The first observable in-situ evidence of Alfvénic turbulence in shock-sheath

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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 controls the energy transport process in space and astrophysical plasmas is an attractive and challenging open problem of 21st century. The literature discuss three types of incompressible magnetohydrodynamics (MHD) shocks as the magnetosonic (fast), Alfvénic (intermediate), and sonic (slow). The magnetosonic shock is most common in the interplanetary medium. However, Alfvénic shocks have not been identified till date in interplanetary space. In fact, the questions were raised on their existence based on the theoretical ground. Here, we demonstrate the first observable in-situ evidence of Alfvénic turbulent shock-sheath at 1 AU. The study has strong implications in the domain of an interplanetary space plasma, its interaction with planetary plasma and astrophysical plasma.

Keywords: Coronal mass ejection (CME), Magnetic Field, Structure, Turbulence, Magnetohydrodynamics (MHD)

1. INTRODUCTION

A 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. Their studies are of paramount importance in view of their natural hazardous effects on humans and the technology in space and ground. (Schrijver & Siscoe 2010; Palmer et al. 1978; Low 1996; Gopalswamy et al. 2005; Schwenn 2006; Moldwin 2008; Vourlidas et al. 2010). 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. 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 & Abrams 1963; Kennel et al. 1985; Papadopoulos 1985; Tsurutani & Lin 1985; Echer et al. 2011; Oliveira & Raeder 2014, 2015; Lugaz et al. 2016; Kilpua et al. 2017). The shock and sheath are responsible mostly for (i) acceleration of solar energetic particles (Tsurutani & Lin 1985; Manchester IV et al. 2005), (ii) significant geomagnetic activity (Tsurutani et al. 1988), (iii) Forbush decrease phenomena (Raghav et al. 2014, 2017; Shaikh et al. 2017; Bhaskar et al. 2016), and (iv) Auroral lightning (Baker & 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). 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. 2015, 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 radiation belt is used as a key parameter in climate models and in the understanding of atmospheric chemistry and associated climatological effects (Andersson et al. 2014; Verronen et al. 2011; 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 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 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 (Schekochihin et al. 2009; Salem et al. 2012; Shaikh 2010; Krishan & Mahajan 2004; Gary & Smith 2009; He et al. 2011; Sahraoui 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 (Osman et al. 2010; Sundkvist et al. 2007). Actually various studies related to the nature of turbulence and generation of wave in shock-sheath region have been reported in 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 fluctuation (in the dynamic pressure and magnetic field) peaks close to the shock-front and sheath-magnetic cloud boundary. Furthermore, large amplitude magnetic field fluctuations, 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; Kajdić et al. 2012; Goncharov et al. 2014). Moreover, Whistler waves associated with weak interplanetary shocks are also observed (Ramírez Vélez et al. 2012). However, Alfvén wave within the shock-sheath of CME was not observed yet. In fact, literature indicates theoretical debate on their existence (Wu 1987; Kunkel 1966; Taniuti & Jeffrey 1964). To the best of our knowledge, here we demonstrate the first in-situ observable evidence of Alfvén wave within the shock-sheath region of CME.

2. EVENT DETAILS & ALFVÉN WAVE CONFIRMATION

The shock-sheath under investigation is engendered by a CME which crossed the WIND and ACE spacecrafts on 06th November 2000. Figure 1 demonstrates the temporal variations of various in-situ plasma parameters and the interplanetary magnetic field (IMF) measured by the ACE spacecraft (The Wind spacecraft measurements are also studied, however not presented here). The commencement of the shock at spacecraft is identified as a sudden enhancement in the $B_{mag}$, $V_p$, $N_p$, $T_p$, and $\beta$ and it is indicated by the first vertical black dashed line. The confirmation of the shock and its properties are given 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 $\delta B$) with enhanced magnetic field strength; high $N_p$, $T_p$ & $P_{dyn}$ 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 $\theta$ and $\phi$, the slow steady trend in $V_p$ and low $\beta$. This
indicates the presence of a CME magnetic cloud region (Zurbuchen & Richardson 2006).

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 & Chao 2013; Yang et al. 2016; Raghav & Kule 2018a,b):

$$V_A = \pm A \frac{B}{\sqrt{\rho_0 \rho}}$$

(1)

where B is a magnetic field, A is the anisotropy parameter, and \(\rho\) is proton mass density. Normally, \(A = \pm 1\) for negligible thermal anisotropic plasma. We can obtain \(\Delta B\) by subtracting an average value of B from each measured value. Hence, the fluctuation in Alfvén velocity is given as:

$$\Delta V_A = \pm A \frac{\Delta B}{\sqrt{\rho_0 \rho}}$$

(2)

Further, we calculate \(\Delta V\) by subtracting averaged proton flow velocity from measured values. Figure 2 represents the comparisons of x, y, and z components of \(\Delta V_A\) and \(\Delta V\) respectively. It clearly demonstrates correlated variations between their respective components within the shock-sheath region and indicates the possible existence of Alfvén wave. Figure 3 represents their correlation and regression analysis. The Pearson correlation coefficients (R) of each x, y, and z components are \(-0.798, -0.921,\) and \(-0.905\) and the corresponding regression slopes are \(-0.50, -0.72,\) and \(-0.68\) respectively. The strong negative correlation confirms the presence of the sun-ward Alfvén wave in the shock-sheath region of the CME (Gosling et al. 2010; Marubashi et al. 2010; Zhang et al. 2014).

3. ANALYSIS & DISCUSSION

We performed minimum and maximum variance analysis (MVA) of the magnetic field data for the shock-sheath region to study the features of the Alfvén wave.

The arc polarization of Alfvén wave. Here, \(B_1\) and \(B_3\) are magnetic field vector corresponding to maximum and intermediate eigenvalue. The color-bar represents the time evolution of the wave.

The \(B_1^*, B_2^*,\) and \(B_3^*\) are the magnetic field vectors after MVA analysis corresponding to maximum, intermediate, and minimum variance direction respectively. Figure 4 shows the time evolution of the Alfvén wave which demonstrates that the wave starts at one point, completes the half circle and then returns to the starting position. This behavior of the wave suggests a feature of arc polarization (Tsurutani et al. 1995; Riley et al. 1995, 1996). Figure 4 depicts that the wave does not have an even rate of wave phase rotation with time indicating phase-steepened phenomena. In each arc, there is 180° phase rotation associated with the initial to an intermediate portion of the wave and the trailing portion of the wave carries 180° of phase rotation (half circle). Therefore, the wave period has doubled and indicates the period doubling phenomenon. These characteristics of Alfvén wave are discussed in detail by Tsurutani et al. (2018) and references therein.
We performed power spectral density (PSD) analysis to study the characterization of the multi-scale nature of shock-sheath turblences/fluctuations. Figure 5 represents the spectral output for the $B_x$ component of the IMF (other components of IMF are also studied and they shows similar behavior, but not shown here). The lower frequency is characterized by a flicker noise $f^{-0.96}$ spectrum, which may be due to the residual uncorrelated coronal structures (Matthaues et al. 2007; Telloni et al. 2009). This implies the equal energy per interval, which is independent of $f$, in $6 \times 10^{-5} Hz - 4 \times 10^{-3} Hz$ range of frequencies. 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 & Carbone 2005). We believed that the entire turbulent interactions within these regimes are governed by the Alfvénic cascade. This region follows and extends up to the ion gyro-frequency.

Figure 5 shows the spectral break at $\sim 0.42 Hz$, and $\sim 2.2 Hz$ in high-frequency region. 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 (i.e. length scale $< \text{ion gyro-radius and temporal scale} > \text{ion cyclotron frequency}$), the power spectrum shows spectral break which halts the Alfvénic cascade. Moreover, the presence of the modes in this region evolves on the timescales associated with dispersive kinetic Alfvénic fluctuations (Leamon et al. 1999; Alexandrova et al. 2008; Bale et al. 2005; Sahraoui et al. 2009; Goldstein et al. 1994; Shaikh & Shukla 2009). 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 & Chen 1976), 2) electromagnetic ion-cyclotron-Alfvén (EMICA) waves (Wu & Yoon 2007; Gary et al. 2008), or the fluctuation associated with the Hall magnetohydrodynamics (HMHD) plasma model (Alexandrova et al. 2008, 2007).

At higher frequencies, the spectrum of the magnetic field fluctuations has power-law dependence as $\sim f^{-\alpha}$, where, the value of $\alpha$ may range from 2 to 4. The average value of the $\alpha$ is close to $7/3$ (Leamon et al. 1998; Smith et al. 2006; Alexandrova et al. 2008). In our study, it is about $\sim 2.97$ and $\sim 2.39$. 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 (Alexandrova et al. 2008; Stasiewicz et al. 2000; Li et al. 2016; Sahraoui et al. 2006, 2009; Galtier & Buchlin 2007). Statwicki et al. (2001) proposed that suppression of the Alfvénic fluctuations are due to the ion cyclotron damping at intermediate wave frequency (wave-number), hence, the observed power spectra are weakly damped dispersive magnetosonic and/or whistler waves (unlike Alfvén waves). Presence of the whistler wave mode in high-frequency regime was proposed by the Beinroth & 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 & 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 steeper spectrum that is close to $f^{-7/3}$.

4. RESULTS & IMPLICATIONS
In this study, we find a good correlation between the fluctuations of the magnetic field and proton velocity vectors using the Walén test. This implies that the fluid velocity and magnetic field are fluctuating together and propagate along the direction of the magnetic tension force. The observed feature confirms the presence of Alfvén waves in shock-sheath. The Sunward Alfvén waves are very rare as compared to anti-Sunward Alfvén waves in the solar wind (Belcher et al. 1969; Daily 1973; Burlaga & Turner 1976; Riley et al. 1996; Denskat & Neubauer 1982; Yang et al. 2016). They are associated with events such as magnetic reconnection exhausts and/or backstreaming ions from reverse shocks and are expected with increasing heliocentric distance (Belcher & Davis 1971; Roberts et al. 1987; Bavassano & Bruno 1989; Gosling et al. 2009, 2011). The Alfvén waves may be generated by (i) the steepening of a magnetosonic wave which forms the shock at the leading edge of the magnetic cloud (Tsurutani et al. 1988, 2011), (ii) velocity shear instabilities (Bavassano et al. 1978; Coleman Jr 1968; Roberts et al. 1987, 1992), (iii) the oblique firehose instability (Matteini et al. 2007, 2006; Hellinger & Trávníček 2008), (iv) kinetic instabilities associated with the solar wind proton heat flux (Goldstein et al. 2000; Matteini et al. 2013; Marsch & Livi 1987), and (v) the interaction of multiple CMEs (Raghav & Kule 2018a) etc. Moreover, the Alfvén waves are commonly observed in interplanetary space (Hellinger & Trávníček 2008) but it would be difficult for them to get into the magnetic cloud.

The MVA technique indicates Alfvén wave characteristics such as, arc polarization, phase steepening and period doubling. The Alfvén waves leads to non-linear interactions (Dobrowolny et al. 1980) which are crucial for the dynamical evolution of a Kolmogorov-like MHD spectrum (Bruno & Carbone 2013). The PSD analysis depicts 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 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. The heating process might happen through either resonant interactions or stochastic jumps. We opine that the plasma heating in shock-sheath could be associated with an above-discussed process. The various simulation studies and spacecraft data analysis in solar wind reveals that the turbulent energy transfers essentially through different regions in the k-space, i.e. $k^{-1}$, $k^{-5/3}$, and $k^{-7/3}$. Our results are clearly consistent with the reported studies and confirm that the shock-sheath is dominated by Alfvénic turbulence.

However, 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 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 & 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 & Kule 2018b). Their presence in the magnetic cloud of CME also controls the recovery phase of the geomagnetic storms (Raghav et al. 2018). 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 magnetosphere, ionosphere, radiation-belt and upper atmosphere of the Earth. In fact, 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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