FIRST *in-situ* OBSERVATION OF SURFACE ALFVÉN WAVES IN ICME FLUX ROPE

A PREPRINT

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ABSTRACT

Alfvén waves (AWs) are inevitable in space and astrophysical plasma. Their crucial role in various physical processes, occurring in plasma, has triggered intense research in solar-terrestrial physics. Simulation studies have proposed the generation of AWs along the surface of a cylindrical flux rope, referred to as Surface AWs (SAWs); however the observational verification of this distinct wave has been elusive to date. We report the first *in-situ* observation of SAWs in an interplanetary coronal mass ejection flux rope. We apply the Walén test to identify them. The Elsaŝser variables are used to estimate the characterization of these SAWs. They may be excited by the movement of the flux rope's foot points or by instabilities along the plasma magnetic cloud's boundaries. Here, the change in plasma density or field strength in the surface-aligned magnetic field may trigger SAWs.

Keywords Coronal mass ejection (CME) — Magnetohydrodynamic wave — Alfvén wave

1 Introduction

The magneto-hydrodynamic Alfvén waves (AWs) are ubiquitous plasma wave modes in space and astrophysical regimes. In these waves, ions collectively respond to perturbations in the ambient magnetic field, such that the ions provide inertia, while the magnetic field supplies the required restoring force [Alfvén, 1942]. The fluid velocity and magnetic field fluctuations propagating along the magnetic tension force, i.e. well-correlated changes in the respective components of the magnetic field and plasma velocity leads to the apparent characterization of AWs [Walén, 1944, Hudson, 1971, Yang and Chao, 2013, Raghav and Kule, 2018a]. In heliospheric plasma, AWs are observed in two forms: arc-polarized Alfvén waves that have often been recognized in the solar wind [Belcher and Davis Jr, 1971, Wang et al., 2012] and tube modes in ideal magnetic flux ropes, such as the torsional mode [Gosling et al., 2010, Raghav et al., 2018]. These modes are appealing as they carry significant energy from the subphotospheric regions to the corona, and provide energy for coronal heating [Van Doorsselaere et al., 2008]. There is a high possibility of identifying AWs in interplanetary space when a magnetic flux rope erupts, no matter the mode in which it is present [Wang et al., 2019].

It is worth to note that the coronal mass ejection (CME) is a eruption of enormous energy and massive magnetized plasma from the solar corona into the heliosphere in form of magnetic flux rope [Webb and Howard, 2012, Howard, 2011]. Magnetic reconnection or catastrophe processes are expected to trigger low-frequency AWs, and fast and slow-mode magnetoacoustic waves during the initiation of CME [Kopp and Pneuman, 1976]. Thus, the Sun is considered a significant source of outward AWs. Moreover, the reported inward AWs suggest different generation mechanisms apart from the ones mentioned above. Inward AWs are observed in back-streaming ions from the Earth's bow shock, and immediately upstream and downstream from reverse shocks associated with corotating interaction regions or interplanetary counter part of CMEs (ICMEs). AWs are also found in the vicinity of reconnection exhausts and during the drifting of Sunward proton beams in the solar wind [Belcher and Davis Jr, 1971, Roberts et al., 1987, Bavassano and Bruno, 1989, Gosling et al., 2009, 2011, 2009, 2011]. It is also proposed that it may be triggered by some physical processes happening locally [Bavassano et al., 2001, Bruno and Carbone, 2013a]. Recently, we found their existence during the CME-CME and CME-HSS interactions, and inside the ICME sheath regions [Raghav and Kule, 2018a,b, Dhamane et al., 2022, Raghav et al., 2022]. Moreover, AWs play a key role in modulating the recovery phase of geomagnetic storms and slowing down the restoration of the magnetosphere toward its pre-storm equilibrium state [Raghav et al., 2018, Shaikh et al., 2019a, Raghav et al., 2019, Choraghe et al., 2021, Telloni et al., 2021].

The most interesting MHD surface wave in the astrophysical domain is the Surface Alfvén Wave (SAW). It forms when there's a finite thickness boundary between two regions of plasma with substantial inhomogeneity in a magnetic field and/or density [Evans et al., 2009]. SAWs may propagate through surface and filamentary structures (e.g., discontinuities) in interplanetary and interstellar space [Wentzel, 1979]. Their coupling with kinetic Alfvén waves dissipate them and heat up the surface [Chen and Hasegawa, 1974, Hasegawa and Chen, 1976]. Moreover, Wentzel [1979] suggested that the SAWs may be triggered by the footpoints movement of the flux tubes, or instabilities along the plasma boundaries. Theory and experiment suggest that the SAW eigenmodes play a crucial role in the AWs heating process [Ruderman and Goossens, 1996, Amagishi, 1986]. The simulation study of the collision between a shock wave and a magnetic flux tube shows that SAWs can be generated and propagated along the flux tube [Sakai et al., 2000]. They further suggest that SAWs are possible for magnetic flux tubes with weak electric current, whereas body AWs may be generated when the current is strong. Moreover, [Lehane and Paoloni, 1972] confirmed the SAWs in the laboratory. Despite the fact that SAWs were expected to exist in magnetic flux rope structures, no one has yet found them in either small- or large-scale (like the ICME) flux ropes. Here, we investigated 401 ICME events listed in the Earth directed ICME catalog measured by WIND Spacecraft and hunted for the evidences of SAWs. Interestingly, we found 3 potential events for SAWs. Out of them, the best event is discussed here in detail. To the best of our knowledge, this is the first report that claims the observation of the SAWs superposed ICME flux rope.

2 Data and Method

The event was identified on 02 September, 2005 by the WIND spacecraft. In this study, we have used plasma and magnetic field data (of 3 sec time resolution) from Magnetic Field Investigation (MFI) [Lepping et al., 1995] and 3DP Experiment (SWE) [Ogilvie et al., 1995] instruments onboard the WIND spacecraft in Geocentric solar ecliptic (GSE) coordinates. Their variation with 92-second time resolution during the studied event is demonstrated in figure 1. The figure describes two regions shaded with cyan and blue colour. The sudden increase in the total magnetic field B_{tot}, number density (N_p), total pressure (P_{tot}), and plasma temperature (T_p) indicates the onset of the shock front. The high fluctuations are observed in each magnetic field components, and δB in the following region is generally referred to as shock-sheath. We observe β to be valued near one along with high proton density, plasma temperature and enhanced solar wind speed in this region. The Rankine–Hugoniot relation confirms the presence of the shock. The details are available at CfA Interplanetary Shock Database, i.e., `https://www.cfa.harvard.edu/shocks/wi_data/00530/wi_00530.html`. The ICME flux rope follows the sheath region. We observed gradual decrease in total magnetic field. The decrease in The fluctuations in magnetic field components, plasma temperature, and plasma β value suggest the flux rope's passage over the spacecraft. The different boundaries are defined in two distinct catalogs available online, i.e., Richardson/Cane ICMEs catalog available at `http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm` and USTC ICME catalog available at `http://space.ustc.edu.cn/dreams/wind_icmes`. Thus, we decide the flux rope front boundary based on electron pitch angle. We observed a nearly bidirectional flow of electron trails. Moreover, ICME trailing edge boundary is decided based on the plasma β, and θ variations.

To identify the existence of Alfvén wave, we have employed the Walén relation. The Walén relation is described as [Hudson, 1971, Walén, 1949]

$$\Delta V \ = \ |R_W| \, \Delta V_A$$

Here, the linear relation between Alfvén velocity (ΔV_A) and solar wind velocity (ΔV) provides the Walén slope (R_w). The fluctuations in the magnetic field ΔB and proton flow velocity ΔV are determined by removing the background field value (B_0) from measured values. The significant correlation between each respective component of ΔV_A and ΔV indicates the presence of Alfvén wave. Determining the background value of V_A and V is challenging while implementing the Walén relation. Reported studies have either used the average values of V_A, and V of the studied duration, or the values derived by de Hoffmann-Teller (HT) frame [Gosling et al., 2010, Yang and Chao, 2013,

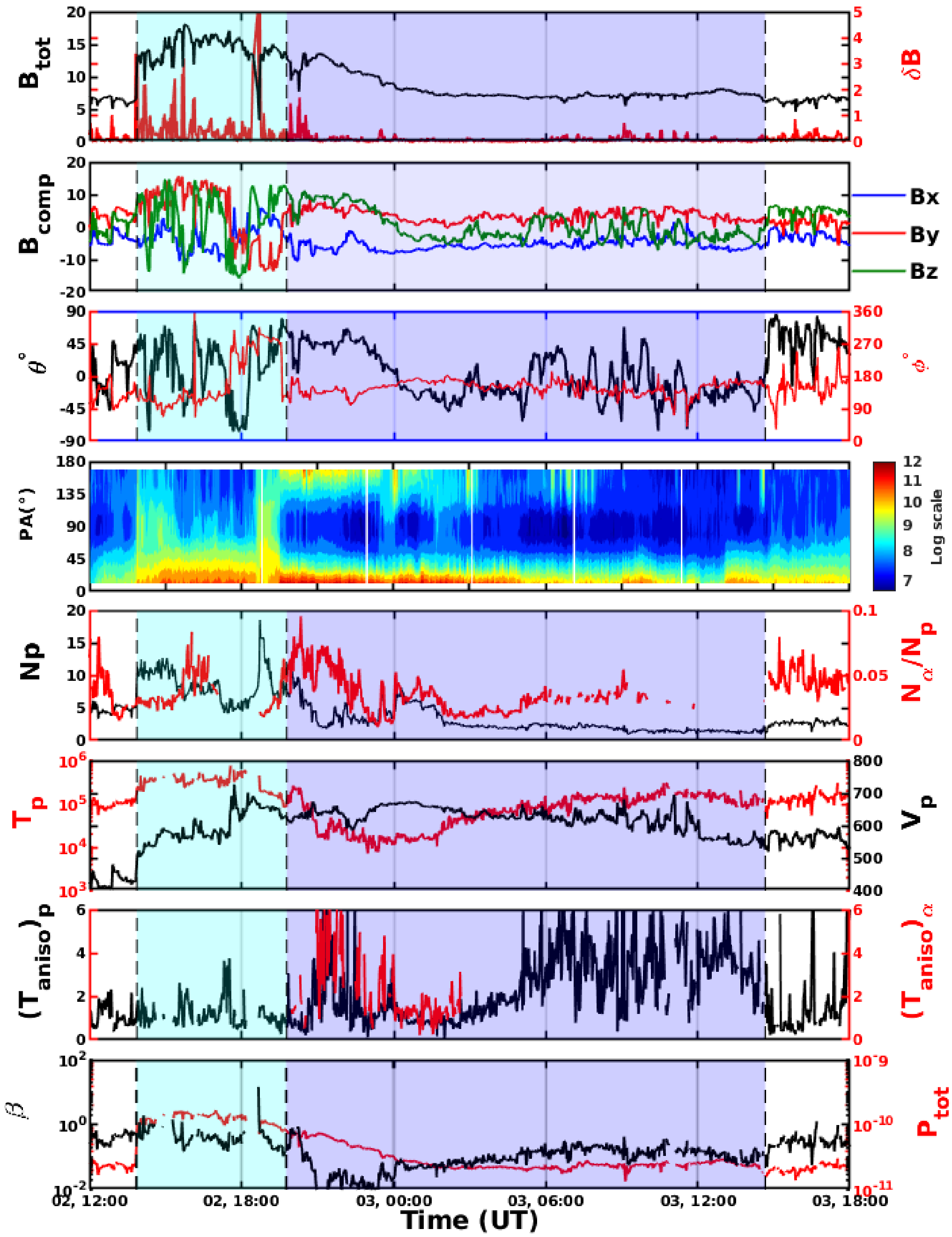

Figure 1: The WIND data over the interval 2005 September 2 12:00:00 to 2005 September 3 18:00:00 UT are plotted. From top to bottom, Interplanetary Magnetic Field (IMF) strength B_{tot} overlaid with δB, a component of the magnetic field B_{comp}, the IMF orientation of θ and ϕ, the pitch angle (PA) of suprathermal electron strahls, the variation of number density N_p and $\frac{N_\alpha}{N_p}$. variation of temperature of proton (T_p) along with velocity of proton (V_p), anisotropy in proton temperature $(T_{aniso})_p$ and α particle $(T_{aniso})_\alpha$, plasma β overlaid with plasma thermal pressure P_{tot} are plotted. All observations are in GSE coordinate system.

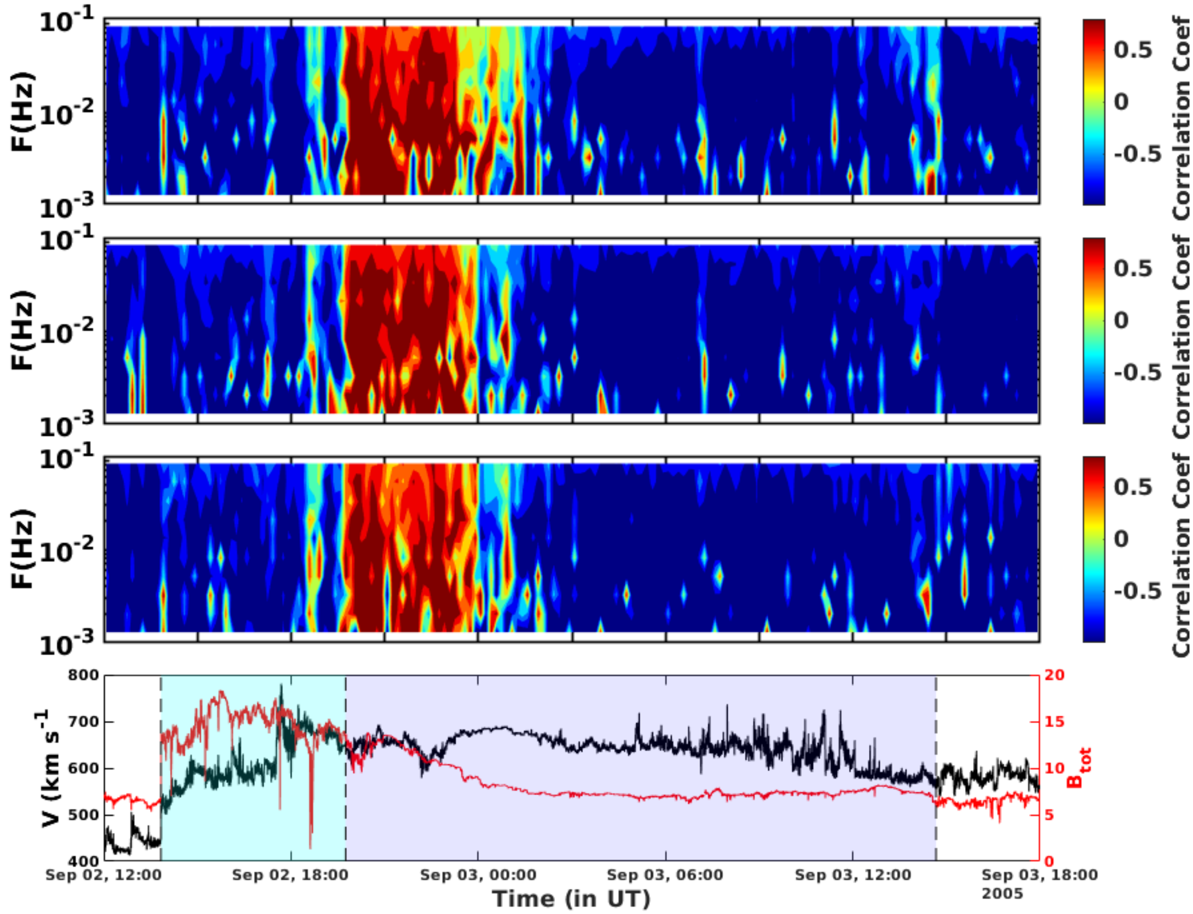

Figure 2: The time-frequency domain gives the correlation coefficient between V_{Ai} and V_i for the entire event. The bottom panel displays the change in the magnetic field and proton velocity over time. The vertical dashed line shows the boundaries of the magnetic cloud and shock sheath of the ICME. For the above analysis, we use 3-second data from the WIND spacecraft.

Raghav and Kule, 2018a, Raghav et al., 2018, Raghav and Kule, 2018b, Shaikh et al., 2019b]. Here, we used the 4^{th} ordered Butter-worth band-pass-filter MATLAB-based algorithm to estimate background values. The evenly divided ten logarithmic frequency bands were selected. The selected bandpass periods are 10s-15s, 15s-25s, 25s-40s, 40s-60s, 60s-100s, 100s-160s, 160s-250s, 250s-400s, 400s-630s, and 630s-1000s. The complete data under examination is split into windows of 200 data points, i.e. 10-minute time window. For every window and filtered band, we find the correlation coefficient between the respective components of V_A and V. Figure 2 describes the contour plot of V_{Ai} and V_i along with the temporal variations of total magnetic field and velocity. The shock sheath and trailing edge of the Magnetic Cloud (MC) indicate a strong negative correlation coefficient (dark blue shade). It confirms that these regions are superposed with the Anti-Sunward flow of AWs. The leading part of the MC exhibits a strong positive correlation coefficient (red shade), confirming the Sunward propagation of AWs.

Figure 3 depicts the plasma properties in the ICME's shock sheath and MC region based on Elsaŝser variables. The top three panels of Figure 3 show the fluctuations in Alfvénic velocity (ΔV_A) and proton flow velocity (ΔV_p) components, respectively. The fluctuations in each component are obtained by passing each measured component through 4^{th} order butter-worth filter (with frequency limits of 10^{-3} to $10^{-1} Hz$) algorithm of MATLAB software. We observed anti-correlated flow fluctuations in the sheath region for each component. Interestingly, we found correlated fluctuations flow at the initial part of the MC, whereas an anti-correlated flow is seen in the trailing part of the MC. Here, we employ

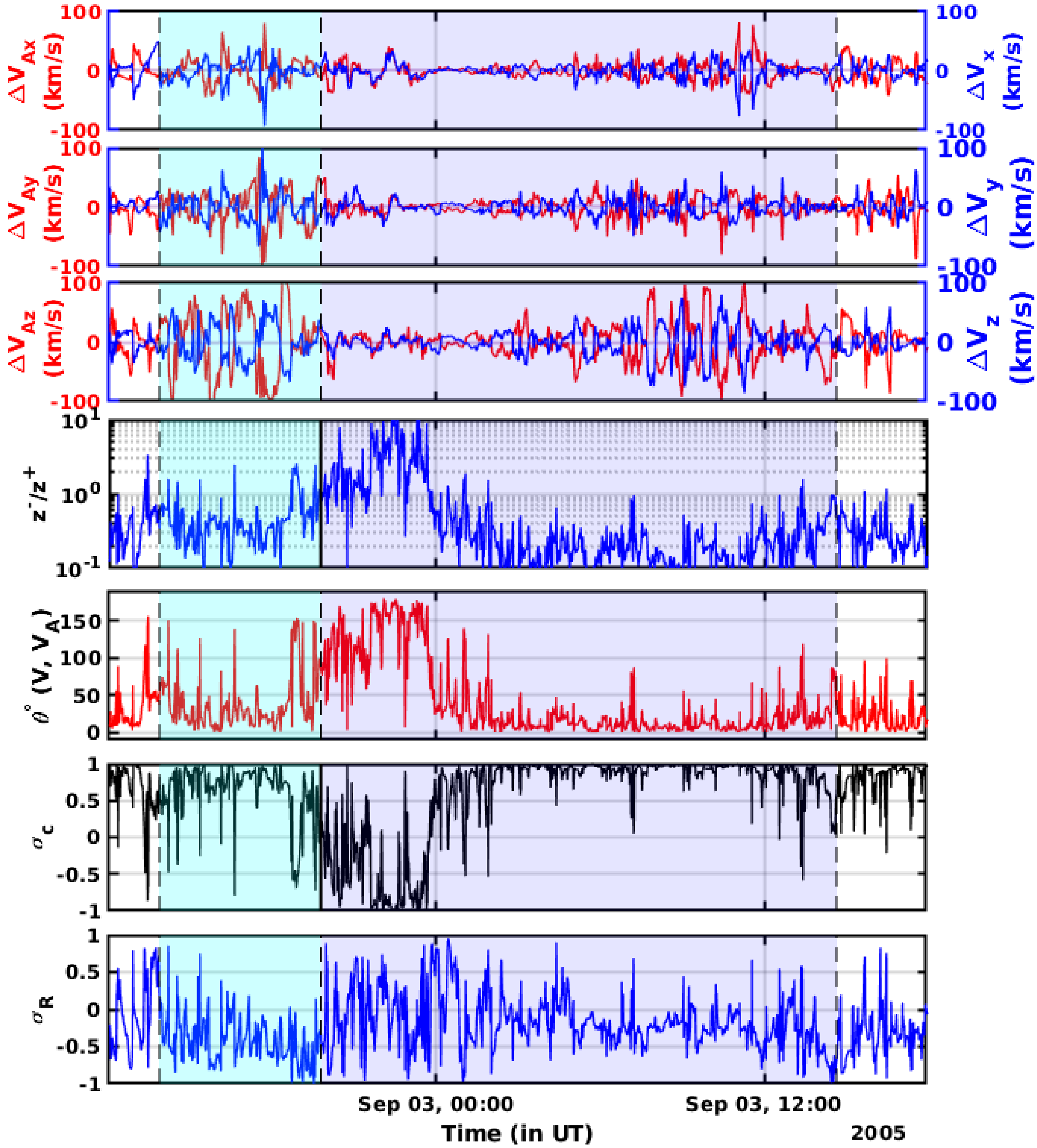

Figure 3: The top three panel shows the temporal variation of Alfvén velocity fluctuation ΔV_{Ai} (red) with proton flow velocity fluctuations ΔV_i (blue). Ratio of Elsaŝser variables z^-/z^+ shown in the fourth panel. The presence of the angle between the magnetic field and solar wind speed is shown in the fifth panel. The last two panels represent the temporal variation of the normalized cross helicity (σ_c) and normalized residual energy (σ_R), respectively.

Elsässer variables to separate the contributions of outward and inward Alfvénic fluctuation flow. The Elsaësser variables are defined as [Dobrowolny et al., 1980, Zhou and Matthaeus, 1989, Marsch and Mangeney, 1987, Elsasser, 1950]

$$\vec{z^{\pm}} = \Delta\vec{V} \pm \frac{\Delta\vec{B}}{\sqrt{4\pi\rho}} = \Delta\vec{V} \pm \Delta\vec{V_A} \tag{1}$$

Here, Elsässer variables $\vec{z}^{+}$ and $\vec{z}^{-}$ are set up to find the waves flow direction, i.e., outward and inward, respectively [Roberts et al., 1987]. The $\pm$ sign in front of $\vec{B}$ depends on the sign of $[-k \cdot B_0]$. For the ratio $(z^-/z^+) < 1$ the outward flow became more effective in the sheath region and trailing part of the MC, whereas for the ratio > 1 the inward Alfvénic fluctuations are dominant in the initial part of MC [Matthaeus and Goldstein, 1982, Tu et al., 1989]. The angle between Alfvén velocity and solar wind velocity $\theta(V, V_A)$ is estimated as

$$\theta(\Delta V_A, \Delta V) = arcos(\frac{\Delta\vec{V}_A.\Delta\vec{V}}{||\Delta\vec{V}_A||\;||\Delta\vec{V}||})$$

At the beginning of the MC, both vectors are almost anti-parallel to each other, while in the sheath region and trailing part of the MC, the flow is concurrent. This strongly suggests flow direction changes in each region.

Cross helicity (H_c) demonstrates a measure of the correlation between velocity and magnetic field [Bruno and Carbone, 2013a], the dimensionless measure of cross helicity is known as normalized cross helicity ($\sigma_c = \frac{H_c}{E}$) ranging from -1 to 1. For $\sigma_c = \pm 1$, the fluctuations are highly Alfvénic.

$$\sigma_c = \frac{e^+ - e^-}{e^+ + e^-} \tag{2}$$

Here e^- & e^+ are the energies related to z^- and z^+ and $e^{\pm}$=$\frac{1}{2}$ $(z^{\pm})^2$. Also, the normalized residual energy is calculated as [Bruno and Carbone, 2013a, Bruno et al., 2005]

$$\sigma_R = \frac{e^v - e^b}{e^v + e^b} \tag{3}$$

where e^v & e^b is kinetic and magnetic energy respectively.
We observe $\sigma_c > 0$, $\sigma_R < 0$ in sheath region and trailing part of the MC(outward). Also, $\sigma_c < 0$, $\sigma_R > 0$ in the leading part of MC(inward). These observations strongly agree with the estimation of Elsässer variables.

The intensity of inward-outward propagating waves or their mixing is investigated by using the temporal variations of Walén slope (or the correlation between the magnetic field and plasma velocity) [Shiota et al., 2017, Yang et al., 2016, Belcher and Davis Jr, 1971, Marsch and Tu, 1993, Bruno and Carbone, 2013b]. Their temporal fluctuations are depicted in figure 4. Both coefficients fluctuate near the value of ~ -1 in the sheath region and trailing part of the MC, whereas they fluctuate ~ 1 in the leading part of the MC.

3 Discussion and conclusion

All the observations and estimations suggest an outward Alfvén fluctuation flow in the sheath region, an inward flow in the front part of MC, and an outward flow in their end part. It implies two possibilities for an AW generation; (i) the interaction between the sheath and MC triggers an oppositely directed wave flow in the sheath region and MC or (ii) the change in the axial current induces Alfvénic fluctuations in the magnetic flux rope. The simulation study corroborates that the collision between a shock wave and a magnetic flux tube describes SAWs generation, or the possibilities of SAWs for magnetic flux tubes with weak electric current [Sakai et al., 2000].

As an analogy, the bidirectional flow of Alfvén wave in the ICME flux rope can be explained as follows. Consider the cartoon picture of the cross-section of the flux rope, as shown in 5. The left image is the ideal circular cross-section of the flux rope, whereas the right image demonstrates the SAW's superposed flux rope cross-section. The red arrow indicates the spacecraft's passage through the ICME flux rope. At the spacecraft's entry point, i.e., the anterior of the flux rope, the surface wave depicts the upward direction of propagation, whereas the posterior shows the downward movement of propagation. The upward and downward directions are proxies for wave propagation. An important fact is that the wave propagates inward, in the initial part of the MC and outward at the trailing region of the MC (see Figure 2). When the spacecraft moves from one end of the flux rope's cross-section to the other, the amplitude of fluctuations on the surface is more significant than at the centre. The outer layer of the flux rope describes higher amplitude of the Alfvénic oscillations. As we move into the inner concentric layers, the amplitude decreases and is minimum at the centre of the flux rope. This is also clearly seen in the top three panels of Figure 3.

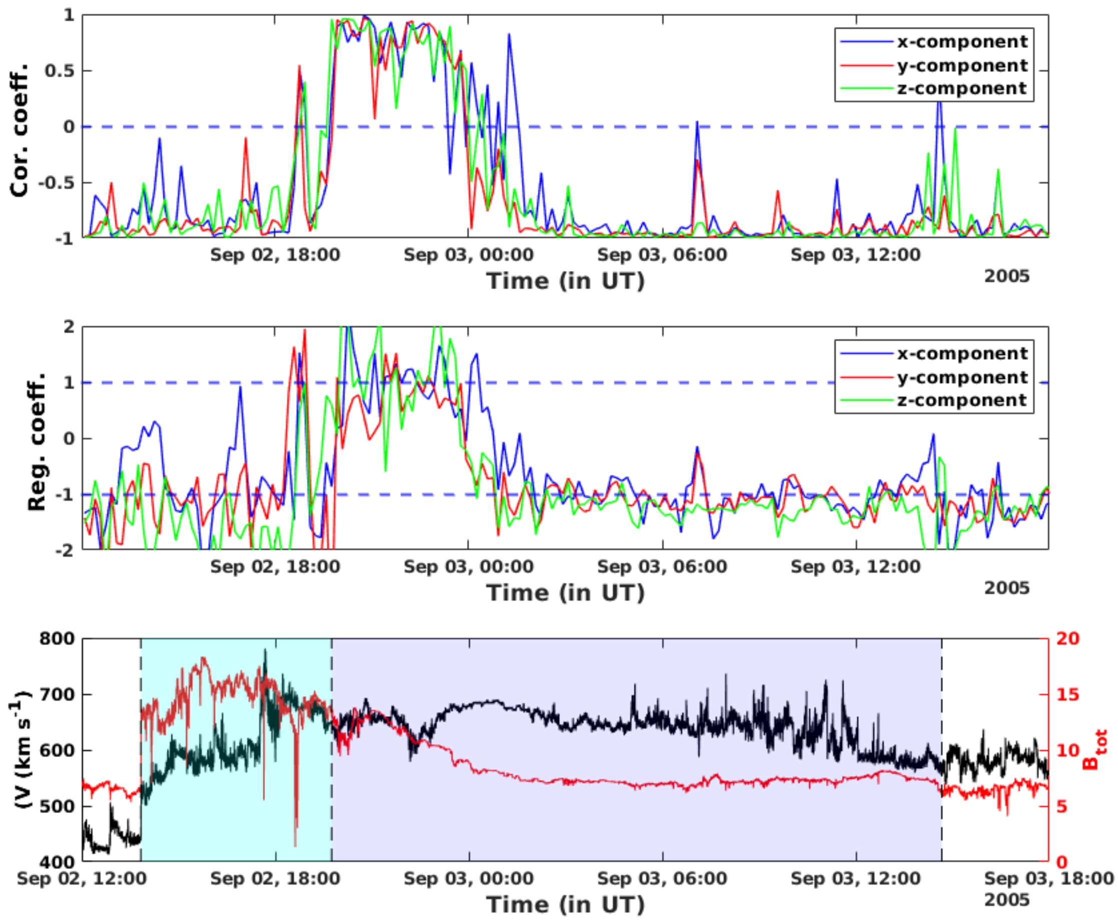

Figure 4: The correlation & regression coefficient is shown in the top two panels, while the variation of Total magnetic field(B_{tot}) & solar wind speed (V) with time is shown in the bottom panel.

SAWs are expected to exist in astrophysical plasmas where density or magnetic field jumps occur. e.g., on the surfaces of magnetic flux tubes in the solar and stellar atmospheres, at the interfaces between plasmas of different properties in the solar wind and Earth's magnetosphere [Cramer, 2011]. We also observed a large proton temperature anisotropy at the front and trailing part of the flux rope, prompting us to believe that the large temperature anisotropy could be the possible source of SAW generation or vice-versa. Besides this, we observed the spike in number density (N_p) and sudden drop in the total IMF strength in the sheath region, just prior to the onset of the MC (see figure 1) which could be attributed to reconnection exhaust. Moreover, Gosling et al. [2005] claims that AWs could be generated by reconnection exhaust at the quasi stationary heliospheric current sheet (HCS), implying that the difference in density variations at the boundary between the sheath region and MC leads to the induction of oppositely directed waves in the sheath region and the MC's front part.

An AW is often observed in interplanetary space and most recently, in the flux ropes [Gosling et al., 2010, Raghav and Kule, 2018b]. The behaviour of a SAW is solely different from that of a classical AW [Goossens et al., 2012]. The observational evidence of SAWs has immense importance in astrophysical settings. The SAWs are linked to tearing mode instability, leading to the time-dependent magnetic reconnection process. This results in the neutral collision effect and ionisation fraction to significantly impact the SAWs [Uberoi, 1994, Uberoi et al., 1996]. The resonant absorption of SAWs appears to be a viable heating process for both, the open regions and coronal loops [Ionson, 1978]. Moreover, SAWs can damp through viscosity, resistivity and other kinetic factors, which results in the plasma wave heating [Evans et al., 2012]. Evans et al. [2009] explored the role of SAWs damping to the solar wind heating. Here, a

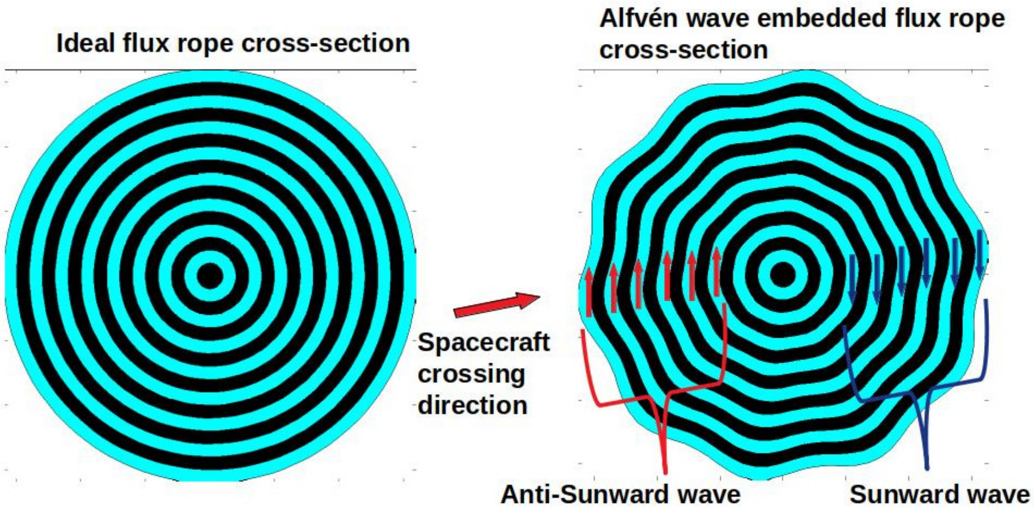

Figure 5: Cartoon demonstration of the generation of SAW, the first image is about the ideal flux rope cross-section, and the second cartoon image manifests the spacecraft crossing one of the cross sections of the flux rope.

number of intriguing scientific questions arise, such as How does SAW alter the properties of the ICME? How do they dissipate? Additionally, how does the SAW amplitude change as the ICME moves across the heliosphere? These issues are beyond the purview of this article, although we might look into them later.

To summarize, we conclude that the SAWs are hypothesized to be essential for the plasma heating process in the solar corona and the solar wind. Here, we unambiguously demonstrated their existence in the ICME flux rope.

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