The first *insitu* observation of torsional Alfvén waves during the interaction of large-scale magnetic clouds.

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**ABSTRACT**

The large-scale magnetic cloud such as coronal mass ejections (CMEs) is the fundamental driver of the space weather. The interaction of the multiple-CMEs in interplanetary space affects their dynamic evolution and geo-effectiveness. The complex and merged multiple magnetic clouds appear as the *insitu* signature of the interacting CMEs. The Alfvén waves are speculated to be one of the major possible energy exchange/dissipation mechanism during the interaction. However, no such observational evidence has been found in the literature. The case studies of CME-CME collision events suggest that the magnetic and thermal energy of the CME is converted into the kinetic energy. Moreover, magnetic reconnection process is justified to be responsible for merging of multiple magnetic clouds. Here, we present unambiguous evidence of sunward torsional Alfvén waves in the interacting region after the super-elastic collision of multiple CMEs. The Walén relation is used to confirm the presence of Alfvén waves in the interacting region of multiple CMEs/magnetic clouds. We conclude that Alfvén waves and magnetic reconnection are the possible energy exchange/dissipation mechanisms during large-scale magnetic clouds collisions. The present study has significant implications not only in CME-magnetosphere interactions but also in the interstellar medium where interactions of large-scale magnetic clouds are possible.

**Key words:** Alfvén (MHD) waves – CME-CME interaction – Multiple magnetic clouds – merged interacting regions – magnetic reconnection

1 INTRODUCTION

The Coronal mass ejections (CMEs) are frequent discharge of huge energy and massive magnetized plasma from the solar corona into the heliosphere. They are of paramount importance in space physics for their key role in extreme space weather and geo-effectiveness *e.g.* (Schrijver & Siscoe 2010; Gosling 1993; Cannon et al. 2013; Low 2001). In last few decades, the understanding of CMEs improved significantly because of space and ground-based observational data with the help of various modeling efforts. The studies are focused on the morphological and kinematic evolution of CMEs in the heliosphere *e.g.* (Lindsay et al. 1999; St Cyr et al. 2000; Chen 2011; Webb & Howard 2012; Lugaz et al. 2017; Wang et al. 2016; Zurbuchen & Richardson 2006). By considering the number of CMEs emitted from the Sun during solar maximum and

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variations in their respective speeds, the interaction between multiple CMEs in the heliosphere is expected to be more frequent. The collision of multiple CMEs highly affect their dynamic evolution properties and contribute to enhanced geoeffectiveness e.g. (Wang et al. 2005; Lugaz et al. 2005, 2012; Xiong et al. 2007; Temmer et al. 2012; Shen et al. 2011, 2012; Wang et al. 2002; Farrugia & Berdichevsky 2004). To predict space weather effects near the Earth, an accurate estimation of arrival time of CMEs at the Earth is crucial (Mishra & Srivastava 2014). Besides this, the study of CME-CME and CME-solar wind interactions provide unique observational evidences to understand energy dissipation of large-scale magnetic clouds in interstellar medium and authenticate the physical processes predicted theoretically. Therefore, interaction of multiple CMEs needs to be examined in detail. The various results obtained from studies have justified CME-CME collision as an in-elastic/elastic collision or super-elastic collision e.g. (Lugaz et al. 2012; Shen et al. 2012; Mishra et al. 2017; Shen et al. 2016; Lugaz et al. 2017). The magnetohydrodynamics (MHD) numerical simulations have striven to understand the physical mechanism involved in CME-CME interaction, CME-CME driven shock interactions and their consequences e.g. (Shen et al. 2016; Niembro et al. 2015; Jin et al. 2016; Wu et al. 2016).

The interaction of multiple CMEs and/or their interaction with any other large-scale magnetic solar wind structures can modify their structural configuration. The first possibility of CME-CME interaction was reported by analyzing in situ observations of CMEs by the Pioneer 9 spacecraft (Intriligator 1976). Burlaga et al. (1987) showed that compound streams are formed due to CME-CME interaction using in situ observations of the twin Helios spacecraft. Burlaga et al. (2002) inferred that a set of successive halo CMEs, merged en route from the Sun to the Earth and formed complex ejecta in which the identity of individual CMEs was lost (Burlaga et al. 2001). Furthermore, CME-CME interactions led to the magnetic reconnection between flux ropes of CMEs and appeared as multiple magnetic clouds in in situ observations e.g. (Wang et al. 2002, 2003; Marić et al. 2014; Farrugia & Berdichevsky 2004). This mechanism is also known to lead to solar energetic particle (SEP) events (Gopalswamy et al. 2002).

It is expected that in the interaction of large-scale magnetic structures, the transfer of momentum and energy takes place in the form of mageto-hydrodynamic (MHD) waves (Jacques 1977). Despite this fact, the MHD waves are not commonly observed within the magnetic clouds of various sizes in the solar wind. Gosling et al. (2010) reported the first observation of torsional Alfvén wave embedded in the magnetic cloud. The Alfvén wave fluctuations in the solar wind is a common observable feature e.g. (Yang et al. 2016; Marubashi et al. 2010; Zhang et al. 2014). The Alfvénic fluctuations are observed in the region where fast and slow solar wind streams interact e.g. (Tsurutani et al. 1995; Lepping et al. 1997). Observations also suggest the presence of the Alfvén waves during interface of magnetic cloud and solar wind stream (Lepping et al. 1997; Behannon et al. 1991). Here, we present the first observation of Alfvén waves embedded in multi-cloud, complex interacting region caused by interaction of multiple CMEs.

2 METHODS AND OBSERVATIONS

The multiple-CMEs collision event under study has been studied in the past; by focusing on (i) their interaction corresponding to different position angles (Temmer et al. 2014) (ii) their geometrical properties and the coefficient of restitution for the head-on collision scenario (Mishra & Srivastava 2014). Marić et al. (2014) studied heliospheric and in situ observations of the same event to understand the corresponding Forbush decrease phenomenon (Marić et al. 2014; Raghav et al. 2017, 2014). It was inferred that there was a combination of three CMEs instead of two CMEs. Those three CMEs ejected on 13th (here onward designated as CME1), 14th (CME2) and 15th (CME3) February 2011 interacted on their way and appeared as a single complex interplanetary disturbance at 1 AU in the WIND satellite data on 18/20 February 2011 (Marić et al. 2014; Vršnak & Žic 2007).

The in situ observations of the highly complex structure is illustrated in Figure 1 consisting of several different regions, which have been marked by numbering on the top with different color shades. The first (reddish-yellow shade) region shows clear sharp discontinuity in all plasma and magnetic field data, which is interpreted as an onset of shock. In general, the presence of the shock should be confirmed with Rankine-Hugoniot relation. The CfA Interplanetary Shock Database available at https://www.cfa.harvard.edu/shocks/wi_data/00530/wi_00530.html validates the observations. The shock-front is followed by

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Figure 1. Wind observation of complex CME-CME interaction event crossed on 18-20 February 2011 (time cadence of 92 sec). The top panel shows total interplanetary field strength IMF (|B|) and total solar wind (V). The 2nd, 3rd and 4th panel from top show IMF components (Bz, By, Bx) and solar wind components (Vz, Vy, Vx) respectively. The fifth panel shows IMF orientation (Φ, Θ). The sixth panel shows plasma proton density and temperature and bottom panel show plasma beta and plasma thermal pressure. All observations are in GSE coordinate system. The sub-regions of the complex event are presented as a number given at the top and different color shades for better understanding of in situ data.

high plasma density, temperature and thermal pressure; large magnetic field fluctuations and enhanced magnetic field strength which is manifested as shock sheath region (Richardson & Cane 2011). In the region 2 (cyan shade), the elevated magnetic field strength, a decrease in plasma temperature and thermal pressure, very low plasma beta (β) and gradual decrease in solar wind speed is observed which is ascribed to a magnetic cloud like-structure (Burlaga et al. 1982; Zurbuchen & Richardson 2006). However, due to the interaction with 2nd CME, the clear signature of the magnetic field rotation is not evident.

Region 3 (purple shade) shows a sharp drop in the magnetic field strength, increase in plasma parameters such as plasma temperature, plasma beta (β), thermal pressure and turbulent nature of solar wind speed. This region is sandwiched between two sharp discontinuities. The demonstrated variations in the magnetic field and plasma parameters indicate the presence of the magnetic re-connection-outflow exhaust (Gosling et al. 2005a,b; Xu et al. 2011) between two CME magnetic clouds (Wang et al. 2003; Lugaz et al. 2017). The detailed justification for this ad-hoc hypothesis is presented in Maričić et al. (2014) based on similar investigation of in-situ data. Region 4 and 5 (pink and green shade) show increase in solar wind speed, lower proton density, gradual decrease in magnetic field strength. The plasma beta is decreasing in regions 4 whereas gradually increasing in region 5. The magnetic field rotation is observed at the beginning of the region 5, but it is not evident during the complete regions of 4 and 5. These observations suggest the highly complex interplanetary region.
Region 6 (pink shade) shows a sudden increase in magnetic field strength and solar wind speed with steep drop in plasma temperature and proton density, which appears like a shock or a magnetic cloud front boundary after sheath region. Furthermore, $B_y$ shows almost no rotation, $B_x$ shows partial rotation. The $\Theta$ angle is more or less constant whereas $\Phi$ varies by about 45 degrees. This manifested that the region 6 is indeed a magnetic cloud or magnetic cloud-like structure, but one with relatively small rotation. It is listed in the Lepping MC list available at https://wind.gsfc.nasa.gov/mfi/mag_cloud_S1.html.

The regions 4 and 6 (pink shade) show peculiar and distinct feature in which similar temporal variations are observed in the respective magnetic field and velocity components. The observations indicate the presence of possible magneto-hydrodynamic plasma oscillations i.e. torsional Alfvén waves. Typically, two analysis methods are used to confirm the presence of Alfvén waves in solar wind/magnetic clouds. In the first method, one can find Hoffman-Teller (HT) frame velocity ($V_{HT}$) using the measured values of $B$ and $V$. The strong correlation between components of ($V$−$V_{HT}$) and Alfvén velocity confirms the presence of Alfvén waves (Gosling et al. 2010). However, here we used another obvious characteristic for identifying Alfvén waves. The well-correlated changes in magnetic field $B$ and plasma velocity $V$ which is described by the Walén relation (Walén 1944; Hudson 1971) as

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

where $A$ is the anisotropy parameter, $B$ is magnetic field vector and $\rho$ is proton mass density. In the solar wind, the influence of the thermal anisotropy is often not important and can be ignored, thus we usually take $A = 1$ (Yang et al. 2016). The fluctuations $\Delta B$ in $B$ are obtained by subtracting average value of $B$ from each measured values. Therefore, the fluctuations in Alfvén velocity is

$$\Delta V_A = \frac{\Delta B}{\sqrt{\rho_0} \rho_0}$$

Furthermore, the fluctuations of proton flow velocity $\Delta V$ are calculated by subtracting averaged proton flow velocity from measured values. Figure 2 shows the comparison of x, y and z components of $\Delta V_A$ and $\Delta V$, respectively. Figure 3 shows the linear regression relation between the fluctuations of Alfvén velocity vector components and the fluctuations of proton flow velocity vector components for region 4 and region 6 of the event shown in Figure 1. The linear equation and correlation coefficient are shown in each panel. The correlation coefficients for x, y, and z components are 0.82 (0.76), 0.91 (0.94), and 0.94 (0.93), while the slopes are 0.57 (0.94), 0.64 (1), and 0.78 (1), respectively for region 6 (4); The observed values of correlation coefficients and slopes are consistent with reported studies of Alfvén waves (Lepping et al. 1997; Yang et al. 2016). The correlation and regression analysis of both the regions (shown in Figure 2 ) suggest strong positive correlation between $\Delta V_{Ax}$ & $\Delta V_A$, $\Delta V_{Ay}$ & $\Delta V_A$, $\Delta V_{Az}$ & $\Delta V_A$. This indicates sunward pointing torsional Alfvén waves are embedded within both these regions (Gosling et al. 2010; Marubashi et al. 2010; Zhang et al. 2014).

3 DISCUSSION AND CONCLUSION

The heliospheric remote imaging analysis concluded that multiple CMEs interacted in interplanetary space before arriving at 1 AU (position of Wind satellite) (Mishra et al. 2017; Maričić et al. 2014; Temmer et al. 2014). The observation manifests that CME1 and CME2 are boosted by CME3 due to its excess speed. The Drag based model suggests region 2 as MC of CME1, combined regions 4 and 5 as MC of CME2 and region 6 as MC of CME3 from Figure 1 (Maričić et al. 2014). The identification of region 3 as magnetic re-connection-outflow exhaust (Gosling et al. 2005a,b; Xu et al. 2011; Maričić et al. 2014) indicates that the magnetic reconnection mechanism is a major interacting mechanism between CME1 and CME2. The middle CME2 MC (regions 4 & 5) is sandwiched between leading, slower CME1 and fast, following CME3. Therefore, it is highly compressed and overheated.

The recent work by Mishra et al. (2017) considered an oblique collision scenario of two CMEs for the same studied event using the heliospheric remote imaging techniques. The CME1 and CME2 merged together by magnetic reconnection and become visible as first CME after collision and CME3 appeared as second CME in heliospheric imaging data. Mishra et al. (2017) estimated the coefficient of restitution (e) as 1.65. The collision leads to an increase in the momentum of first CME by 68% and a decrease of 43% in the second CME, in comparison to their values before the collision. Thus, the collision results in an increase of 7.33% in the total kinetic energy of the CMEs and was interpreted as
Figure 2. Right 3 panels (region 4) and left 3 panels (region 6) illustrate relative fluctuation of Alfvén velocity vector $\Delta V_A$ (blue lines) and that of proton flow velocity vector $\Delta V$ (red lines). (time cadence of 92 sec)

Figure 3. The linear relation between $\Delta V_A$ and $\Delta V$ for region 4 (left) and region 6 (right) for the event shown in Figure 1. The scattered blue circles are observations from Wind satellite with time cadence of 92 sec. The R is the correlation coefficient. The equation in each panel suggest the straight-line fit relation between respective components of $\Delta V_A$ and $\Delta V$.
super-elastic by nature (Mishra et al. 2017). Moreover, they also indicate 18 hrs of collision time, after which there is a separation of the two CMEs (Mishra et al. 2017). The 18 hrs of collision time indicates the large-scale plasmoid collision is not as simple as solid body collision. Therefore, we hypothesize that the leading edge of CME3 is continuously exerting a force on the trailing edge of CME2. The high distortion with compression and heating of magnetic cloud of CME2 (region 5 of Figure 1) is evident in insitu observation. Thus, magnetic energy of the magnetic cloud of CME2 converts to the kinetic energy of the colliding system, which leads to CME-CME super-elastic collision (Shen et al. 2012; Mishra et al. 2017). It can also cause a change in the force balance conditions of flux ropes. This induces magneto-hydrodynamic wave in which ions plasma oscillate in response to a restoring force provided by an effective tension on the magnetic field lines. The presence of torsional Alfvén waves in region 4 (front of CME2 magnetic cloud) and region 6 (CME3 magnetic cloud) suggests conclusive evidence of this possible physical mechanism. It implies that the MHD waves are the possible energy and momentum exchange/dissipation mode during large-scale plasmoids interaction. The presence of magnetic reconnection-outflow exhaust at the boundary of region 2 and 4 may have prohibited Alfvén waves in region 2.

The dissipation rate of kinetic energy in clumpy, magnetic, molecular clouds is estimated by Elmegreen (1985). Their results indicate that for pressure-equilibrium magnetic field strengths, low-density clouds lose most of their kinetic energy by Alfvén wave radiation to the external medium. This implies that the presence of sunward torsional Alfvén waves in the magnetic cloud of the CME causes decreases in kinetic energy. Hence, this lowers down the speed of magnetic cloud of CME3 which further leads to the separation of CMEs.

The Alfvén waves are thought to pervade many astrophysical plasmas. They have been observed in the solar wind e.g. (Yang et al. 2016; Lepping et al. 1997; Tsurutani et al. 1995) and are expected to exist in the interstellar medium on many length scales and in many environments (Goldstein 1978). It is likely to be one of the major energy exchange/dissipation mode in large-scale magnetic cloud collisions (Elmegreen 1985; Jacques 1977). The present study confirms this and demonstrates that torsional Alfvén waves is the possible energy dissipation mechanisms during large-scale magnetic cloud collisions.

The energy exchange mechanism in CME and planetary magnetosphere interactions is one of the intriguing problems in space-physics or space-weather studies. Each planetary magnetosphere is considered as one type of plasmoid in the heliosphere, with a particular orientation of magnetic field. It is clearly noticeable that the slow-fast solar wind stream interaction, magnetic cloud-solar wind stream interaction and magnetic cloud-cloud interaction give rise to torsional Alfvén waves in space plasma. In a condition of opposite magnetic orientation of the plasmoids, the magnetic reconnection is the possible physical mechanism of their interaction e.g. geomagnetic storms. The fluctuating $B_z$ fields comprising Alfvén waves are expected to cause a type of auroral electro-jet activity called High-Intensity, Long Duration, Continuous AE Activity (HILDCAAs)(Tsurutani & Gonzalez 1987). Their presence may contribute substantially to geo-effectiveness of magnetic cloud-magnetosphere interaction (Zhang et al. 2014). Therefore, the interaction of these Alfvén waves with the magnetic cloud and planetary magnetosphere should be investigated further.

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