



# Coalescence of Magnetic Flux Ropes Within Interplanetary Coronal Mass Ejections: Multi-cases Studies

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Coronal mass ejections (CMEs) are intense solar explosive eruptions and have significant impact on geomagnetic activities. It is important to understand how CMEs evolve as they propagate in the solar-terrestrial space. In this paper, we studied the coalescence of magnetic flux ropes embedded in five interplanetary coronal mass ejections (ICMEs) observed by both ACE and Wind spacecraft. The analyses show that coalescence of magnetic flux ropes could persist for hours and operate in scale of hundreds of earth radii. The two merging flux ropes could be very different in the axial orientation and the plasma density and temperature, which should complicate the progress of coalescence and have impact on the merged structures. The study indicates that coalescence of magnetic flux ropes should be an important factor in changing the magnetic topology of ICMEs.

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## KEY POINTS

1. Coalescence of magnetic flux ropes within five interplanetary coronal mass ejections was studied.
2. The process of coalescence could be steady and large-scaled.
3. The process of coalescence is an important factor in changing the magnetic topology of interplanetary coronal mass ejections.

## INTRODUCTION

Coronal mass ejections (CMEs) are large-scale solar explosive eruptions and their counterparts in the interplanetary space, interplanetary coronal mass ejections (ICMEs), are known to be an important cause of intense geomagnetic disturbances [1–3]. The geomagnetic effectiveness of ICMEs has strongly relation with their magnetic structures. For example, Magnetic Clouds (MCs), a subset of ICMEs, are found to be more effective than non-MC ICMEs in causing intense geomagnetic storms [4]. CMEs are thought to originally be of magnetic flux rope structures (e.g., [5–7]). However, ICMEs appearing as flux rope (i.e., MCs) only account for 30–40% of ICMEs observed at 1 AU [8, 9]. Therefore, understanding how CMEs evolve as they propagate in the solar-terrestrial space is very important for the space weather forecasting.

As an ICME propagates in the interplanetary space, its interaction with ambient solar wind or being caught up by other ICMEs from behind can cause the change of its magnetic topology [10–17]. Multiple rope-like substructures have been detected within ICMEs [18–22]. Feng et al. [22] reported observations of three merging flux ropes within an ICME and they thought that the coalescence would lead to the

formation of a bigger rope. However, the potential of coalescence of flux ropes in altering the magnetic topology (e.g., the scale of coalescence in space and time) is still unclear.

Phan et al. [23] made a statistical study of extended reconnection X-lines in the solar wind at 1 AU with the combined observations of ACE and Wind spacecraft. In the work presented here, we surveyed the reconnection current sheet listed in Phan et al. [23] and found five of them were formed during coalescence of magnetic flux ropes embedded in ICMEs. The analyses show that the operation of coalescence can extend hundreds of earth radii and persist for several hours. The two merging flux ropes could be very different in some aspects. We think that coalescence of flux ropes should play important roles in the evolution of ICMEs.

## DATA

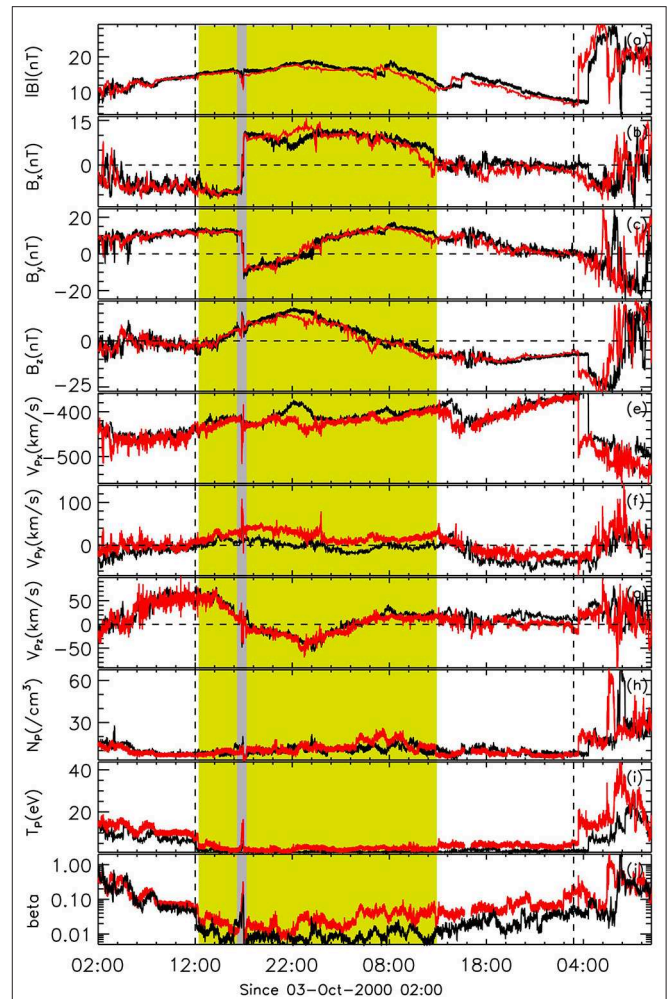
The data used in this paper are obtained from several instruments onboard ACE and Wind spacecraft. Wind magnetic field data and plasma data with time resolution of 3 s are taken from the Fluxgate Magnetometer experiment and the 3DP instrument, respectively [24, 25]. ACE magnetic field data (1 and 16 s resolution) are from MAG and plasma data (64 s resolution) are from SWEPAM instrument [26, 27]. If not specified, the GSE coordinate system (the Geocentric Solar Ecliptic coordinate system in which the  $x$ -axis directs from the Earth to the Sun, the  $z$ -axis points north, perpendicular to the ecliptic plane, the  $y$ -axis completes the right-handed coordinate system) is used in this paper.

## OBSERVATIONS

In this section we first show one example to illustrate the identification of ICMEs and the merging flux ropes, then the procedure for estimating the X-line length formed during the coalescence progress and the other four cases are presented.

**Figure 1** shows observations made by ACE (black) and Wind (red) from Oct. 3rd, 2000 to Oct. 5th, 2000. For clarity, the time series of ACE are shifted 110 min for forward. During the whole interval showed in **Figure 1**, the data curves of the magnetic field and plasma at the two spacecraft were generally similar. From  $\sim 12:00$  on Oct. 3rd (the first vertical line), the magnetic field became smoother and its strength gradually increased (**Figures 1a–d**). In the meantime, the proton temperature and the plasma beta values dropped (**Figures 1i,j**). At  $\sim 03:00$  on Oct. 5th (the second vertical line), the speed of the plasma, the proton temperature and the plasma beta values suddenly increased (**Figures 1e,i,j**). Based on the above observations, we think the spacecraft encountered an ICME during the interval bounded by the two dashed vertical lines.

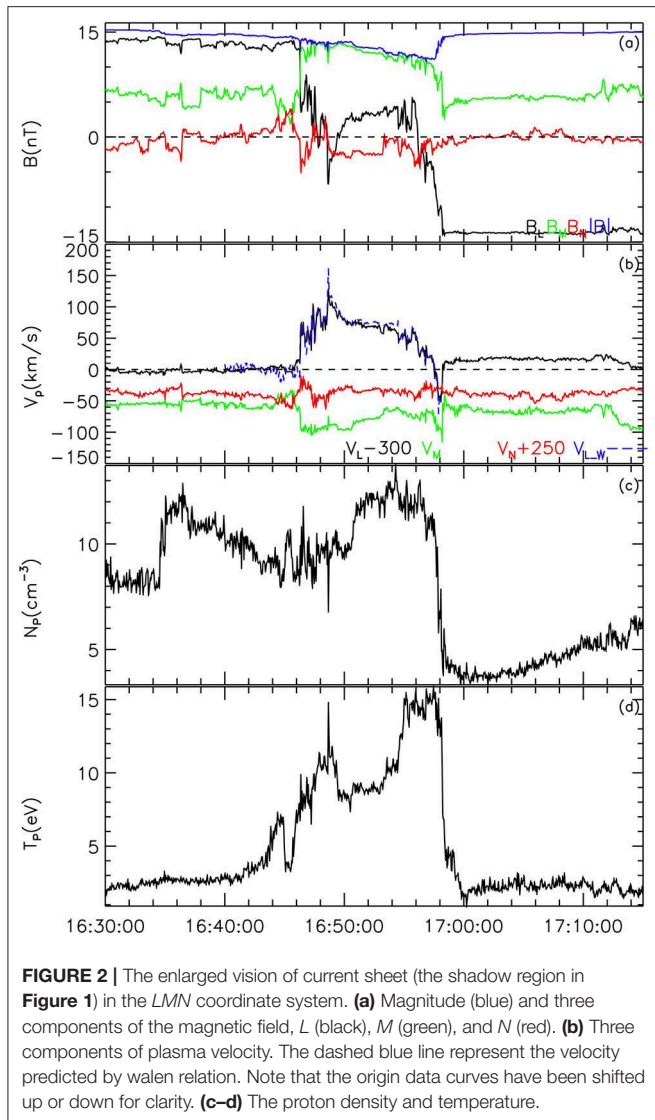
During the two intervals covered by the orange color, the magnetic field rotated. For the first orange region,  $B_z$  gradually increased from  $-2$  nT to 7 nT (**Figure 1d**). For the second orange region,  $B_y$  gradually increased from  $-6$  to 15 nT (**Figure 1c**) and  $B_z$  first increased to 15 nT, then decreased to  $-8$  nT (**Figure 1d**). Along with the rotation, the strength of the magnetic



**FIGURE 1** | Measurements of ACE (black) and Wind (red) from 02:00 UT on Oct 03 to 11:00 UT on Oct 05, 2000. The observations of ACE have been shifted 110 min for forward. **(a–d)** Magnitude and three components of the magnetic field. **(e–g)** Three components of plasma velocity. **(h–j)** Proton density, temperature and proton plasma beta values. The two vertical dashed lines indicate the boundary of the ICME. The two orange regions denote the two merging flux ropes. The shadow region denotes the reconnection current sheet intermediating the coalescence.

field enhanced. The rotation of the magnetic field and the concurrent enhancement in its strength indicated that the two orange regions corresponded to crossing of two flux ropes. With the assumption of two dimension and quasi-steady state, the axis of a flux rope can be determined by Grad-Shafranov (G-S) reconstruction method [28]. According to the G-S equation, the thermal pressure and the magnetic pressure are constant along one magnetic field line in the plane perpendicular to the axial direction [28]. Applying the G-S reconstruction method to the data of the two orange regions, the obtained axis of the two flux ropes was  $(\varphi = 116.08, \theta = 19.45)$  for the earlier, and  $(\varphi = 1.82, \theta = 29.88)$  for the latter, where  $\varphi$  and  $\theta$  are the longitude and latitude with respect to the ecliptic plane.

In the intermediate region (the shadow region) between the two magnetic flux ropes, the spacecraft detected steep



changes in  $B_x$  and  $B_y$  with  $B_x$  jumping from  $-9$  to  $11$  nT and  $B_y$  dropping from  $12$  to  $-10$  nT (**Figures 1b,c**). Meanwhile, the plasma velocity in the  $V_x$  and  $V_y$  component locally peaked (**Figures 1e,f**). The proton temperature and the plasma beta values also showed a local peak (**Figures 1i,j**). The above observations indicated that the spacecraft might cross exhaust of magnetic reconnection, which can be more clearly in **Figure 2**.

In **Figure 2**, all vectors are presented in a local *LMN* coordinate system, where *L* was assumed to be along the reconnection outflow direction, *M* along the X-line direction and *N* along the normal direction of the reconnection current sheet. *N* was determined by minimum variance analysis of the magnetic field across the current sheet [29] and that *M* was chose so that the *M* components of the in-plane asymptotical magnetic field in both sides of the current sheet are same [30].  $L = M \times N$  forms the right-hand coordinate system. The most remarkable feature of the magnetic field is

the two-step decrease in  $B_L$  (**Figure 2a**), which corresponded to a bifurcated current sheet. Within the current sheet, the proton temperature increased (**Figure 2d**). The changes in  $V_L$  (**Figure 2b**) during the crossing of the current sheet were consistent with these predicted (the dashed lines) by walen relation, which were calculated from the following equation [31, 32]:

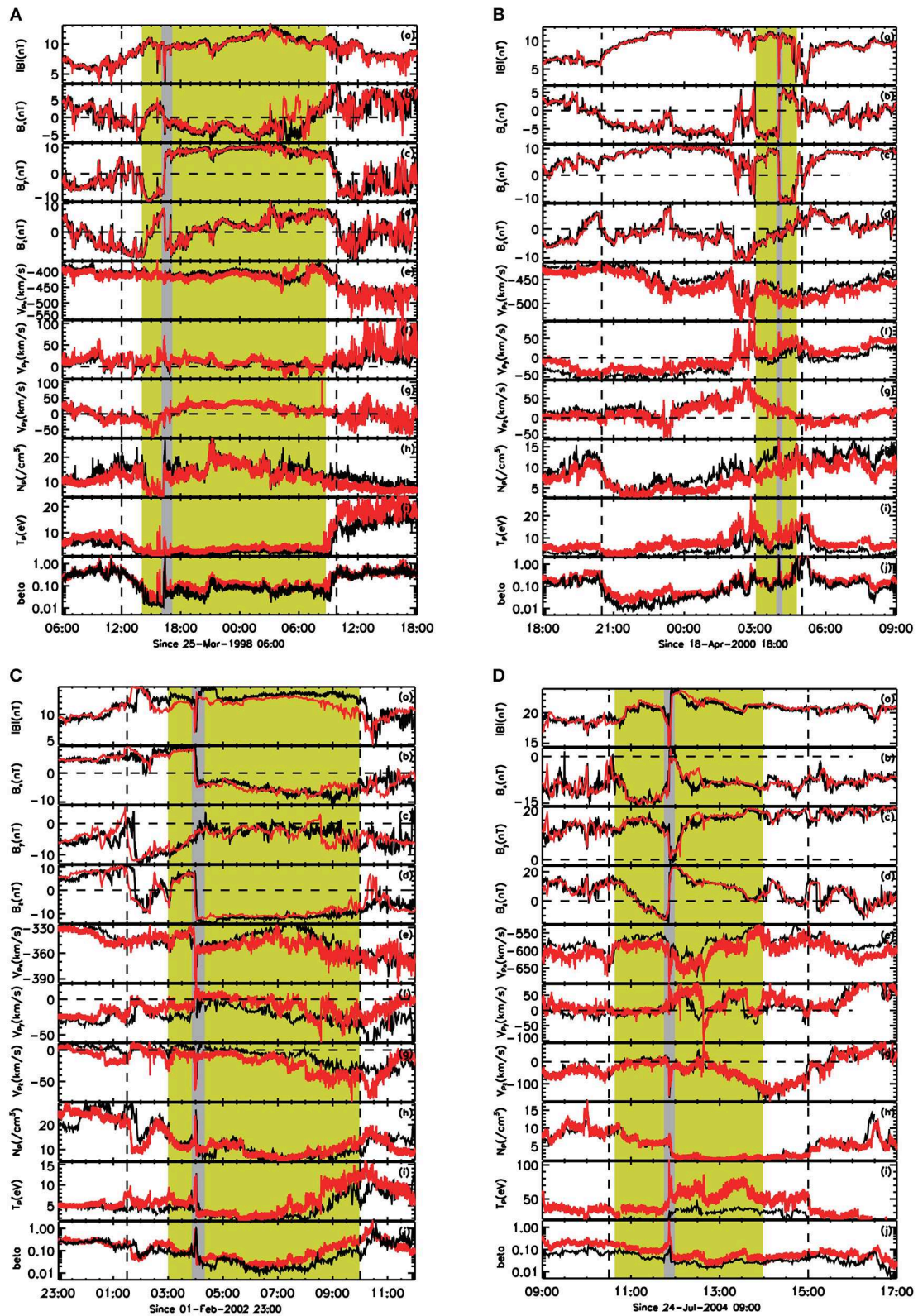
$$V_{\text{predicted}} = V_{\text{reference}} \pm (1 - \alpha_{\text{reference}})^{1/2} (1 - \mu_0 \rho_{\text{reference}})^{-1/2} (B \rho_{\text{reference}} / \rho - B_{\text{reference}})$$

Note that the pressure anisotropy factor,  $\alpha$ , was assumed to be zero. Therefore, we thought that the spacecraft crossed exhaust of magnetic reconnection [33]. Detection of the reconnection current sheet between two flux ropes indicated that the two flux ropes were merging [22].

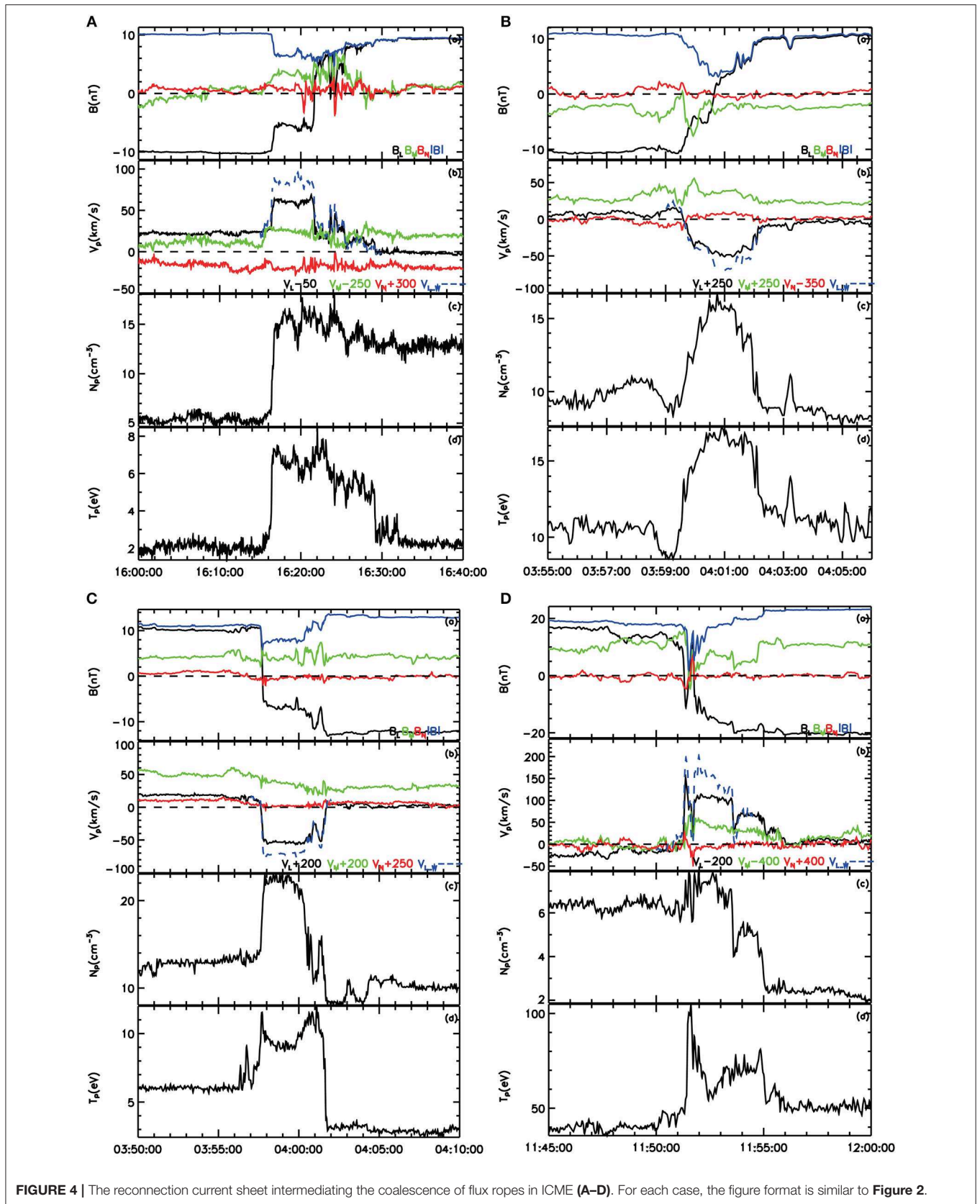
Adopting a similar procedure as that in Phan et al. [32], the extent of the X-line associated with the coalescence was estimated. The reconnection current sheet intermediating the coalescence was assumed to be planar and its normal direction obtained by minimum variance analysis was ( $\varphi = 41.19$ ,  $\theta = -17.41$ ). The separation of the two ships was  $[193, 223, -3.8] R_E$  in GSE. Using this normal direction and the planar assumption, the predicted temporal delay from ACE to Wind was 103 min which was close to the observed temporal delay, 110 min. This agreement indicated that the obtained normal direction and the planar assumption were valid. The direction of the X-line, *M* was ( $\varphi = 52.55$ ,  $\theta = 72.26$ ) [30]. With the knowledge of *N*, *M* and the separation of the two ships, the distance along the X-line between the locations where the two ships intersected the current sheet was calculated to be  $14 R_E$ , which meant that the extend of the coalescence in space was at least  $14 R_E$ . The temporal delay between the two ships was  $\sim 110$  min and the interval covered by the reconnection current sheet was  $\sim 12$  min. Therefore, the progress of coalescence at least operated for 122 min.

With similar procedure, another four events of coalescence of flux ropes within an ICME were analyzed. The four events and the reconnection current sheet intermediating the coalescence are, respectively, presented in **Figures 3, 4**. Some of the five ICMEs have been studied by other researches [21, 22]. The details of the five cases are listed in **Table 1**. These cases were different in some aspects. The interval of the two merging flux ropes only occupied a small portion ( $\sim 23\%$ ) of the whole duration of the ICME in Apr. 2000 (**Figure 3B**). However, for the other four cases, the two merging flux ropes occupied most of the ICME that they were embedded in **Figures 1, 3A,C,D**. The angle formed by the axes of the two merging flux ropes varied from case to case with a range from  $\sim 70^\circ$  to  $\sim 160^\circ$  (**Table 1**, in column Fr2-to-fr1). The plasma carried by the merging flux ropes could also be different in temperature and density (**Figures 3Ah,Ci,Dh**). For example, the plasma density was much higher in the latter flux ropes than that in the former one for the case in Mar. 1998 (**Figure 3Ah**). There were also significant differences in the estimated mini duration of the magnetic reconnection and length of X-line associated





**FIGURE 3 |** The other four ICMEs in Mar. 1998 (A), Apr. 2000 (B), Feb. 2002 (C), and Jul. 2004 (D). The observations of ACE have been shifted 5 min for case A (28 min for case B, 147 min for case C, -13 min for case D) forward. For each case, the figure format is similar to Figure 1.



with the coalescence (Table 1, in columns len and dur). For example, the duration and the length were 34 min and 8  $R_E$ , respectively, for the case in Apr. 2004, while for the case in Feb. 2002, the values were 150 min and 393  $R_E$ , respectively. Finally, the density and temperature of plasma were not symmetric on both side of the reconnection current sheet in some cases (e.g., Figures 4Ac,Cd,Dc).

## DISCUSSION AND CONCLUSION

ICMEs consisting of multiple flux ropes have been reported [20, 21]. Recently, Feng et al. [22] reported observations of an ICME within which a series of merging flux ropes was detected. They thought the coalescence would lead to the formation of bigger ropes in the ICME. However, if the magnetic reconnection intermediating the coalescence is patchy and transient, the change made by coalescence in the magnetic topology of ICMEs will be localized in space. The cases presented here shows that coalescence of magnetic flux ropes can operate in scale of hundreds of Earth radii and persist for hundreds of minutes. Note that the presented values in scale and duration of coalescence were likely to be much underestimated. Therefore, the progress of coalescence should be an important factor in the evolution of CMEs, If CMEs originally are of magnetic flux rope structures.

Simulations show that coalescence of magnetic flux ropes with same axis direction will end up with one bigger rope [14, 34]. The case in the real interplanetary space shall be more complex. In Feng et al. [22], the axis of the first two merging flux ropes had nearly opposite directions, which they thought the coalescence may lead to the formation of a bigger rope with weak axial field. For the five case reported here, the axes of the two merging flux ropes were not parallel but formed an angle ranging from  $\sim 70^\circ$  to  $\sim 160^\circ$ . The direction of the X-line also formed big angles with the ropes' axis (the last column in Table 1). The relative attitude of the two merging flux ropes should have significant impact on the structures formed by the process of coalescence. Awasthi et al. [35] reported a non-MC ICME whose pre-eruptive structure consisted of multiple-braided flux ropes with different degrees and they thought reconnection occurring between these flux ropes was responsible for the complex structure of the ICME. The presented results are consistent with the observations in Awasthi et al. [35]. The difference in the plasma (e.g., in the temperature and density) carried by the merging flux ropes could cause asymmetric conditions at both side of the reconnection current sheet (Figures 4Ac,Cd,Dc), which may further complicate the progress of coalescence.

In summary, we reported five ICMEs observed by both ACE and Wind spacecraft, within which merging flux ropes were detected. The coalescence of magnetic flux ropes could be steady and large scale. The two merging ropes could be different in the axial orientation and the plasma density and temperature. The results showed here indicates that coalescence of magnetic flux ropes is an important factor for understanding of the evolution of CMEs.

TABLE 1 | A list of the parameters of the five ICMEs.

Case	Year	ICME			Fr1			Fr2			CS			X-line						
		sta	end	len	sta	end	lon	lat	lon	end	lon	lat	lon	lat	lon	lat	lon	dur	to-fr1	
1	1998	03/25 12:00	03/26 09:50	03/25 14:00	03/25 16:00	260	-10	03/25 16:40	03/26 09:20	96	19	162.10	03/25 16:16	32.66	22.30	141.31	37.94	17	18	118.66
2	2000	04/18 20:30	04/19 05:00	04/19 03:00	04/19 03:56	140.67	-13.08	04/19 04:07	04/19 04:40	278.65	5.32	137.86	04/19 03:59:19	210.80	32.78	23.73	57.02	8	34	115.47
3	2000	10/03 12:00	10/05 02:00	10/03 12:15	10/03 16:20	116.08	19.45	10/03 17:17	10/04 13:00	1.82	29.88	99.79	10/03 16:45:35	41.19	-17.41	52.55	72.26	14	122	63.56
4	2002	02/02 01:30	02/02 10:00	02/02 03:00	02/02 03:50	332.67	25.4	02/02 04:17	02/02 10:00	306.49	-71.77	98.85	02/02 03:57:10	40.20	-21.70	300.75	-22.99	393	150	57.48
5	2004	07/24 10:30	07/24 15:00	07/24 10:40	07/24 11:43	123.06	-15.21	07/24 11:58	07/24 14:00	88.29	49.66	71.75	07/24 11:51:19	46.22	-4.02	134.71	20.58	55	19	37.57

Fr1, the first flux rope encountered by spacecraft within the ICME; Fr2, the second flux rope encountered by spacecraft within the ICME; CS, the reconnection current sheet detected between Fr1 and Fr2; sta, the start date and time of the structure; end, the end date and time of the structure; lon, the longitude of the axis of the flux rope (normal of the current sheet/ the direction of X-line) with respect to the ecliptic plane, in degrees; lat, the latitude of the axis of the flux rope (normal of the current sheet/ the direction of X-line) with respect to the ecliptic plane, in degrees; t-fr1, the angle of the direction of the axis of Fr1, in degrees; time, the time when cs was observed; len, the estimated length of x-line, in earth radii; dur, minimum duration of reconnection, in minutes.



## AUTHOR CONTRIBUTIONS

YZ drafted the manuscript and led the observational analysis. HF provided heuristic advice and revised the manuscript. QL and GZ conducted the G-S reconnection. All authors contributed to the interpretation of the results and helped draft the manuscript.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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