

PLASMA HEATING INSIDE ICMEs BY ALFVÉNIC FLUCTUATIONS DISSIPATION

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Abstract

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Full Text

Preamble

PLASMA HEATING INSIDE ICMEs BY ALFVÉNIC FLUCTUATIONS DISSIPATION

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ABSTRACT

Nonlinear cascade of low-frequency Alfvénic fluctuations (AFs) is regarded as one candidate of the energy sources to heat plasma during the non-adiabatic expansion of interplanetary coronal mass ejections (ICMEs). However, AFs inside ICMEs were seldom reported in the literature. In this study, we investigate AFs inside ICMEs using observations from Voyager 2 between 1 and 6 au. It is found that AFs with high degree of Alfvénicity frequently occurred inside ICMEs, for almost all the identified ICMEs (30 out of 33 ICMEs), and 12.6% of ICME time interval. As ICMEs expand and move outward, the percentage of AF duration decays linearly in general. The occurrence rate of AFs inside ICMEs is much less than that in ambient solar wind, especially within 4 au. AFs inside ICMEs are more frequently presented in the center and at the boundaries of ICMEs. In addition, the proton temperature inside ICME has a similar distribution. These findings suggest significant contribution of AFs on local plasma heating inside ICMEs.

Keywords: Sun: coronal mass ejections (CMEs) –acceleration of particles – solar wind –turbulence –waves

1. INTRODUCTION

Coronal mass ejections (CMEs) are spectacular large-scale disturbed structures involving great explosion of solar material into heliosphere. Solar wind structures or interplanetary manifestations of CMEs are now generally referred to as interplanetary coronal mass ejections (ICMEs), which are the heliospheric counterparts of CMEs at the Sun (e.g., Gosling 1990; Neugebauer & Goldstein 1997).

ICMEs often expand in size with radial distance in the inner heliosphere since their internal pressures are generally higher than the ambient solar wind, and their leading edges usually move faster than the trailing edges (see Burlaga 1995, and references therein). The radial width increases with distance out to 15 au (astronomical unit) (Wang & Richardson 2004; Liu et al. 2005); beyond this distance the widths are relatively constant because ICMEs reach equilibrium with the background solar wind (Wang et al. 2005; Liu et al. 2006; Richardson et al. 2006).

For an expanding ICME, the proton temperature would be expected to decrease more quickly within the ICME than in the ambient solar wind due to adiabatic cooling. However, the proton temperature inside ICMEs does not behave even qualitatively as expected. Liu et al. (2005) and Wang et al. (2005) found that

the proton temperature inside the ICMEs from 0.3 to 5.4 au decreases slower than in the background solar wind. Wang & Richardson (2004), Richardson et al. (2006) and Liu et al. (2006) combined Voyager 1 and Voyager 2 data and extended such findings out to 30 au. The polytropic index was determined empirically to be 1.15–1.33, implying considerable local plasma heating within ICMEs.

The most probable energy source of plasma heating within ICMEs is believed to come from the magnetic field. However, the mechanism which dissipates magnetic energy into thermal energy is still an open question. In the literature, several candidate mechanisms were proposed to heat the CME plasma, which are listed as follows: (1) Outflows from the CME current sheets have the potential to heat CMEs far from the flare sites (Bemporad et al. 2007); (2) Kinking is frequently observed in prominences and during solar eruptions (e.g., Rust & LaBonte 2005). The kink instability could heat CME plasma by injecting energy at outer scale for turbulence development through large-scale motions; (3) Heating by small-scale magnetic reconnection is another candidate mechanism and is similar to the nanoflare model of coronal heating. The frequently occurred tearing mode is one possible manifestation of this mechanism (Furth et al. 1963); (4) The damping of MHD waves driven by photospheric motions is also one of the mechanisms of heating ICMEs; (5) Thermal conduction along magnetic field is quick and therefore regarded as a potential contributor to the heating of ICME plasma (Landi et al. 2010); (6) Energetic particles accelerated during the impulsive phase of solar flares could contribute to CME heating; (7) Counteracting flows, such as upward concave flux rope segments yield shocks from colliding flows accelerated by gravity, may heat CME plasma (Filippov & Koutchmy 2002); and (8) Ohmic heating from net current in the flux rope (see Murphy et al. 2011 and the references therein for more details).

Nonlinear cascade of low-frequency Alfvénic fluctuations (AFs), which transfers energy from large scales down to small kinetic scales for further dissipation, is generally regarded as one candidate energy source for the heating of ICME plasma. It can preferentially heat heavy ions within ICMEs as observed (Tu & Marsch 1995; Tam & Chang 1999; Kasper et al. 2008; Wang et al. 2014). Galinsky & Shevchenko (2012) showed that heavy ions could be heated due to interactions between anti-sunward and sunward AFs. Liu et al. (2006) found turbulence inside an ICME at 3.25 au and suggested that magnetic turbulence dissipation seems sufficient to explain the ICME heating; they assumed that the turbulence was driven by AFs, though AFs were seldom reported inside ICMEs from 0.3 to 20 au. To our knowledge, quite limited numbers of AF events have been published in the literature. Marsch et al. (2009) found possible AFs lasting for almost one hour in an ICME detected at 0.7 au. Yao et al. (2010) later presented clear AFs with 2-hr duration inside an ICME observed at 0.3 au.

Traditional diagnosis of AFs may underestimate the degree of Alfvénicity, and thus possibly miss some AFs. Li et al. (2016a) proposed a new approach to search for AFs, which could reduce the uncertainties in identifying AFs. In this

study, we apply this AF diagnosis approach to identify AFs inside ICMEs from 1 to 6 au based on Voyager 2 data. Abundant AFs are found within ICMEs. Clear indirect evidence of the contributions of AFs on ICME plasma heating is provided.

2. DIAGNOSIS OF AFS WITHIN ICMES

The differences of ICMEs lie in the different signatures of magnetic field, plasma, composition and energetic particle. However, the identification of ICMEs still remains a subjective undertaking. No single characteristic has proved both necessary and sufficient to define the presence of ICMEs. The currently used signatures for the in situ identification of ICMEs at 1 au have been well summarized (see Zurbuchen & Richardson 2006, and references therein), such as smooth magnetic field rotation and enhancement, low proton temperature, extreme density decrease, enhanced alpha/proton ratio, abundance and charge state anomalies of heavy ion species, bidirectional electron beams and cosmic rays, and so on.

In the outer heliosphere, ICME identification becomes even more difficult. On one hand, some signatures of ICMEs are blurred through interaction with the ambient solar wind. On the other hand, current available measurements from the limited instruments cannot supply the complete set of variables required for comprehensive identification.

Wang & Richardson (2004) identified 147 probable ICMEs from hourly averaged solar wind plasma and magnetic field data by Voyager 2 between 1 and 30 au. The primary criterion they used is abnormally low solar wind proton temperature proposed by Richardson & Cane (1995). This criterion compares the observed proton temperature T_p with the “expected” temperature T_{ex} appropriate for “normally expanding” with the observed solar wind speed V . T_{ex} (in unit of 10^3 K) is calculated from the relationship derived by Lopez (1987):

$$T_{ex} = \frac{(0.031V - 5.1)2/R0.6 < 500 \text{ km/s} (0.51V - 142)/R0.6}{500 \text{ km/s}}$$

They also examined the magnetic field and plasma parameters to exclude regions which may not be ICMEs, such as regions associated with heliospheric current sheet crossings. The determination of ICME boundaries is uncertain since different signatures usually have different boundaries. The boundaries chosen by them were generally coincident with the regions where $T_p/T_{ex} = 0.5$ with some adjustments based on reduced magnetic field fluctuations.

In this work, we identify ICMEs mainly based on the probable ICME list of Voyager 2 given by Wang & Richardson (2004). In order to ensure the availability of combined magnetic field and plasma data with temporal resolution of 48 s or 96 seconds (which is adequate for analyzing AFs suggested by Li et al. (2016b)) and to avoid the complications caused by the heating of interstellar pickup ions (Richardson & Smith 2003), we only use Voyager 2 data from 1977 December 1

to the end of 1979. During this time period, a total of 33 probable ICMEs are identified. Note that some minor adjustments of ICME boundaries have been done based on the data sets with a higher time resolution compared to hourly data sets used by Wang & Richardson (2004).

To reduce the uncertainties of AFs diagnosis introduced in the determinations of the background magnetic field and the deHoffmann-Teller (HT) frame, we apply the approach proposed by Li et al. (2016a) to identify AFs within ICMEs. Instead of the original data sets, the bandpass filtered signals of the plasma velocity and magnetic field observations are used to check the Walén relation as follows:

$$V = \pm V$$

Here, V and V represent the bandpassed V (solar wind velocity) and V (local Alfvén velocity) with the i -th filter, respectively. The $-/+$ signs respectively denote the propagation parallel and anti-parallel to the background magnetic field. The parameter proposed by Li et al. (2016a,b), Err , is used to assess the goodness of the degree of the Alfvénicity. For each filtered data set, we calculate the following eight parameters: 1) $||c| - 1|$; 2) $||cx| - 1|$; 3) $||cy| - 1|$; 4) $||cz| - 1|$; 5) $(cid:12) (cid:12) (cid:12)$ 6) $(cid:12) (cid:12) (cid:12)$ components of V and VA , V represents the standard deviation of all the components of V , $-1(cid:12) (cid:12) (cid:12)$. Here, c is the correlation coefficient between all the $-1(cid:12) (cid:12) (cid:12) - 1(cid:12)$; 7) $(cid:12) (cid:12) (cid:12) (cid:12)$ $(cid:12) - 1(cid:12)$; 8) $(cid:12) (cid:12) (cid:12) (cid:12) (cid:12) VA_y VA_x VA_z$ and VA represents the standard deviation of all the components of VA . The terms with subscript x , y , and z are for the x , y , and z components. The parameter Err is the average value for these eight parameters. Compared to previous parameters defined to represent the Alfvénicity, such as the Alfvén ratio, the Walén slope, the normalized cross helicity, the normalized residual energy, and the velocity-magnetic field correlation coefficient, Err is a more comprehensive and reliable quantity (Li et al. 2016b).

We apply a moving window with a width of 1 hr and a moving step of 5 min to calculate Err for each filtered data sets. The AFs are defined as the intervals with $Err < 0.15$ as used by Li et al. (2016a). For 48 s Voyager 2 data, the filters are chosen to be 100–135 s, 135–180 s, 180–250 s, 250–330 s, 330–450 s, 450–600 s, 600–810 s, 810–1100 s, 1100–1480 s, and 1480–2000 s. For 96 s Voyager 2 data, the filters are chosen to be 200–250 s, 250–320 s, 320–400 s, 400–500 s, 500–630 s, 630–800 s, 800–1000 s, 1000–1260 s, 1260–1580 s, and 1580–2000 s.

[Figure 1: see original paper] shows the overview of an ICME (hatched area) observed by Voyager 2 at 4.73 au. From top to bottom, the panels show the magnetic field strength ($|B|$), the solar wind bulk speed (V_p), the proton number density (N_p), the proton thermal speed (V_{th}), the ratio of the observed to the expected temperature (T_p/T_{ex}), and Err , respectively.

Figure 1 shows the overview of an ICME observed by Voyager 2 at 4.73 au during 1979 February 17–23. From top to bottom, the panels show the mag-

netic field strength ($|B|$), the solar wind bulk speed (V_p), the proton number density (N_p), the proton thermal speed (V_{th}), the ratio of the observed to the expected proton temperature (T_p/T_{ex}), and Err , respectively. The threshold value $T_p/T_{ex} = 0.5$ is plotted as the horizontal dashed line in the fifth panel. As described previously, the primary criteria for identifying possible ICMEs, T_p/T_{ex} , is well under 0.5 inside the ICME (hatched area). A monotonic declining of solar wind bulk speed and a cool proton thermal speed (< 20 km/s) are other typical characteristics of a candidate ICME event observed beyond 1 au (Russell & Shinde 2003).

For this event, the solar wind bulk speed decreases nearly monotonically across the ICME and the proton thermal speed within the ICME is less than 15 km/s. The speed of the leading edge is 450 km/s, which is faster than that of the trailing edge of 390 km/s. The speed difference of 60 km/s suggests that the ICME is still expanding as it moves outward. This value is a little larger than the average expansion speed of an ICME at 4.73 au (48 ± 4 km/s) estimated based on the empirical formula given by Liu et al. (2005). The density inside ICMEs beyond 1 au is often smaller than in the ambient solar wind. For this event, the density is generally 0.3 cm^{-3} , less than the value in the ambient solar wind of 0.4 cm^{-3} . In addition, the magnetic field strength has an enhancement during this event. These additional signatures give us more confidence that this event is an ICME event.

The duration of this ICME is about 154.0 hr with an average solar wind speed of about 420 km/s, which gives a radial width of about 1.55 au, which is a little larger than the average radial width of an ICME at 4.73 au (1.16 ± 0.04 au) estimated based on the empirical formula given by Liu et al. (2005). The time-frequency distribution of Err reveals that there exists many intervals of relatively pure AFs in the center and at both boundaries of the ICME, which are denoted by the green and blue regions.

[Figure 2: see original paper] shows two examples of AFs inside the ICME shown in Figure 1. The first three panels show the magnetic field (B , in red) and solar wind velocity (V , in blue) in the RTN coordinates, the fourth panels shows the magnetic field strength ($|B|$, in red) and proton number density (N_p , in blue), and the bottom panel shows Err .

Figure 2 shows two examples of AFs inside the ICME shown in Figure 1. The left panel shows the AFs during 0050–0250 UT on 1979 February 21. During this time interval, the solar wind is essentially incompressible with relative fluctuations N_p/N_p of 7.7% and $|B|/|B|$ of 1.1%. However, the three components of B and V have large-amplitude fluctuations which have a strong positive correlation. The correlation coefficients for the R, T, and N components are 0.84, 0.89, and 0.88, respectively. Such a strong correlation and incompressibility indicate the presence of AFs propagating anti-parallel to the background magnetic field, which is assumed to be the mean magnetic field during this time interval ($-0.79, 0.60, 0.22$) nT. From the time-frequency distribution of Err , it is clear that the AFs during this interval are not periodic like a monochromatic wave, instead,

are broadband with different frequency at different time. For example, the wave periods of relatively pure AF during 0050 and 0150 UT are generally 630-800 s, and the wave periods during 0135-0230 UT change to 800-2000 s.

The right panel shows the AFs from 2100 UT on 1979 February 22 to 0040 UT on 1979 February 23. The relative fluctuations of N_p/N_p and $|B|/|B|$ are insignificant, 5.6% and 2.2%, respectively. This indicates that the solar wind is incompressible. However, the fluctuations in the three components of B and V in the RTN coordinates have large amplitudes and strong positive correlation. The correlation coefficients for the R, T, and N components are 0.93, 0.88, and 0.82, respectively. The background magnetic field, which is assumed to be the mean magnetic field during this time interval, is $(-0.17, 0.22, 0.70)$ nT. Obviously, there exists relatively pure AFs during this time interval, and propagate anti-parallel to the N axis in the RTN coordinates. This is confirmed from the time-frequency distribution of Err as well. The wave periods of relatively pure AF during 2110 and 2210 UT are generally 1260-2000 s, and the wave periods during 2310-0010 UT change to 630-1000 s.

4. STATISTICAL CHARACTERISTICS OF AF INSIDE ICMES

The results shown in section 3 suggest that relatively pure AFs can and do exist inside ICMEs. [Figure 3: see original paper] shows the dependence of the percentage of AF duration inside ICMEs on heliocentric distance. Among 33 probable ICMEs observed by Voyager 2 from 1977 December 1 to the end of 1979, AFs could be identified inside 30 ICMEs, 91% percentage. Besides, it is obvious that the percentage of AF duration reduces generally linearly as ICMEs expand and move outward. The dashed line represents the linear fitting result with the correlation coefficient of -0.73 . For ICMEs at 2 au, the percentage of AF is about 20%, while for ICMEs at 6 au, the percentage of AF decreases significantly to about 5%.

Figure 3. Dependence of the percentage of AF duration inside ICME on heliocentric distance. The dashed line denotes the linear fitting result. CC represents the correlation coefficient.

gives some statistical characteristics of AF occurrence rate inside ICMEs and in ambient solar wind at different heliocentric distance. For all events, the total duration of AFs with ICMEs is 252.9 hr, about 11.4% of the total ICME duration (2211.7 hrs) with data gap removed. The occurrence rate of AFs decreases as ICMEs expand and move outward. For AFs within ICMEs at between 1–4 au, the total duration is 72.2 hr, about 14.8% of the total ICME duration (488.5 hr). For AFs within ICMEs at between 4–6 au, the total duration is 180.7 hr, about 10.5% of the total ICME duration (1723.2 hr). In general, the occurrence rate of AFs inside ICMEs is found to be much less than that in ambient solar wind at 1 au (Liu et al. 2006). For all events, the total duration of AFs in ambient solar wind is 1371.3 hr, about 16.0% of the total duration of solar wind observation

with data gaps and ICMEs removed. For AFs in ambient solar wind at between 1–4 au, the total duration is 762.8 hr, about 22.5% of the total solar wind duration (3385.2 hr), which is indeed much larger than that inside ICMEs and is consistent with previous findings. For AFs in ambient solar wind at between 4–6 au, the total duration is 608.5 hr, about 11.8% of the total solar wind duration (3385.2 hr), which is similar to that inside ICMEs.

Table 1. AFs inside ICMEs and in ambient solar wind

Region	ICME duration ³	ICME AFs within ICMEs	Percentage	SW duration	SW AFs in ambient SW	Percentage
1–4 au	-	72.2 hr	14.8%	3385.2 hr	762.8 hr	22.5%
4–6 au	-	180.7 hr	10.5%	3385.2 hr	608.5 hr	11.8%
All events	2211.7 hr	252.9 hr	11.4%	-	1371.3 hr	16.0%

³ Data gaps have been removed.

Data gaps and data during ICMEs have been removed.

5. INDIRECT EVIDENCE OF LOCAL ICME PLASMA HEATING BY AF DISSIPATION

By using the new approach of AF diagnosis, many intervals of AFs are identified inside ICMEs from 1 to 6 au. In addition, the percentage of AF duration inside ICME decreases generally linearly with heliocentric distance. Based on these two findings, we are more confident that AFs dissipation inside ICMEs could contribute to local ICME plasma heating. Here we will show some indirect evidence to link local ICME plasma heating with AFs inside ICMEs.

We divide each ICME duration into 10 segments and obtain the distribution of AF occurrence rate and normalized T_p/T_{ex} across ICMEs based on the superposed epoch analysis, shown in the top of [Figure 4: see original paper]. Note that the AF occurrence rate have been multiplied by 1.5 and then plus 0.3 in order to be shown better together with normalized T_p/T_{ex} . The background figure, as adopted from Figure 9 in Hu & Sonnerup (2002), is used to illustrate the spacecraft trajectory through the magnetic cloud. The horizontal axis represents the relative location across the ICME cross-section. 0–10 denotes the leading edge of an ICME, 90–100 denotes the trailing edge of an ICME, and 40–60 denotes the center of an ICME. The green bars show the distribution of AF occurrence rate inside ICMEs, and the green line represents the polynomial fitting result. The distribution of AF occurrence rate inside ICMEs represents a clear “W” shape, indicating that the AFs are more frequently found in the

center and at the boundaries of ICMEs. The blue bars give the distribution of normalized T_p/T_{ex} , and the blue line represents the polynomial fitting result. Similarly, the “W” shaped distribution is obviously found in normalized T_p/T_{ex} , indicating that the ICME plasma seems to be more heated in the center and at the boundaries of ICMEs.

To interpret these phenomena physically, some assumptions need to be made in advance: 1) The temperature inside ICMEs is nearly uniform at the beginning; 2) The whole ICME structure experiences the same expansion; 3) AFs inside ICMEs originate from the Sun’s surface when the CME occurs; 4) AF distribution inside ICMEs is nonuniform; 5) The dissipation rates of AF inside ICMEs are identical. The bottom of Figure 4 gives a sketch of ICME plasma heating due to AF dissipation. AFs are more frequently found in the center and at the boundaries of ICMEs. Considering a nearly identical dissipation rate, more AFs would be dissipated in the center and at the boundaries of ICMEs, whereafter more energy would contribute to ICME plasma heating in the center and at the boundaries. As ICMEs expand and propagate outward, the percentage of AF duration inside ICMEs keeps on decreasing with heliocentric distance, which has been confirmed in section 4.

Figure 4. Top: Distribution of AF occurrence rate and normalized T_p/T_{ex} across ICMEs based on the superposed epoch analysis. Note that the AF occurrence rate have been multiplied by 1.5 and then plus 0.3 to be shown better together with normalized T_p/T_{ex} . The background figure, as adopted from Figure 9 in Hu & Sonnerup (2002), is used to illustrate the spacecraft trajectory through the magnetic cloud. Bottom: A sketch of ICME plasma heating due to AF dissipation. The white wave-like curve represents AF. Its spacing indicates the occurrence rate of AF inside ICMEs. The color represents the plasma temperature. The light blue denotes cold and the light red denotes warm.

6. SUMMARY

Nonlinear cascade of low-frequency Alfvénic fluctuations (AFs) is regarded as one of the major candidate mechanisms of local ICME plasma heating during its expansion and transportation. However, AFs inside ICMEs have been rarely reported in the literature. In this study, we identify 33 probable ICMEs observed by Voyager 2 between 1 and 6 au, finding that relatively pure AFs could be frequently seen inside 30 ICMEs with an average occurrence rate of 12.6%. Statistically, the percentage of AF duration inside ICMEs decays generally linearly as ICMEs expand and move outward. Compared to in ambient solar wind, the occurrence rate of AFs inside ICMEs is much less, especially within 4 au. Furthermore, the occurrence rate of AFs and the proton temperature inside ICMEs have similar “W” -shaped distributions, large in the center and at the boundaries of ICMEs. By assuming a uniform dissipation rate of AFs inside ICMEs, our findings provide an indirect evidence of local ICME plasma heating due to AF dissipation.

We thank the Voyager Mission for the use of their data. The high-resolution Voyager 2 plasma data are publicly available at the Voyager Data Page of the Massachusetts Institute of Technology Space Plasma Group (<ftp://space.mit.edu/pub/plasma/vgr/v2>). The 48 s resolution magnetic field data are accessible at the NSSDC (<ftp://nssdcftp.gsfc.nasa.gov>). The authors would like to thank Dr. Shuo Yao for helpful discussions. This work was supported by 973 program 2012CB825602, NNSFC grants 41574169, 41574168. H. Li was also supported by Youth Innovation Promotion Association of the Chinese Academy of Sciences and in part by the Specialized Research Fund for State Key Laboratories of China.

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