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A Special Kind of Interplanetary Coronal Mass Ejection

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Abstract

It is generally believed that coronal mass ejections (CMEs) have magnetic flux rope structures because of their helical shapes. However, only about 30%–40% of interplanetary CMEs (ICMEs) have a local magnetic flux rope structure. The usual explanations are that the spacecraft only crossed the flank of the ropes and failed to detect the complete magnetic flux rope structure or that some processes destroyed these magnetic flux rope structures. Several studies suggest that some ICMEs inherently possess disordered magnetic fields and consequently exhibit no magnetic flux-rope structures. We introduce a special kind of ICME which has a low magnetic field magnitude and stable magnetic field direction, relatively fast expansion speed, and lower proton temperature and density. All three of the measured magnetic field components are relatively stable. We want to know whether these ICMEs also have magnetic flux rope structures or not. We identified 20 special ICMEs and analyzed their evolution based on their observed characteristics. We took a special ICME as an example, which had an apparent rope configuration at 1 au but evolved to a special ICME at 5.4 au, to illustrate that this kind of ICME could come from magnetic clouds (MCs) whose rope structure had been being stretched due to expansion. We inferred that the missing obvious flux rope structure may be due to the expansion of MCs, not the flank crossing effect. However, more than 50% of the events were associated with the dominant x-component of the magnetic field, which indicates a leg crossing. Therefore, the detection of part of these special ICMEs may also be the result of the leg-crossing effect.

Key words: Sun: coronal mass ejections (CMEs) – (Sun:) solar wind – interplanetary medium

1. Introduction

Coronal mass ejections (CMEs) are intense solar explosive eruptions that eject huge amounts of material from the corona into interplanetary space, and are thought to be the main source of intense geoeffectiveness (Tsurutani et al. 1988; Brueckner et al. 1998). It is generally believed that CMEs have magnetic flux rope configuration because of their helical shapes (Rust & Kumar 1996; Canfield et al. 1999; Liu et al. 2010; Zhang et al. 2012). However, observations from spacecraft near 1 au show that only about 30%–40% of interplanetary CMEs (ICMEs) are magnetic clouds (MCs), which have a local magnetic flux rope structure (Bothmer & Schwenn 1996; Richardson & Cane 2004). MCs are defined empirically using three necessary properties: enhanced magnetic field magnitude, smooth rotation of magnetic field direction and lower proton temperature (Burlaga et al. 1981; Burlaga & Behannon 1982). The question of whether or not all ICMEs have a local rope structure is still open (Wang et al. 2019; Müller et al. 2020; Song et al. 2020). Many researchers believe that all ICMEs have rope structures, or at least at the time when the CMEs explode (Gopalswamy et al. 2013; Kim et al. 2013; Yashiro et al. 2013; Zhang et al. 2013; Song et al. 2020). What causes the rope structures to be missing during the observation of most ICMEs? The usual explanation is that the spacecraft crosses the flank of the ropes and fails to detect the complete magnetic flux rope structure (Gopalswamy et al. 2013; Zhang et al. 2013; Song et al. 2020). The magnetic flux rope structures of MCs usually can be described with the Lundquist (1950) solution (Lepping et al. 1990). Based on the Lundquist solution, if a spacecraft passed through the flank of a magnetic flux rope, all three measured magnetic field components should exhibit relatively stable curves and slight rotations (Wang et al. 2019). In addition, almost all MCs have gradually declining speed profiles, which indicates that these ICMEs are expanding. The expansion of MCs is mainly caused by the higher magnetic pressure in their interior relative to the surrounding background solar wind, so the expansion should mainly occur in the direction perpendicular to the axis of the rope structure. The decreasing velocity profile can be observed when the spacecraft crosses the magnetic flux rope. If the spacecraft passes through the flank of the magnetic flux rope, it is difficult to detect the decreasing velocity profile, just as the smooth rotation feature of the magnetic fields cannot be detected. Some studies believed that all CMEs have rope structures when CMEs erupt, but some ICMEs lose their flux rope structure due to interactions with the ambient solar wind or adjacent CMEs as they propagate in the interplanetary space (Lugaz et al. 2012; Temmer & Rollett 2012; Ruffenach et al. 2012; Feng et al. 2019;

Liu & Luhmann 2012; Liu et al. 2014). Reports from several studies suggest that some ICMEs inherently possess disordered magnetic fields and consequently exhibit no magnetic flux rope structures (Burlaga et al. 2001; Wang et al. 2019), i.e., different initiation mechanisms exist through which some CMEs produce ropes whereas some do not.

In this study, we report a special kind of ICME, in which all three measured magnetic field components are relatively stable or have only slight rotations. As a usual ICME, this kind of ICME has a lower proton temperature and density. These ICMEs also have some unusual observation features: weakened magnetic field magnitude, and most of their velocities show an approximately monotonically decreasing profile with the maximum located near the front of these ICMEs. Since these ICMEs have weakened magnetic field magnitudes and lower proton temperatures, they must have lower total internal plasma (thermal and magnetic) pressures. Why are these ICMEs still expanding rapidly? What are the magnetic structures of this kind of ICME? Do these ICMEs also have magnetic flux rope structures or not? We will introduce this special kind of ICME and discuss their magnetic structures in the following sections.

2. Observations and Interpretation

Figure 1 shows an example of this special kind of ICME. From top to bottom, the panels show the magnetic and plasma data, flow pressure and total plasma (thermal and magnetic) pressure measured by Advanced Composition Explorer (ACE) during the ICME passage of 2003 February 17–19. The ICME does not have most of the typical features of MCs, such as a smoothly rotating, enhanced magnetic field; on the contrary, the magnetic field magnitude keeps a low value throughout the ICME, and all three magnetic field component curves remain stable except for some fluctuations. The elevation and azimuthal angles of the magnetic field direction are around 20° and 170° respectively. The ICMEs were identified as a non-MC event in ICME lists of Richardson & Cane (http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm#(g)).

From the speed profile, it can be inferred that the ICME is expanding. In the bottom panel, the dotted black line is for total plasma pressure, and the red line is for flow pressure. From the total pressure curve, one can find that the total pressure is enhanced before the front boundary of the ICME, drops to a low value at the front boundary, then remains the low value throughout the ICME, and it begins to rise slowly at the rear boundary. Therefore, the internal pressure is not enough to maintain the expansion speed of this ICME. The total pressure difference before and after the front boundary is relatively large, which will decelerate the solar wind speed near the front boundary of the ICME to a certain extent. However, the flow pressure near the front boundary is also relatively large, so the speed reduction is limited. Behind the rear boundary, both total pressure and flow pressure are higher than those before the rear boundary, which may cause the velocity near the rear boundary to increase slightly. To sum up, although the internal pressure is not sufficient to maintain the expansion speed of the ICME, we think the ICME still continues to expand, but at a slower speed. The continual expansion causes the low magnetic field magnitude within the ICME.

Figure 2 shows another example of this kind of ICME, which was measured by ACE during 2005 February 18–19. Both Kim et al. (2013) and Wang et al. (2019) have discussed whether this ICME has a magnetic flux rope structure. They all agreed that this ICME has a magnetic flux rope structure, but ACE crossed the flank of the magnetic flux rope structure and did not detect the smooth field rotations. According to the Lundquist solution, a spacecraft that crosses the flank of a rope will measure relatively stable magnetic field components and low magnetic field magnitude. Therefore, Wang et al. (2019) believed that both stable magnetic field components and weakened magnetic field magnitude were the results of the ACE satellite passing through the flank of the magnetic flux rope. However, if the ACE satellite passed through the flank of the magnetic flux rope, it should not detect the decreasing speed profile (the fifth panel), which is inconsistent with this observation. We also agree that the ICME initially has a magnetic flux rope structure with enhanced magnetic field magnitude and smooth rotation of magnetic field direction, but we think that it is the continual expansion of the ICME, not the flank crossing, that caused its stable magnetic field direction and low magnetic field intensity. The specific evolution process may be as follows: (1) After the CME with magnetic flux rope structure is ejected from the corona, the flux rope will begin to expand and the expansion is accelerated due to its internal enhanced magnetic field magnitude (magnetic pressure); (2) The magnetic field magnitude, proton density and temperature of the CME will decrease with its accelerated expansion, at the same time, the rotating magnetic field lines will also be stretched, and the magnetic field rotation characteristics will be weakened; (3) With the decrease of magnetic field strength, proton density and temperature, the internal total pressure of the CME will continue to decrease. When the total pressure inside and outside is balanced, the expansion speed of the CME starts to slow down, but this CME will continue to maintain a relatively fast expansion speed. Thus, the magnetic field magnitude continues to decline, and the magnetic field lines are straightened, just like what was detected at the ACE satellite. Based on the above discussion, we call this kind of ICME a "stretched magnetic obstacle." According to the two criteria of weakened magnetic field magnitude and stable magnetic field direction, we examined the ICME lists of Wang et al. (2019) and identified 20 such ICMEs, which are listed in Table 1. The boundaries of these ICMEs are experientially determined. Besides the above two criteria, another two aspects frequently used are smooth magnetic field and lower beta values. Sometimes the profiles of velocity, density and

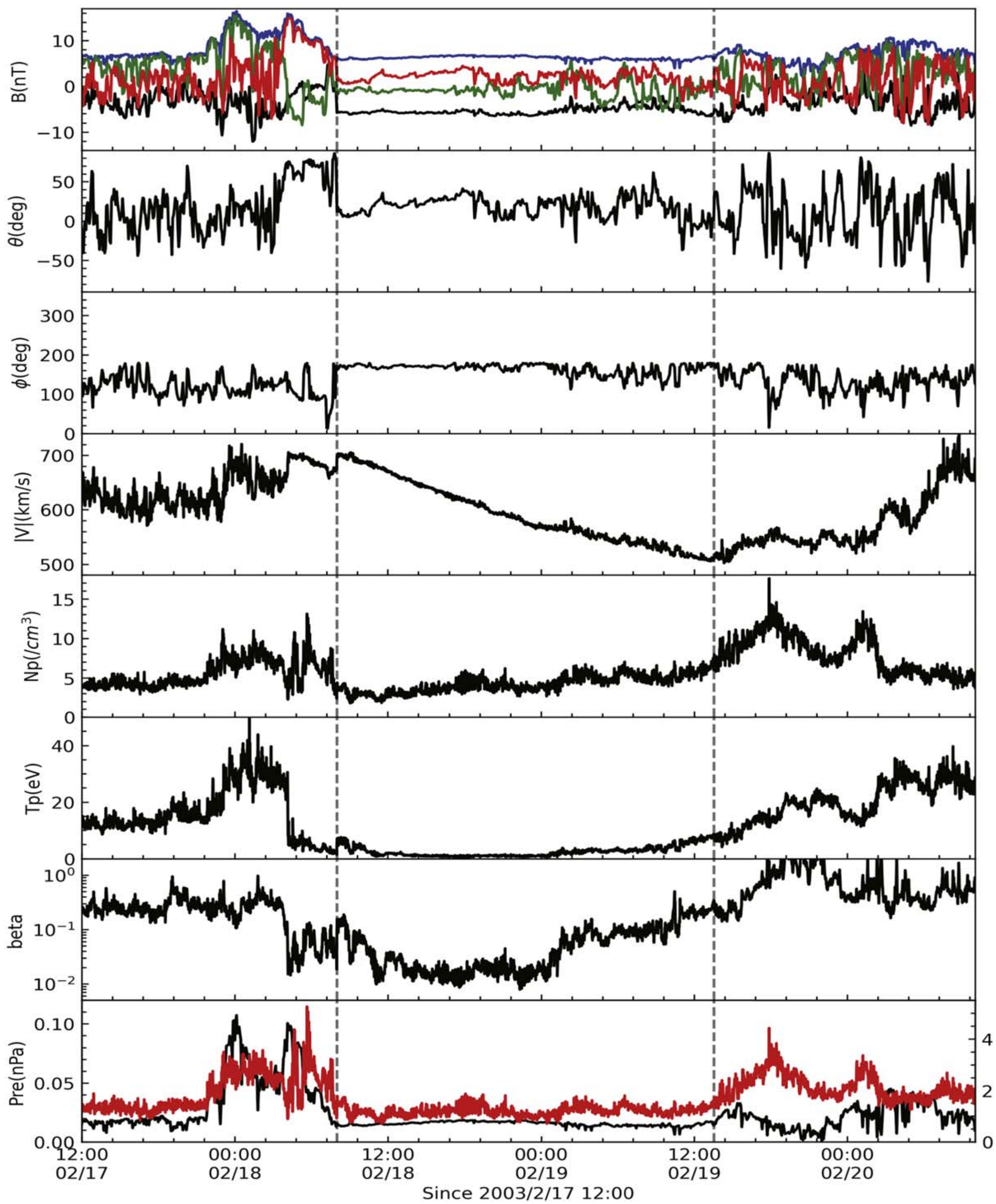

Figure 1. Observations of an ICME detected during 2003 February 17–19, by ACE. From top to bottom, the panels show the magnetic field in the Geocentric Solar Ecliptic (GSE) coordinate system with a color scheme of black, green, red, and blue for the x, y, and z components and the magnitude, the elevation and azimuthal angles of the magnetic field direction, the plasma bulk speed, the proton density and temperature, the plasma beta values, the flow pressure and total plasma (thermal and magnetic) pressure respectively. In the bottom panel, the dotted black line is for total plasma pressure, and the red line is for flow pressure.

temperature are also used in aiding the decision about the boundaries (e.g., #10, 11, and 13). The second and third columns give the start time and end time of stretched MCs. The fourth and fifth columns respectively signify whether stretched MCs appear to have low proton density and temperature, with "*T*" indicating appearance and "*F*" corresponding to no appearance. The sixth column states whether the stretched magnetic obstacles are still expanding. Table 1 shows that most

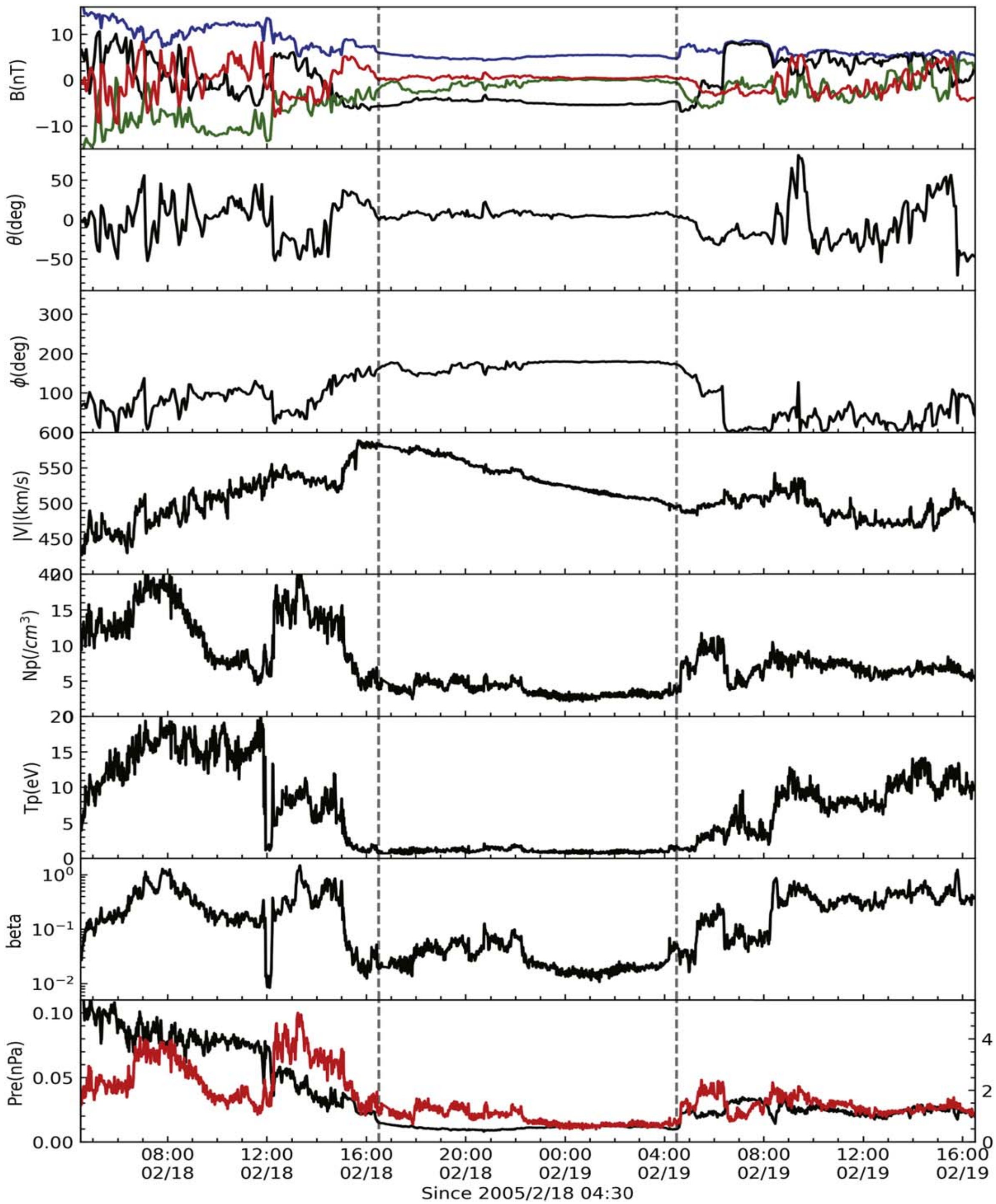

Figure 2. Observations of an ICME detected during 2005 February 18–19, by ACE in the same format as Figure 1.

of the 20 stretched magnetic obstacles have descending speed curves, low proton density and temperature.

In this paragraph, we introduce an ICME that was observed to be an MC by ACE near 1 au, but was observed as a stretched magnetic obstacle by Ulysses near 5.4 au to test the evolution process discussed above. Figure 3 shows the ICME measured by ACE during 1998 March 4–6. The ICME displays outstanding MC characteristics, such as enhanced magnetic field strength, low proton temperature, and a smooth rotation in the direction of the magnetic field. The ICME is a typical example of MC events. The cylindrically symmetric flux rope model fits well to its observed magnetic fields, which indicates

Table 1
Stretched MCs with their Partial Observed Features

No.	Start[a]	End[b]	Low Proton Density[c]	Low Proton Temperature[d]	Expanding[e]
001	1998/05/02 11:47	1998/05/04 02:30	T	T	T
002	1999/05/16 08:45	1999/05/18 00:03	T	T	T
003	1999/11/12 18:28	1999/11/13 12:13	F	T	T
004	2000/02/11 07:54	2000/02/11 23:17	F	T	T
005	2000/06/24 06:32	2000/06/26 00:12	T	T	T
006	2000/07/13 12:28	2000/07/14 15:00	T	T	T
007	2000/11/27 08:10	2000/11/28 02:45	T	T	T
008	2001/04/12 18:02	2001/04/13 07:08	T	T	T
009	2001/04/28 15:30	2001/05/01 21:43	T	F	T
010	2001/06/27 03:02	2001/06/28 16:56	F	T	T
011	2001/10/30 09:42	2001/10/31 12:51	T	T	T
012	2002/03/22 13:45	2002/03/23 10:53	T	T	T
013	2002/12/21 02:43	2002/12/22 09:42	T	T	T
014	2003/02/18 08:00	2003/02/19 13:34	T	T	T
015	2003/08/16 02:00	2003/08/17 13:40	F	T	T
016	2003/10/27 00:46	2003/10/28 01:30	T	T	F
017	2004/07/23 17:35	2004/07/24 05:37	T	T	F
018	2005/02/18 14:30	2005/02/19 04:30	T	T	T
019	2005/08/24 20:33	2005/08/25 13:08	T	T	T
020	2006/12/15 20:48	2006/12/16 17:20	T	T	T

Note. (a) the start time and (b) end time of stretched MCs; whether stretched MCs have low (c) proton density and (d) temperature or not. "T" is for true, "F" for false; (e) whether stretched MCs are still expanding or not. "T" is for true, "F" for false.

that its local magnetic configuration is a symmetric flux rope and the ACE spacecraft almost crossed the flux rope axis (Lanabere & Dasso 2020). The decreasing velocity curve in Figure 3 indicates that this MC is expanding. From the total pressure curve, one can find that the total pressure inside the MC is much greater than the external one. This means that the expansion speed of the MC is still increasing. Nineteen days later, this ICME was also observed by the Ulysses spacecraft at 5.4 au. Figure 4 displays the measured values of these parameters as functions of time for this event. The latitude and longitude of the position of Ulysses is respectively 18°.2 and 77°.8 in heliographic coordinates and remained nearly constant during the observation. The latitudinal and longitudinal separations between ACE and Ulysses are respectively ~2° and ~6°, when ACE makes observations in Figure 3 and Ulysses in Figure 4. With the nearly radial alignment of the two spacecraft, Skoug et al. (2000) confirmed that the two spacecraft crossed the same ICME by comparing the observed characteristics of the ICME itself and the ambient structure. Figure 4 shows that the total pressure stays at a lower value in the interval between the front boundary and 21:30 UT on March 26. In the same interval, all three magnetic field component curves remain stable, and the magnetic field magnitude remains at a low value. The magnetic structure in this interval looks like a stretched MC, but the magnetic structure occupied only the front part of the whole ICME. The rear part of this ICME maintains enhanced magnetic field magnitude and smooth rotation of magnetic field direction. Combined with Figures 3 and 4, it is easy to infer that the MC is overtaken by the following fast flow, and a fast shock is formed at the interface, then the shock enters into the cloud and restricts the expansion of the rear part of the cloud. Although this MC did not eventually evolve into a whole stretched magnetic obstacle, this event gives a hint that this kind of ICME comes from MCs being stretched due to their expansions.

3. Summary and Discussion

In summary, we introduced a special kind of ICME that has a low magnetic field magnitude and stable magnetic field direction. We analyzed its observed characteristics of magnetic field magnitude, magnetic field direction, proton temperature, total pressure and flow pressure, and discussed its possible magnetic structures. The obviously decreasing speed excludes the flank crossing effect, which is usually used to explain the missing flux rope structure in many ICMEs. We also compared the magnetic and plasma signatures of an ICME observed by ACE at about 1 au with that observed by ACE and Ulysses at 5.4 au. For a twist tube with constant length, it will become more twisted as it expands, unless it is uniformly twisted (Priest 1990). However, some researches show that the mean

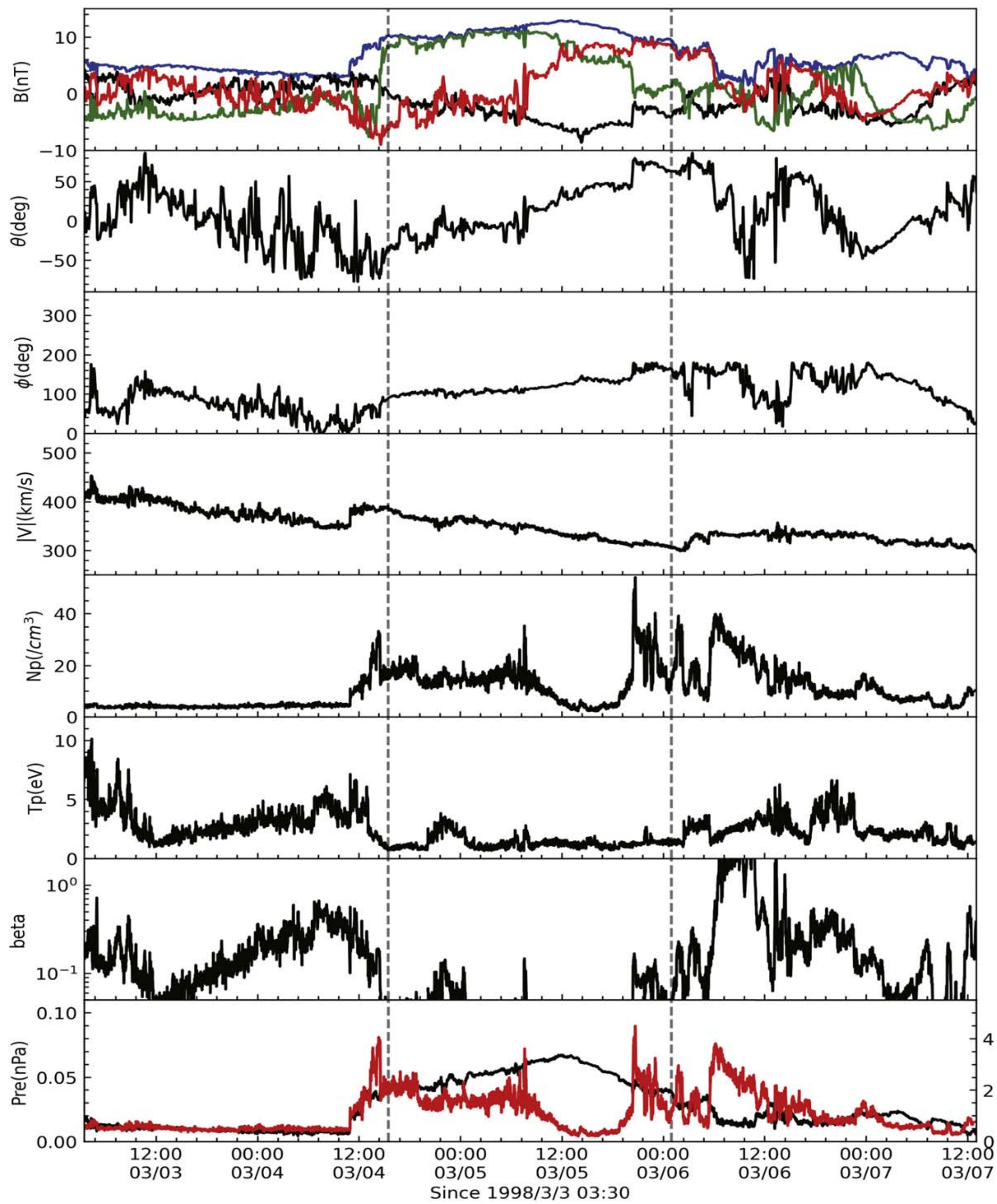

Figure 3. Observations of an ICME detected during 1998 March 4–6, by ACE in the same format as Figure 1.

twist number per unit length of MCs stays nearly constant as they propagate away from the Sun, during which they generally expand (Du et al. 2007; Zhao et al. 2022). For cases presented in this paper, most of them exhibit stable magnetic field direction, except near the boundaries. Within the ICME shown in Figure 3, a nearly constant-θ interval (21:35 on March 4—07:10 on March 5) exists and the velocity decreases throughout this event. When it was detected by Ulysses (Figure 4), the nearly constant-θ region enlarged and different from that in Figure 3, the decreased velocity profile appears only associated

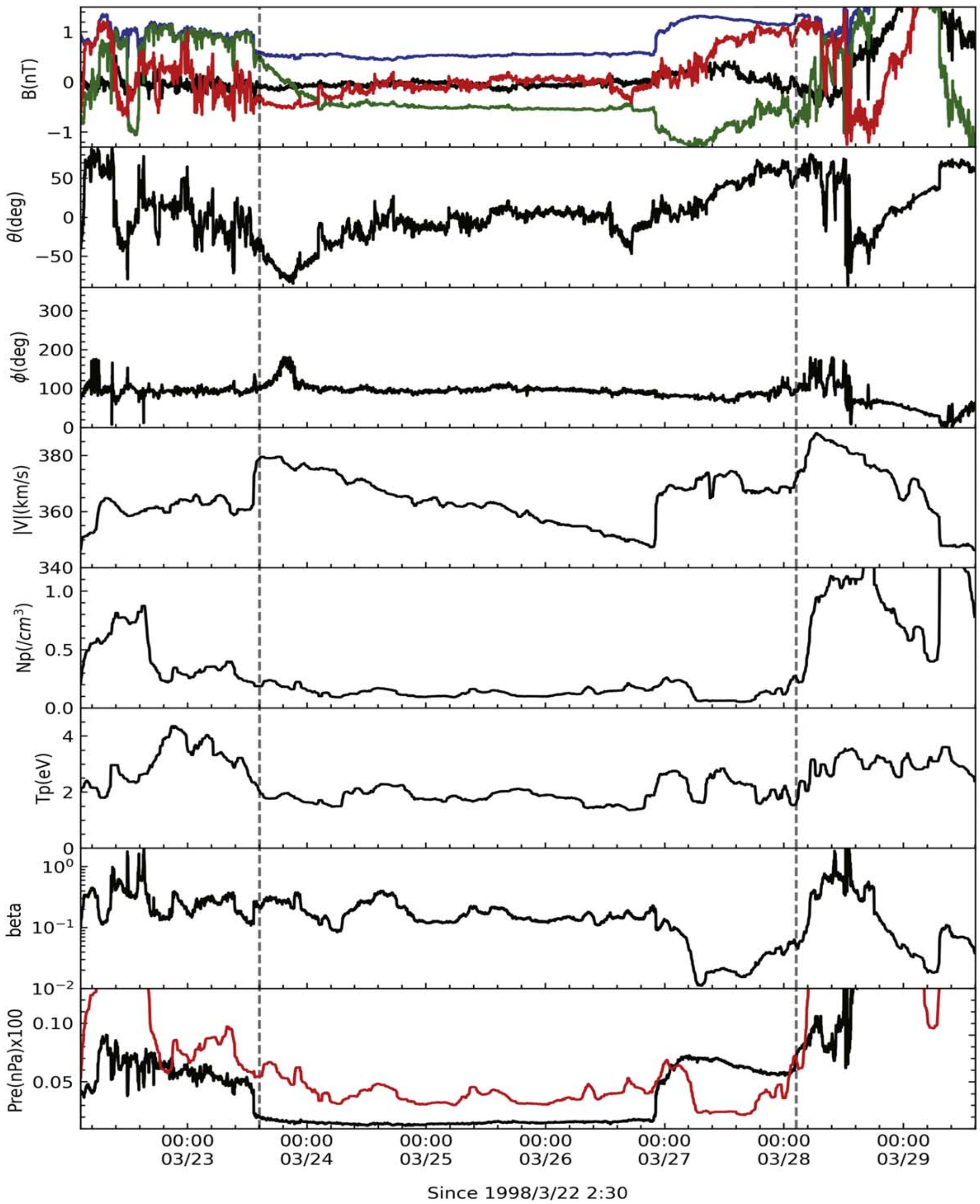

Figure 4. Observations of an ICME detected during 1998 March 23–28, by Ulysses in the same format as Figure 1, except that the three components of the magnetic field are in the Radial-Tangential-Normal (RTN) coordinate system. Note that the pressure is multiplied by one hundred.

with the constant-θ region, which indicates that the expansion manner becomes different in different regions of the ICME as it propagates outward. Therefore, we think that the expansion may change the distribution of the twist and make the flux rope less and more twisted in the inner part and near the boundaries, respectively. Moreover, suppose that the magnetic helicity of a flux rope originating from the Sun is conserved, then its magnetic field lines will be less twisted as it moves away from the Sun (Zhao et al. 2022). Based on the above observations and analyses, we think that the special kind of ICME

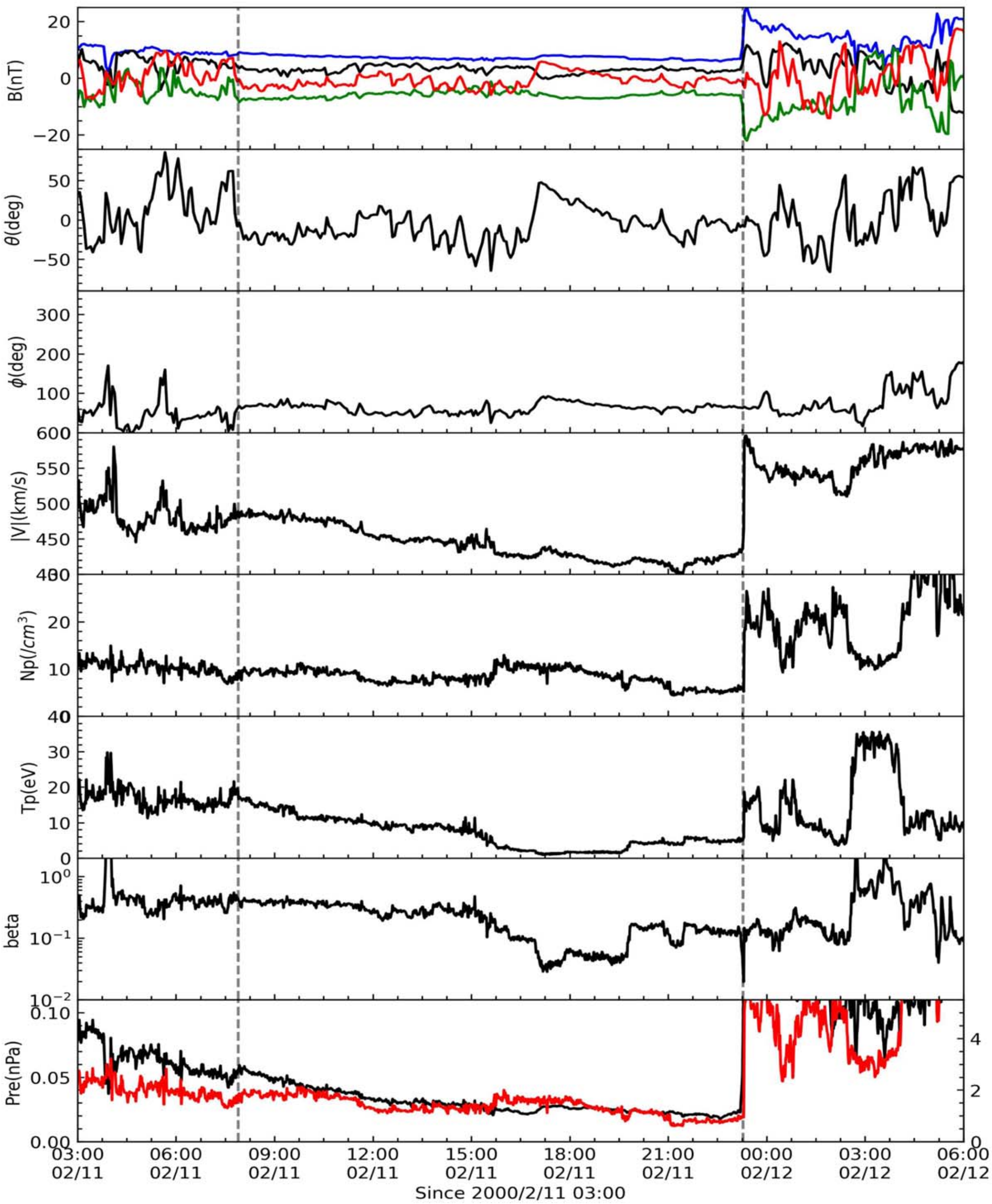

Figure 5. Observations of an ICME detected during 2000 February 11–12, by ACE in the same format as Figure 1.

introduced in this paper comes from stretched flux ropes due to its continual expansions, which also cause the lower magnetic field strength. By comparing the axis direction distribution of 196 MCs with their two MC models, Owens (2016) indicates that the legs of MCs contain no flux rope structure. That is, if the spacecraft crosses the MC‘s leg, it can also detect the typical signature of MCs (e.g., strong magnetic field, low beta values and so on) except for the rotation of the magnetic field. Besides, the decreasing speed (the signature of expansion) can still be detected due to the relatively high magnetic pressure.

The strong x-component of the magnetic field in Figures 1 and 2 indicates that the lack of flux rope signature may also be the result of leg crossing according to Owens (2016). Inspecting all the cases listed in Table 1, we find that the strong magnetic field component can appear in any one of the three directions. Figure 5 shows a case associated with a strong y-component of the magnetic field. However, more than 50% of these events were associated with the dominant x-component of the magnetic field. Therefore, the leg crossing may be a possible reason for the stable magnetic field direction. As ICMEs move away from the Sun, they maintain approximately constant angular width with respect to the Sun (St. Cyr et al. 2000; Schwenn et al. 2005) and the cross-section of ICMEs becomes more elliptical (McComas et al. 1988; Riley & Crooker 2004). For cases with a moderate impact parameter, such an effect may strengthen the rotation signature and partly cancel the result caused by expansion, which may be one reason that causes the appearance of slight rotations in some cases listed in Table 1 (Owens 2009). Some researches indicate that MCs can be eroded through magnetic reconnection as they propagate outward (Ruffenach et al. 2012). However, the erosion effect cannot cause the weakening of the magnetic field strength. MCs observed by satellites near 1 au may also evolve into stretched MCs as they continue to propagate outwards. As is well known, all non-MC ICMEs with disordered magnetic fields also have enhanced magnetic field magnitude, low proton temperature, and a gradually decreasing velocity curve. As these ICMEs with disordered magnetic fields continue to expand, what will their observed characteristics change to? Do their magnitudes also become lower, or their magnetic field directions also become relatively stable? In addition, what are the geomagnetic effects of these stretched MCs? Can they still induce strong magnetic storms? Further research is needed to clarify these questions.

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