Advances in the Dynamic Evolution of Magnetic Cloud Propagation: Postprint

Authors: Feng Hengqiang, Zhao Yan, Wang Jiemin

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Abstract

Magnetic clouds, due to their unique magnetic field structures, are often the driving source of severe space weather events. Recent research on the dynamic evolution of magnetic clouds during their propagation has made progress in several aspects, including boundary layer structure, toroidal flux, and large-scale configuration. A boundary layer structure formed by magnetic reconnection exists at magnetic cloud boundaries. During propagation, such magnetic reconnection occurring at the boundaries may erode the magnetic field of the magnetic cloud, leading to reduction and asymmetry in the toroidal flux of its magnetic flux rope structure. Within magnetic clouds, multiple sub-flux rope structures are frequently observed. These sub-flux ropes with distinct characteristics can merge via magnetic reconnection, thereby altering the magnetic structure of the magnetic cloud. Regarding the evolution mechanism of the large-scale magnetic field topological configuration of magnetic clouds, in addition to the interchange reconnection proposed earlier, current studies indicate that in interplanetary space, the reconnection process at magnetic cloud boundaries can also open or disconnect the closed or semi-open magnetic field lines of magnetic clouds. Although significant progress has been achieved in related research, many questions regarding the dynamic evolution of magnetic clouds during propagation remain unresolved. Boundary layer structures have also been identified at the boundaries of interplanetary small-scale magnetic flux ropes; thus, could magnetic clouds become small-scale flux ropes through erosion? Could interactions among sub-flux rope structures within magnetic clouds trigger instabilities that cause the collapse of the entire flux rope system? The resolution of these issues awaits further theoretical, observational, and numerical simulation studies.

Full Text

Preamble

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Advances in the Study of the Dynamic Evolution of Magnetic Cloud Propagation

FENG Heng-qiang, ZHAO Yan, WANG Jie-min
(Institute of Space Physics, Luoyang Normal University, Luoyang 471022)

Abstract

Magnetic clouds, owing to their unique magnetic field structures, frequently serve as the primary drivers of major disastrous space weather events. Recent research on the dynamic evolution of magnetic cloud propagation has made progress in several areas, including boundary layer structure, azimuthal flux, and large-scale configuration. A boundary layer structure exists at magnetic cloud boundaries, formed by magnetic reconnection. During propagation, this reconnection at the boundaries may gradually erode the magnetic cloud's field, leading to reduction and asymmetry in the azimuthal flux of its flux rope structure. Multiple sub-flux rope structures are often observed within magnetic clouds, and these distinct sub-structures can merge through magnetic reconnection, thereby altering the magnetic configuration of the cloud. Regarding the evolution mechanism of the large-scale magnetic topology of magnetic clouds, in addition to the exchange reconnection proposed earlier, current studies indicate that reconnection processes at magnetic cloud boundaries in interplanetary space can also open or disconnect the closed or semi-open field lines of the cloud. Despite significant progress in related research, many questions about the dynamic evolution of magnetic cloud propagation remain unresolved. Boundary layer structures have also been discovered at the boundaries of small-scale interplanetary flux ropes, raising the question of whether magnetic clouds can be eroded into small-scale flux ropes. Could interactions among sub-flux rope structures within a magnetic cloud trigger instabilities that cause collapse of the entire flux rope system? Resolving these issues will require further theoretical, observational, and numerical simulation studies.

Key words coronal mass ejections (CMEs), solar wind, magnetic reconnection

1. Introduction

Coronal Mass Ejections (CMEs) are violent large-scale eruptive phenomena in the solar atmosphere, involving the rapid ejection of substantial amounts of plasma and magnetic field from the corona into interplanetary space. When CMEs propagate to Earth's vicinity, they are frequently observed by satellites and referred to as Interplanetary Coronal Mass Ejections (ICMEs) [1–3]. During their propagation through interplanetary space and interaction with the solar wind, CMEs generate various plasma disturbances and structures, providing an experimental environment for plasma physics processes that is difficult to achieve in ground-based laboratories. Since CMEs often exhibit helical structures when erupting from the Sun, they are generally believed to possess closed magnetic flux rope structures near the Sun [4–6]. Furthermore, all models studying CME eruption mechanisms and propagation evolution assume that CMEs have flux rope structures [7–15]. However, satellite observations near 1 AU show that only about 30% of ICMEs actually exhibit flux rope structures [16]. Burlaga et al. [1] first introduced the term "magnetic cloud" to describe ICMEs with flux rope structures, empirically defining a magnetic cloud as having three observational characteristics: (1) the magnetic field direction undergoes smooth rotation through a large angle over an extended period; (2) relatively strong magnetic field strength; and (3) relatively low proton temperature. Currently, magnetic clouds are generally considered equivalent to ICMEs with flux rope structures. Due to their helical magnetic configuration, which can continuously and stably provide southward magnetic fields, magnetic clouds arriving near Earth can interact with Earth's magnetosphere, causing dramatic changes in the magnetosphere's magnetic morphology, structure, and dynamic processes, thereby generating geomagnetic storms, ionospheric storms, thermospheric storms, and particle storms that pose significant threats to human activities in space exploration, communications, navigation, tracking, positioning, power systems, resource exploration, and national security [17–21]. Therefore, research on magnetic clouds is critically important from both scientific and practical perspectives.

As a subset of ICMEs, magnetic clouds often cause intense geomagnetic activity. To accurately predict the space environmental impact of CMEs, studying the propagation and dynamic evolution of magnetic clouds in interplanetary space is particularly crucial. Key questions include: How do magnetic clouds, as flux ropes, interact with the background solar wind? How do their boundaries evolve during this interaction? Does the azimuthal flux of a magnetic cloud's flux rope structure change during propagation, and if so, how? How does a magnetic cloud, as a flux rope with both ends connected to the Sun, become disconnected from the solar atmosphere during propagation? Do sub-structures within magnetic clouds interact with each other? Many researchers believe that all ICMEs possess flux rope structures, or at least had them at the time of CME eruption [22–26]; could non-magnetic-cloud ICMEs be the evolutionary products of magnetic clouds? This paper will focus on reviewing research progress related to these questions concerning magnetic cloud propagation and dynamic evolution, and discuss relevant issues.

2. Evolution of Magnetic Cloud Boundaries

After being ejected from the solar corona as a CME, a magnetic cloud inevitably interacts with the background solar wind during its propagation through interplanetary space. This interaction primarily involves compression and magnetic reconnection, with compression potentially promoting reconnection. Compression between magnetic clouds and background solar wind is common at both leading and trailing boundaries. Nearly all magnetic clouds show evidence of compression near their boundaries, such as enhanced magnetic field strength, proton density, and temperature in regions adjacent to the boundaries. However, compressive interaction does not destroy the flux rope structure; it only alters the shape of the flux rope [23]. In contrast, magnetic reconnection occurring near magnetic cloud boundaries can erode the overall flux rope structure and even destroy it entirely. Since the flux rope structure can be eroded through magnetic reconnection, magnetic cloud boundaries should be dynamically evolving. This evolution process affects how magnetic clouds interact with Earth's magnetosphere, influencing the transfer of energy, momentum, and mass during their interaction and the resulting geomagnetic activity. Wei et al. [27] statistically analyzed parameters reported in the literature for 70 magnetic cloud boundaries, including temperature, density, and plasma beta (the ratio of plasma thermal pressure to magnetic pressure), concluding that magnetic cloud boundaries possess a boundary layer structure. This boundary layer forms through magnetic reconnection between the magnetic cloud and background medium during propagation in interplanetary space.

Gosling et al. [28] established criteria for identifying interplanetary magnetic reconnection outflows in 2005 based on a reconnection model. Subsequently, numerous reconnection outflow events within magnetic cloud boundary layers have been reported [29–30]. These observational evidences reveal the formation mechanism of magnetic cloud boundary layers. The very definition of a magnetic cloud boundary layer implies that the boundary is not static but evolves dynamically as the cloud propagates, making it a dynamic structure. What, then, are the decisive conditions for reconnection between a magnetic cloud and background wind magnetic field during propagation? How long does the reconnection process last, and is it steady-state? These questions concern not only boundary evolution but the entire dynamic evolution of magnetic clouds. Wei et al. [27] noted that reconnection near magnetic cloud boundaries would gradually "peel off" the cloud's outer magnetic field, reducing the flux rope's magnetic flux. If this process occurs rapidly, could small-scale interplanetary flux rope events (referred to as "small magnetic clouds" in the literature) that last only a few hours be evidence of magnetic clouds being "peeled"? Feng et al. [31] examined Wind spacecraft magnetic field and plasma observations from 1996, identifying 21 small-scale interplanetary flux ropes. Their statistical study revealed that all 21 events exhibited boundary layer structures with durations ranging from several minutes to half an hour, characterized by high proton temperatures and densities and relatively high plasma beta values. Feng et al. [31] also identified multiple magnetic reconnection outflow events near the boundaries of these small flux ropes. This demonstrates that magnetic reconnection occurs near the boundaries of both large- and small-scale flux ropes and is not an isolated phenomenon. Based on the geometric relationship between these reconnection outflows and the small flux ropes, it can be determined that the magnetic flux of these small flux ropes is being consumed by the reconnection.

These observations further indicate that the boundaries of both magnetic clouds and small-scale flux ropes are in a state of evolution during propagation. This also indirectly suggests that small-scale flux ropes observed near 1 AU do not originate locally but have propagated for considerable time. Whether magnetic clouds gradually become small-scale flux ropes through "peeling" and how rapid this process might be are difficult to determine from individual events, but estimates can be made through the evolution of their azimuthal flux, which will be discussed next.

3. Evolution of Azimuthal Flux in Magnetic Cloud Structure

Continuous or intermittent magnetic reconnection near magnetic cloud boundaries inevitably affects changes in the overall magnetic flux. It is difficult to estimate how much the flux rope's magnetic flux decreases from when a magnetic cloud is ejected from the corona to when it reaches near 1 AU, as current observational methods cannot accurately calculate its magnetic flux at eruption. Ruffenach et al. [32] attempted to estimate the degree of reduction in a magnetic cloud's azimuthal flux by examining the asymmetry of its flux rope structure's azimuthal flux, thereby assessing the extent of magnetic field erosion at the cloud's boundary. Using the November 19–20, 2007 magnetic cloud as an example, Ruffenach et al. [32] estimated that the flux rope structure had been eroded by 44%–49%. This event was detected in situ by five spacecraft: ACE (Advanced Composition Explorer), Wind, THEMIS (The Time History of Events and Macroscale Interactions during Substorms), and STEREO (Solar TErrestrial RElations Observatory) A and B. Figure 1 [Figure 1: see original paper] is adapted from Figure 3 [Figure 3: see original paper] in Ruffenach et al. [32]. From top to bottom, the panels show suprathermal electron pitch angle distribution and normalized suprathermal electron pitch angle distribution (Figures 1(f) and (g)), proton temperature (red curve) and proton number density (black curve) (Figure 1(h)), solar wind speed (Figure 1(i)), and magnetic field strength and three components (Figure 1(j)). Figure 1 reveals a shock driven by the magnetic cloud near 17:15 UT on the 19th, where magnetic field strength, proton speed, and proton temperature all jumped sharply. The two red vertical dashed lines at approximately 23:00 UT on the 19th and near 24:00 UT represent two possible leading boundaries of the magnetic cloud identified by Ruffenach et al. [32], while the rightmost dashed line marks the trailing boundary. A magnetic reconnection outflow event was observed near 22:20 UT on the 19th; detailed information about this event can be found in the description in reference [32]. Figure 2 [Figure 2: see original paper] presents idealized magnetic field component variations for an uneroded magnetic cloud (Figure 2(a)) and an eroded magnetic cloud (Figure 2(c)), with corresponding curves (Figures 2(b) and 2(d)). For an uneroded magnetic cloud (Figure 2(a)), the azimuthal magnetic field component By (blue curve) is symmetric about the cloud's center. Integrating the By component from the front boundary to calculate the azimuthal flux, the accumulated azimuthal flux (red curve) should return to zero at the rear boundary. If a magnetic cloud has been eroded (Figure 2(c)), its magnetic structure is no longer a symmetric flux rope, and integrating the azimuthal component from front to rear boundary will not yield zero. Using the asymmetry of azimuthal flux as an indicator of flux rope disruption, the erosion degree of this magnetic cloud was estimated at 44%–49%.

However, the method of calculating magnetic cloud erosion using azimuthal flux asymmetry is unreliable. First, numerous observations show that magnetic clouds are not ideal axisymmetric flux ropes, leading to significant errors in axial estimation. Even for uneroded magnetic clouds, interaction with background solar wind during propagation typically compresses the front and elongates the rear, still resulting in substantial axial estimation errors. Second, Ruffenach et al. [32] only considered erosion from reconnection events near the front boundary, neglecting erosion from reconnection near the rear boundary. If a flux rope experiences equal erosion at both front and rear boundaries, its azimuthal flux asymmetry could still be zero. Currently, reported magnetic reconnection events near magnetic cloud (or interplanetary flux rope) boundaries occur more frequently near the rear boundary. The first reported event of an interplanetary flux rope being eroded by magnetic reconnection was also observed near the rear boundary [33]. Figure 3 shows an interplanetary flux rope event observed by Wind on March 25, 1998, with an associated reconnection outflow event reported by Feng et al. [33]. From top to bottom, the panels display: magnetic field strength, three components in GSE (Geocentric Solar Ecliptic) coordinates, solar wind proton speed and thermal speed, plasma beta, and proton density. The two vertical lines marked FB and RB indicate the flux rope's front and rear boundaries, while the shaded region immediately following the flux rope represents a magnetic outflow event. Through magnetic field fitting and reconstruction of the flux rope combined with analysis of surrounding magnetic field directions, Feng et al. [33] provided a schematic diagram illustrating the flux rope being eroded by magnetic reconnection (Figure 4 [Figure 4: see original paper]). Figure 4 clearly shows that this flux rope is being eroded by reconnection at its rear, demonstrating that the method of using azimuthal flux asymmetry to calculate erosion degree is unreliable. Later, Ruffenach et al. [34] conducted a statistical study of 50 magnetic clouds near 1 AU, still using azimuthal flux asymmetry to estimate erosion and concluding that magnetic clouds are eroded by an average of 40%.

Recently, Zhao et al. [35] studied the flux rope structure of magnetic clouds near 5 AU from the perspective of azimuthal flux variation, using the event list from Crooker et al. [36]. Calculating the azimuthal flux of a flux rope first requires determining its axis, typically assuming the magnetic cloud is a two-dimensional, static magnetic structure. For such structures, the Grad–Shafranov (G-S) equation indicates that thermal pressure and axial magnetic field remain constant along a magnetic field line. Based on this property, Zhao et al. [35] employed the method of Hu et al. [37] to first determine the magnetic cloud's axis, then calculated the azimuthal flux per unit length along the axis using the following formula [38]:

$$F_y(x) = \int_{x_1}^{x_2} B_{y;cloud}(x')dx' = \int_{t_1}^{t_2} B_{y;cloud}(t')V_{x;cloud}dt'$$

where the terms are defined as in Figure 2. Assuming the flux rope axis is along the z-direction and the x-direction is the spacecraft's motion relative to the flux rope in the plane perpendicular to the axis, $F_y(x)$ represents the accumulated azimuthal flux, with y denoting the azimuthal component, L the length along the flux rope axis, x_1 and x_2 the front and rear boundary positions, t_1 and t_2 the front and rear boundary times, $B_{y;cloud}$ the azimuthal magnetic field component (perpendicular to $V_{x;cloud}$), and $V_{x;cloud}$ the spacecraft's traversal speed across the flux rope in the plane perpendicular to the axis. For a flux rope structure, this integral should equal zero, meaning the azimuthal flux is symmetric. Through calculations, Zhao et al. [35] found that in most cases, the azimuthal flux near 5 AU is also asymmetric, with asymmetry levels essentially consistent with Ruffenach et al.'s [34] statistical results at 1 AU. This indicates that the asymmetry of magnetic cloud azimuthal flux remains essentially unchanged starting from near 1 AU, making it an unreliable reference for estimating erosion degree. Therefore, Zhao et al. [35] estimated the azimuthal flux per unit length from the flux rope boundary to the center, excluding the asymmetric portion, for 23 magnetic clouds near 5 AU, obtaining an average azimuthal flux of 2.42×10^{12} Wb/au. Similarly, using Ruffenach et al.'s [34] results, the average azimuthal flux of magnetic clouds near 1 AU is approximately 1.3×10^{13} Wb/au. This means the azimuthal flux of magnetic cloud flux rope structures near 5 AU is less than 20% of that near 1 AU, implying that a substantial portion of the magnetic cloud's flux rope structure is eroded during propagation from 1 AU outward.

4. Evolution of Large-Scale Magnetic Structure of Magnetic Clouds

The bidirectional suprathermal electron beam signature within magnetic clouds reveals that both ends of their large-scale flux rope structures remain connected to the Sun [39]. As mentioned earlier, all CMEs are generally believed to have closed flux rope structures near the Sun, and all models studying CME eruption mechanisms and propagation evolution assume CMEs possess flux rope structures. However, if magnetic clouds (or all CMEs) with closed flux rope structures were continuously ejected from the Sun into interplanetary space, the magnetic field strength in the heliosphere would continuously increase, eventually leading to a magnetic field magnitude catastrophe [40–42]. Obviously, this does not occur, as the closed flux rope structure eventually becomes completely disconnected from the solar magnetic field. The process by which the closed flux rope structure disconnects from the solar magnetic field remains unclear. To address this issue, Crooker et al. [42] proposed that the closed magnetic flux rope could disconnect from the solar magnetic field through a two-step process illustrated in Figure 5 [Figure 5: see original paper]: (1) one end of the closed flux rope is opened near the Sun through exchange reconnection with surrounding open magnetic fields blowing out from coronal holes; (2) subsequently, the open magnetic field of the flux rope reconnects with nearby open magnetic fields of opposite direction at the other end, completely disconnecting the entire flux rope from the solar magnetic field, or the flux rope's open magnetic field continues to undergo exchange reconnection with other nearby closed field lines. All reconnection processes suggested by Crooker et al. [42] occur near the Sun, and some solar observations have confirmed that one end of a flux rope can be opened or disconnected through reconnection near the Sun [43–46]. If this scenario proposed by Crooker et al. [42] were correct, magnetic reconnection within and at the boundaries of magnetic clouds would play no role in their overall evolution. However, abundant observational evidence shows that magnetic reconnection events are frequently detected near magnetic cloud boundaries, making it difficult to imagine that such reconnection has no effect on flux rope evolution. In fact, observations indicate that interplanetary magnetic reconnection not only can alter the configuration of interplanetary flux ropes and affect their geomagnetic effects but also plays an important role in the evolution of their large-scale structure and is crucial for resolving the catastrophe of unlimited heliospheric magnetic field strength enhancement. Specific observational evidence and explanations are presented below.

Figure 6 [Figure 6: see original paper] shows data from a magnetic cloud observed by ACE during 00:00–09:00 UT on February 2, 2002. The top panel displays the pitch angle distribution of 272 eV suprathermal electrons [47], with blue and red coding representing minimum and maximum electron flux, respectively. Below are magnetic field data and proton speed in GSE coordinates, proton density, and proton temperature. The two vertical lines in Figure 6 indicate the magnetic cloud's front and rear boundaries. The suprathermal electron distribution shows that bidirectional electron flows exist throughout nearly the entire magnetic cloud period, indicating that both ends of the interplanetary flux rope remain connected to the Sun at 1 AU. However, between 00:38–01:35 UT at the front of the magnetic cloud, no suprathermal electron flows along the magnetic field direction were observed. These results indicate that for approximately a one-hour interval preceding this flux rope, the field lines were open, meaning one end of the field lines had disconnected from the Sun. Figure 6 also shows: (1) a clear decrease in magnetic field strength near the flux rope's front boundary; (2) magnetic field direction reversal at both ends of this interval; (3) significant enhancement of proton density and temperature; and (4) noticeably increased plasma flow speed in the x and z directions. All these observations are classic signatures of magnetic reconnection outflows, and this event was confirmed as a reconnection outflow by Phan et al. through the Walén relation [48]. The left panel of Figure 7 [Figure 7: see original paper] provides an enlarged view of this reconnection event, showing from top to bottom: pitch angle distribution of 272 eV suprathermal electrons, magnetic field strength and three components, three components of plasma flow velocity, and proton density and temperature. Figure 7 shows that counter-streaming suprathermal electron flows briefly disappear near 01:33 UT, indicating that two oppositely directed open field lines have reconnected, producing U-shaped field lines disconnected from the Sun. The right panel of Figure 7 illustrates the ACE spacecraft trajectory and the topological distribution of the flux rope and surrounding magnetic field. The presence of unidirectional suprathermal electrons before the reconnection outflow indicates that field lines during this period were open and that the opposite open field lines likely originated from the front of the flux rope. As shown in Figure 7, initially the front field lines of the flux rope were opened through exchange reconnection near the Sun, and then the open field lines were disconnected through interplanetary magnetic reconnection. Additionally, ACE observations show that field lines before the flux rope front boundary and after the reconnection outflow are all open, while subsequent flux rope field lines are closed. This indicates that reconnection between the open field lines preceding the flux rope and its closed field lines caused these field lines to be opened. These observations demonstrate that closed magnetic field lines of a flux rope can be opened not only through exchange reconnection near the Sun but also through interplanetary magnetic reconnection.

Figure 8 [Figure 8: see original paper] presents suprathermal electron distribution, magnetic field, and plasma data from a magnetic cloud observed by Wind during October 31–November 1, 2001 [49]. The top panel shows the pitch angle distribution of 264.8 eV suprathermal electrons with angular and temporal resolutions of 22.5° and 100 s, respectively, with blue and red coding representing minimum and maximum electron flux. Below are magnetic field data and proton speed in GSE coordinates, proton density, and proton temperature. The two vertical lines indicate the interplanetary flux rope's front and rear boundaries. The suprathermal electron pitch angle distribution reveals: (1) suprathermal electron flows parallel to the magnetic field exist throughout the entire duration of the interplanetary flux rope; (2) from 15:30 UT on November 1 to the rear boundary of the interplanetary flux rope, no suprathermal electron flows anti-parallel to the magnetic field are present; (3) anti-parallel suprathermal electron flows persist from the rear boundary to 19:30 UT on November 1; and (4) no parallel suprathermal electron beams exist after the interplanetary flux rope. Since suprathermal electron beams originate from the Sun, these observations indicate: (1) field lines from the front boundary to 15:30 UT on November 1 remain connected to the Sun at both ends; (2) other field lines within the interplanetary flux rope are connected to the Sun only at the parallel end; and (3) field lines from the rear boundary to 19:30 UT are connected to the Sun only at the anti-parallel end. Additionally, a magnetic reconnection event is occurring at this interplanetary flux rope's rear boundary, whose impact on the flux rope's evolution will be discussed in detail below.

Figure 9 [Figure 9: see original paper] shows details of the reconnection outflow near 17:59 UT on November 1, 2001 at the rear boundary of this interplanetary flux rope. The figure reveals a clear accelerated flow along the z-direction, with magnetic field direction reversal on both sides of the flow, anti-correlation between velocity and magnetic field components near the front boundary, and positive correlation near the rear boundary. These observational characteristics all indicate a reconnection outflow event, which Feng et al. [49] verified using the Walén relation, showing good correspondence between predicted and observed velocity profiles. The suprathermal electron distribution in Figure 9 shows neither parallel nor anti-parallel suprathermal electron beams within the reconnection outflow, but only parallel beams before and anti-parallel beams after the outflow. These observations indicate that open magnetic field lines on both sides have reconnected through the magnetic reconnection event, producing U-shaped field lines disconnected from the Sun. Therefore, some semi-open field lines of this interplanetary flux rope are being disconnected by the reconnection event. Consequently, flux rope evolution is a hybrid process in which closed field lines can be opened or disconnected either near the Sun or simultaneously in interplanetary space.

In addition to erosion of large-scale flux rope structures and opening/disconnection of closed structures during propagation through interplanetary space, observations suggest that magnetic clouds may initially consist of multiple sub-flux ropes that can merge into larger-scale flux ropes through magnetic reconnection during their interaction. Figure 10 [Figure 10: see original paper] shows solar wind observations by Wind during a magnetic cloud event on March 25–26, 1998. From top to bottom are magnetic field, proton density, temperature, proton speed, and plasma beta [50]. From 12:00 UT on March 25 to 09:50 UT on March 26 (the shaded region), Wind encountered a region with relatively strong and smooth magnetic field and low proton temperature (Figures 10(a)–(d) and (f)). During approximately the same interval, the plasma beta was also very low (mostly below 0.1, Figure 10(j)), and suprathermal electron beams were bidirectional. Therefore, this shaded interval is a typical magnetic cloud included in many magnetic cloud lists [16]. However, between 13:30 UT on March 25 and 09:30 UT on March 26, Wind observed two distinct bipolar variations in the z-component of the magnetic field (indicated by the two red bars at the bottom of Figure 10(d)). Within this interval, the y-component of the magnetic field and the total magnetic field strength both reached maximum values at the center of each bipolar variation (Figures 10(a) and (c)). These are typical flux rope signatures, indicating that Wind detected two interplanetary flux ropes within this magnetic cloud. The axes of these interplanetary flux ropes can be determined using the G-S reconstruction method. Figures 11(a) and (c) [Figure 11: see original paper] show the cross-sections of these two interplanetary flux ropes, while Figures 11(b) and (d) present the fitted curves of transverse total pressure as a function of A (the vector potential corresponding to the magnetic field in the plane perpendicular to the axis), where R_f is the fitting variance indicating reconstruction quality, with values below 0.15 generally considered reliable. Enlarging Figure 11(c) yields Figure 11(e), which shows that the larger flux rope resulted from the interaction and merging of the two smaller flux ropes labeled FR2 and FR3 in Figure 10(d). From the magnetic cloud observed by Wind on March 25–26, 1998, we can infer that this ICME likely initially contained three or more small flux ropes at eruption, which merged with each other through magnetic reconnection. The axes of the first two flux ropes observed locally by Wind were nearly opposite in direction, and as the merging process progressed, the two flux ropes would combine into a large-scale flux rope with weaker central magnetic field strength. Such flux ropes are frequently observed by spacecraft in interplanetary space.

5. Discussion and Outlook

The propagation and dynamic evolution of magnetic clouds in interplanetary space is a critically important topic, relating not only to the reliability of space weather forecasting but also to the relationship between magnetic clouds and non-magnetic-cloud ICMEs. As mentioned earlier, CMEs are generally believed to possess closed flux rope structures when ejected from the Sun, yet only about 30% of ICMEs exhibit flux rope structures. What causes in situ spacecraft to detect flux rope structures in only a minority of ICMEs? Could the flux rope structures of magnetic clouds be destroyed during evolution? While we now have a basic understanding of magnetic cloud dynamic evolution, the details and complete process remain unclear and require further in-depth study. For instance, we know that magnetic clouds interact with background solar wind through magnetic reconnection, causing boundary positions to change and forming an evolving quasi-static boundary layer structure, but the conditions for magnetic reconnection initiation are not fully understood, nor is the duration of reconnection. If reconnection ceases temporarily after a period, the mechanism for its reactivation is also unclear. While we know that magnetic reconnection at magnetic cloud boundaries can erode the flux rope structure, how the erosion degree of a magnetic cloud as a flux rope varies with propagation distance remains unknown. Erosion degree estimates are based on two-dimensional models, yet magnetic clouds are three-dimensional large-scale magnetic structures, and whether local magnetic reconnection can affect the entire flux rope structure is uncertain. Although specific cases have demonstrated that interplanetary magnetic reconnection plays a role in disconnecting flux ropes from the solar magnetic field, whether its role is greater than that of reconnection near the Sun remains unclear. While observations suggest that two “sub-flux ropes” with opposite helicity and axial field direction may merge through magnetic reconnection into a larger flux rope with weaker axial field, the extent to which such merging can proceed and whether the process might trigger sausage instability due to reduced axial field strength, causing collapse of the entire flux rope system, are still unknown. This could be key to determining whether non-magnetic-cloud ICMEs can form through interactions among multiple “sub-flux ropes” within them. Comprehensive understanding of magnetic cloud propagation and dynamic evolution in interplanetary space, and effective forecasting of associated space weather, require in-depth investigation of these issues. Solving these problems will require not only analysis of current satellite in situ observations but also magnetohydrodynamics (MHD) numerical simulations of magnetic cloud propagation and dynamic evolution.

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Note: Figure translations are in progress. See original paper for figures.