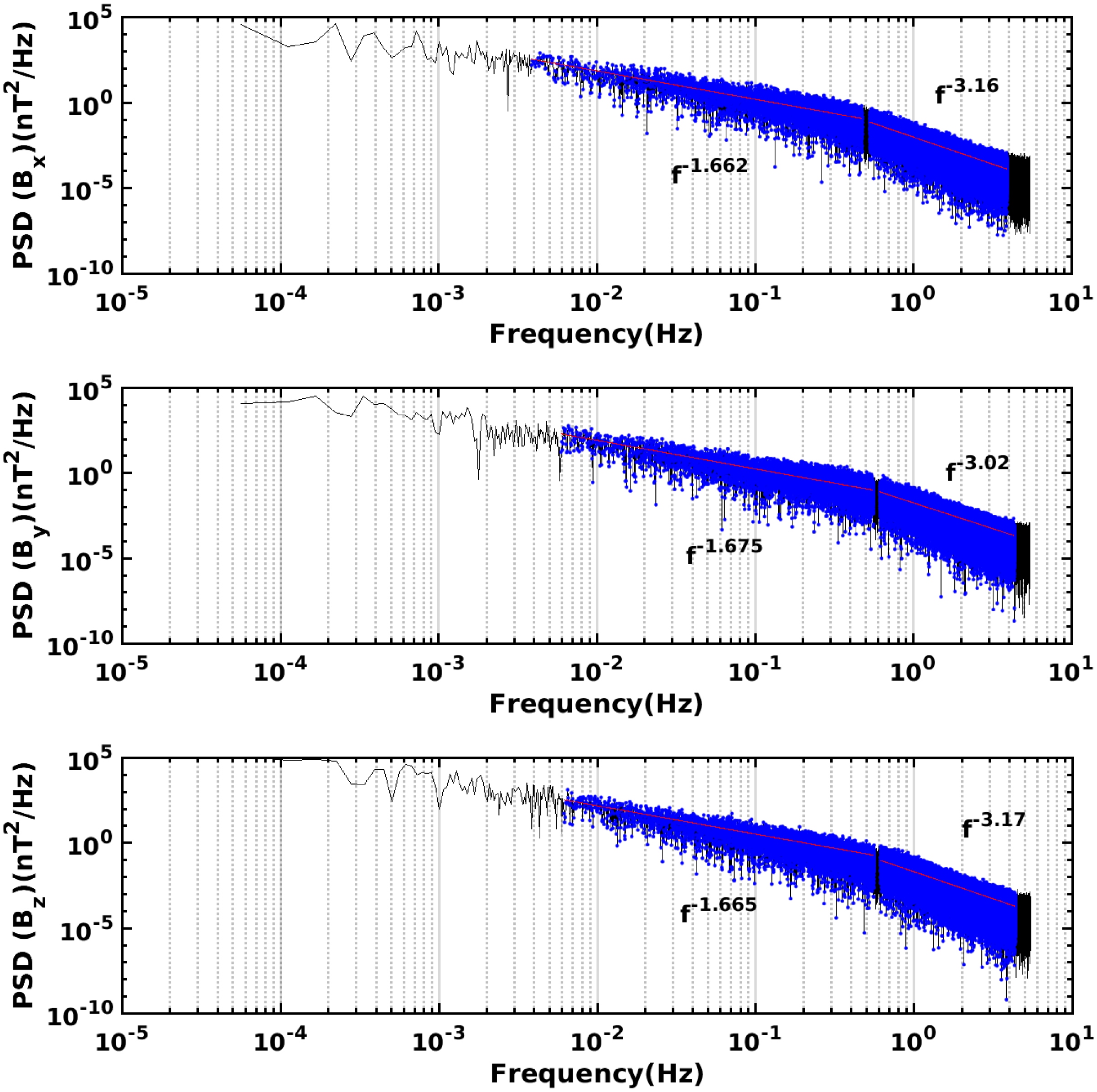

Figure 7: Power spectra of magnetic fluctuations along the B_x direction in GSE coordinate (black color) as a function of frequency in the spacecraft frame as measured by Wind on 2000 November 06, from 09:15 to 14:16 UTC, computed with FFT (black) algorithms. We have used WINDS high resolution (11 Hz) IMF data.

density (PSD) analysis for all IMF vector components. It depicts Kolmogorov-like turbulent nature (The PSD analysis follows $f^{-1.66}$ spectrum) for the frequency range between 0.4×10^{-3} Hz to 0.5 Hz in the studied the shock-sheath region. Thus the existence of Alfvén waves with the Kolmogorov-like turbulence depicts Alfvénic turbulent nature of the shock-sheath. Thus, we observed the continued cascade of energy from large scales to smaller scales of wavelengths and eventually to such small scales that the plasma no longer behaves like a fluid due to a change in velocity and magnetic field fluctuations. At this scale, the particle distribution is affected by the magnetic field which may lead to plasma heating through resonant interactions [Tsurutani and Lakhina, 1997]. We opine that the plasma heating in shock-sheath could be associated with an above-discussed process.

Alfvénic-like fluctuations may also occur in the impact sheath, but the dominant one will be the quasi-2D structure [Zank et al., 2018]. For example, Zheng and Hu [2018] used the Grad-Shafranov reconstruction method to show the flux rope in the impact sheath area. However, our observations clearly demonstrate the existence of Alfvén waves in the sheath region. It does not mean that Alfvénic fluctuations dominantly seen in the sheath, rather a statistical study will put some light on the aforementioned issue.

7 Implications

Several open questions need to be addressed in view of turbulent nature in highly compressed and heated shock-sheath such as, (i) What is the origin of a turbulent cascade in shock-sheath? Is it the coronal plasma or local driving?; (ii) How does the cascade modify the shock-sheath plasma?; (iii) How do the turbulent fluctuations get dissipated into heat?; (iv) What is more important for energy dissipation, non-linear turbulent heating, or resonant wave-particle interactions?; (v) Can shock-sheath turbulence be parameterized and included in heliospheric models for space weather prediction?

Recently, the presence of the Alfvén wave has been seen in a magnetic cloud of CME [Raghav and Kule, 2018a]. It is manifested that the Alfvénic oscillations in a magnetic cloud of CME may cause the internal magnetic reconnection and/or thermal anisotropy in plasma distribution which leads to the disruption of the stable magnetic structure of the CME [Raghav and Kule, 2018b]. Their presence in the magnetic cloud of CME also controls the recovery phase of the geomagnetic storms [Raghav et al., 2018, 2019]. In the introduction section of the article, we emphasize that the shock-sheath of CME not only affects the interplanetary plasma characteristics but also affects the dynamics of the magnetosphere, ionosphere, radiation-belt, and upper atmosphere of the Earth. It affects the other planetary exospheres as well. Therefore how the typical configuration such as Alfvén fluctuations embedded shock-sheath influence the overall solar-terrestrial plasma will be intriguing and may activate the possible direction of future studies. One can also expect similar features of shock-sheath in interstellar medium as well e.g. supernovae shocks and associated sheaths.

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