

KINEMATIC AND MORPHOLOGICAL EVOLUTION AND DYNAMICS OF
CORONAL MASS EJECTIONS IN INTERPLANETARY SPACE

by

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Dedication

This is dedicated to my mother and my father, who always encourage and support me through my entire work and study.

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I would like to acknowledge the following people who contributed to this dissertation in many ways. I would especially like to thank my advisor, Dr. Jie Zhang for continuous support and generous time. He has encouraged me to develop my research skill throughout my entire doctoral work. Without him, this dissertation would not have been possible and I would not have reached this stage.

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Abstract

KINEMATIC AND MORPHOLOGICAL EVOLUTION AND DYNAMICS OF CORONAL MASS EJECTIONS IN THE INTERPLANETARY SPACE

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George Mason University, 2010

Dissertation Director: Dr. Jie Zhang

Studies of Coronal mass ejections (CMEs) are scientifically intriguing and practically important. CMEs are the main driver of space weather that specifies plasma, magnetic and particle conditions in near-Earth space. When CMEs pass through and interact with the Earth's magnetosphere, they can cause significant disruption in space and produce a variety of harmful effects on human's technological systems from space to the ground. Many studies have been carried out to understand their evolution. However, their kinematic and morphological evolution as they pass from Sun to Earth is still poorly understood, largely due to the lack of direct observations. Since the launch of the twin-STEREO spacecraft in 2006, tracking of CMEs in interplanetary space was made available for the first time. Further, one could make unprecedented 3-D measurement of CMEs, thanks to the simultaneous observations from two vantage points in space. In this dissertation, I make use of STEREO observations to study the kinematic and morphological evolution of CMEs in interplanetary space. The Raytrace model is utilized as a powerful tool to measure CMEs evolution in 3D. I find that CME leading edge (LE) velocity converges from an initial range between 400 km/s and 1500 km/s at 5 to 10 R_S to a narrow range between 500 km/s and 750 km/s at 50 R_S . The expansion velocity is also found to converge into a narrow range

between 75 km/s and 175 km/s. Both LE and

expansion velocities are nearly constant after $50 R_S$. I further find that the acceleration of CMEs in the inner heliosphere from ~ 10 to $90 R_S$ can be described by an exponential function, with an initial value as large as $\sim 80 m/s^2$ but exponentially decreasing to almost zero (more precisely, less than $\pm 5 m/s^2$ considering the uncertainty of measurements). These results are important for constructing accurate space weather prediction models.

In addition to the observational study, I have used the theoretical flux rope model to explain the observations, and find consistency between theory and observation. The evolution of CMEs can be explained by different forces that act on them: Lorentz force, thermal pressure force, gravity force, aero-dynamic drag force, and magnetic drag force. Based on a set of four events, I find that the drag coefficient from CME to CME is between 2.5 to 3.0, which is much smaller than the factor of twelve suggested by earlier studies. Therefore, we have been able to narrow down the range of drag coefficient, which helps improve the prediction of CME arrival time at the Earth.

In the early stage of my Ph.D. study, working with a team, we have identified solar and interplanetary sources of all 88 major geomagnetic storms from 1996 to 2005. We classify the Solar-IP sources into three broad types: (1) S-type, in which the storm is associated with a single ICME and a single CME at the Sun; (2) M-type, in which the storm is associated with a complex solar wind flow produced by multiple interacting ICMEs arising from multiple halo CMEs launched from the Sun in a short period; (3) C-type, in which the storm is associated with a Corotating Interaction Region (CIR) formed at the leading edge of a high-speed stream originating from a solar coronal hole (CH). For the 88 major storms, the S-type, M-type, and C-type events number 53 (60 %), 24 (27 %), and 11 (13 %), respectively. For the 85 events for which the surface source regions could be investigated, 54 (63 %) of the storms originated in solar active regions, 11 (13 %) in quiet Sun regions associated with quiescent filaments or filament channels, and 11 (13 %) were associated with coronal holes. This study improves our understanding of geo-effective CMEs.

In conclusion, the dissertation work has improved our understanding about the kinematic and morphologic evolution of CMEs in interplanetary space. In the future, a larger

number of events need to be measured and modeled to further constrain CME evolution models, in particular, the drag coefficient and the polytropic index. We are confident with these studies. We are confident that our studies enable us to construct an accurate empirical model to predict the travel times of CMEs from the Sun to the Earth, thus improving our ability to forecast space weather events.

Chapter 1: Introduction

Space weather entails the varying physical conditions, concerning the states of plasma, magnetic fields, particles, and radiation, in the vast space beyond the Earth's lower atmosphere. In addition to the space close to the Earth, it also embraces interplanetary space and extends to the Sun's atmosphere. It is well known that the major driver of space weather is coronal mass ejections (CMEs), which originate in the Sun's inner corona. When a CME propagates through interplanetary space (called ICME) and happens to pass through the Earth's magnetosphere, the CME may transfer a large amount of energy into the Earth's magnetosphere causing a geomagnetic storm (Sugiura, 1960). Another space weather effect of CMEs is the so-called solar energetic particle (SEP) event, which may cause damage in electronic circuits in spacecraft and pose hazards to astronauts (e.g. Townsend *et al.*, 2005; Stephens Jr. *et al.*, 2005). In addition, geomagnetic induced current, the ground end of space weather effects (Trivedi *et al.*, 2007), may cause disturbance in the electric grid resulting in power outage. Therefore, the study of CMEs is important from both scientific and practical points of view. Figure 1.1 illustrates the composition of a solar eruption from the Sun on the left and the earth's magnetosphere on the right. In this chapter, I briefly introduce the properties of CMEs and ICMEs and the motivation for this dissertation work.

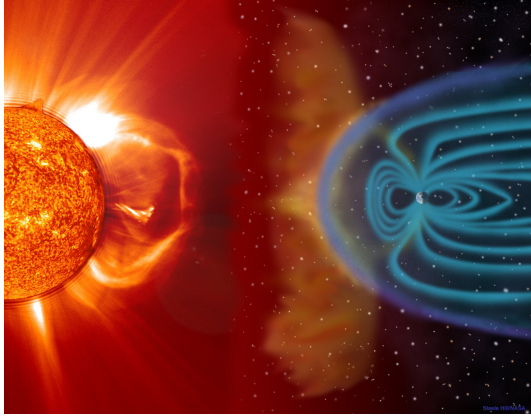


Figure 1.1: Illustration of a CME from the sun (left) and the Earth's magnetosphere (right), indicating the connection between the Sun and the Earth.

1.1 CMEs and Their Properties

We know that the major causes of large geomagnetic storms generally come from coronal mass ejections (CMEs) that evolve into their counter part in interplanetary space (e.g. Brueckner *et al.*, 1998; Berdichevsky *et al.*, 2002; Zhang *et al.*, 2003; Gopalswamy *et al.*, 2005). Geoeffective activity tends to follow the number of sunspots. During solar maximum, the number of sunspots increases and CMEs occur about 4 times per day on average. On the other hand, the number of sunspots decreases in solar minimum and the rate of occurrence of CMEs is around 0.2 per day (St Cyr *et al.*, 2000; Webb, 2000).

CMEs are routinely observed by white light coronagraphs. Since 1972, CMEs have been observed by several spacecrafts including Skylab, P78-1 (SOLWIND), and the Solar Maximum Mission (SMM). On December 2, 1995, the Solar and Heliospheric Observatory (SOHO) was launched from the Kennedy Space Flight Center, Cape Canaveral, Florida, carrying the Large Angle and Spectrometric Coronagraph (LASCO) instrument. LASCO is composed of a set of three coronagraphs that observe the solar corona from 1.1 to 32 R_s : C1 from 1.1-3 R_s , C2 from 2-6 R_s , and C3 from 3.7-32 R_s). LASCO has observed more than 10,000 CMEs.

Illing & Hundhausen (1985) are the first to describe CMEs as consisting of a three part

structure: bright core, dark cavity and leading edge. The leading front is caused by compression and piling-up of ambient plasma following the CME initiation. The dark cavity is caused by the rapid expansion of the coherent CME magnetic structure, presumably a 3-D flux rope. In near-Earth space, the cavity corresponds to the well known magnetic cloud structure seen in ICMEs. About one-third of ICMEs are seen to have a well-defined magnetic cloud structure. The plasma compression in the leading front may evolve into an interplanetary shock, often observed in-situ as an abrupt change of plasma temperature and density. The three-part structure is illustrated in Figure 1.2, which shows the CME that occurred on February 27, 2000.

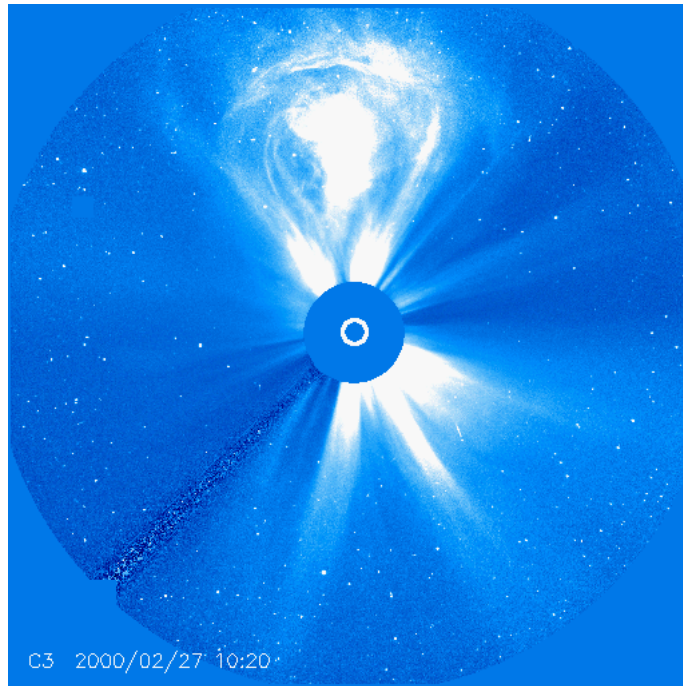


Figure 1.2: CME at 10:30 UT on February 27, 2000 from SOHO/LASCO, showing the CME propagation into the interplanetary space in C3. This figure also displays the three part structure of the CME: leading edge, dark cavity and bright core.

Halo CME refers to a CME that has the moving direction either towards or away from the earth along the Sun Earth line. They appear to propagate radially outward in all direction from the sun with a circular brightness structure around the coronagraph occulting disk

(Howard *et al.*, 1982). Webb *et al.* (2001) reported that full Halo CMEs are about $\sim 4\%$ of all CMEs. Another type of CMEs, which expand in large apparent angle ($\geq 120^\circ$), but are not completely halo, are called "partial halo" CMEs. Halo and partial halo CMEs (e.g. Gonzalez *et al.*, 2004; Arge *et al.*, 2005; Tripathi & Mishra, 2005) are of particular interest in space weather sciences, because they may be directed toward the Earth causing many space weather effects.

Table 1.1, taken from Gopalswamy *et al.* (2006) shows the statistical properties of CMEs observed by satellite since 1971. The average angular width (degree $^\circ$) is found to be between 42° and 47° , and the average mass of CMEs is on the order of 10^{14} to 10^{16} grams. Many studies of the true mass of CMEs have been explored by Hundhausen (1987); Vourlidas *et al.* (2000, 2002); Colaninno & Vourlidas (2009); Aschwanden *et al.* (2010). The medium velocity (km/s) in table 1.1 is between 350 km/s and 480 km/s but the range of CME velocities can vary from 50 to 2,500 km/s (e.g. Zhang *et al.*, 2004; Zhang & Dere, 2006). More discussion on the topic of CME velocity distribution will be provided in a later chapter.

Table 1.1: Properties of CMEs in various coronagraph (Gopalswamy *et al.*, 2006)

spacecraft	OSO-7	skylab	Solwind	SMM	LASCO
Epoch	1971	1973-1974	1979-1985	1980, 1984-89	1996-2005
FOV	2.5-10.0	1.5-6.0	3.0-10.0	1.6-6.0	1.2-32
# CMEs	27	115	1607	1206	10510
Vel (km/s)	-	470	460	350	482
Width(degree)	-	42	43	47	45
Mass (10^{15} g)	-	6.2	4.1	3.3	0.4

Since 1996, the white light coronagraphs from SOHO/LASCO (Brueckner *et al.*, 1995) have played an important role in space weather research because LASCO data have been extensively utilized in studying the initiation and propagation of CMEs. However, one limitation of CME study from SOHO/LASCO is that the measured speed is not the actual speed in 3-D space; it is the projected speed measured from the plane-of-sky. I discuss how to overcome the projection effect in the following section.

1.2 CMEs in 3D observation

The Solar TERrestrial RElations Observatory (STEREO) (Kaiser *et al.*, 2008), the strategic mission in NASAs Solar Terrestrial Probes (STP) Program, is designed to make much better observations of CMEs. STEREO launched on 26 October, 2006, consists of two identical spacecrafts, one ahead and the other behind the Earth's orbit on ecliptic plane (Figure 1.3). The major advantage of the STEREO mission is that, for the first time, one can infer information in 3-D space: 3-D position, 3D velocity, and 3-D acceleration of evolving CMEs, from pairs of STEREO images obtained from two separate vantage points in the heliosphere. The bulk of the work in this thesis is based on STEREO observations. Details will be given in Chapter 4.

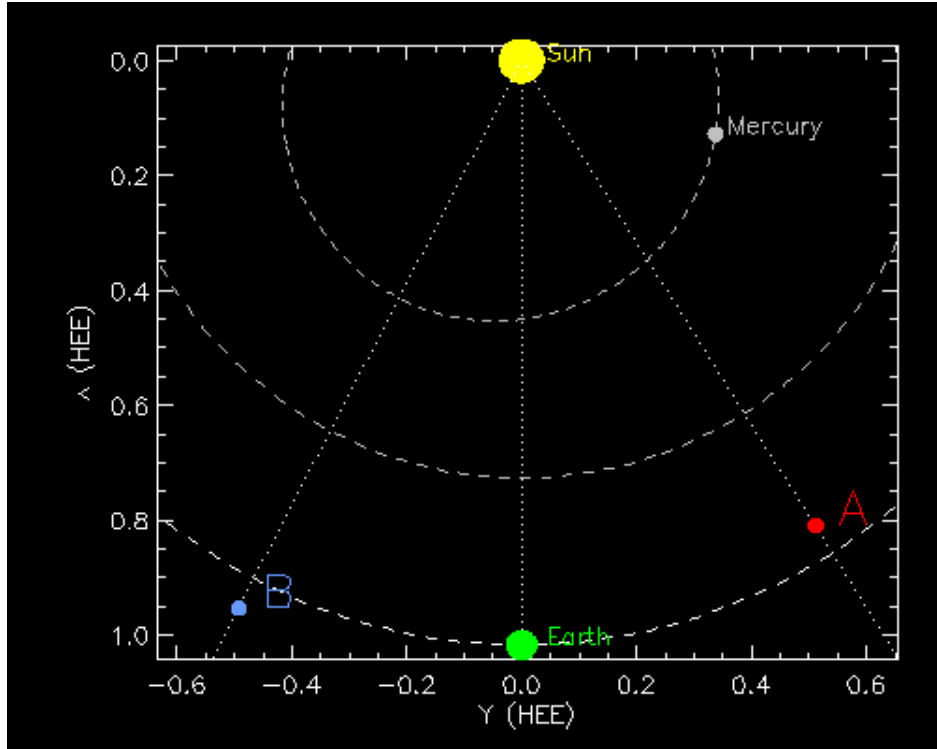


Figure 1.3: Positions of STEREO spacecrafts A and B (small red and blue circles), sun (yellow circle) and earth (green circle). Credit: NASA

The SECCHI suite on STEREO is more advanced than SOHO/LASCO in terms of studying CME evolution. It has a much larger field of view, providing us more complete observations of CME propagation and expansion. SECCHI has five complementing instruments: EUVI (Extreme Ultra Violet Imager), COR1 (Inner Coronagraph), COR2 (Outer Coronagraph), HI 1 (Heliospheric Imager 1) and HI 2 (Heliospheric Imager 2). COR1 has the ability to take images of the solar corona from $1.5-4.0 R_s$. On the other hand, COR2 can take images of the solar corona from $3-15 R_s$ and HI 1 gives the field of view of the solar corona from $12-84 R_s$.

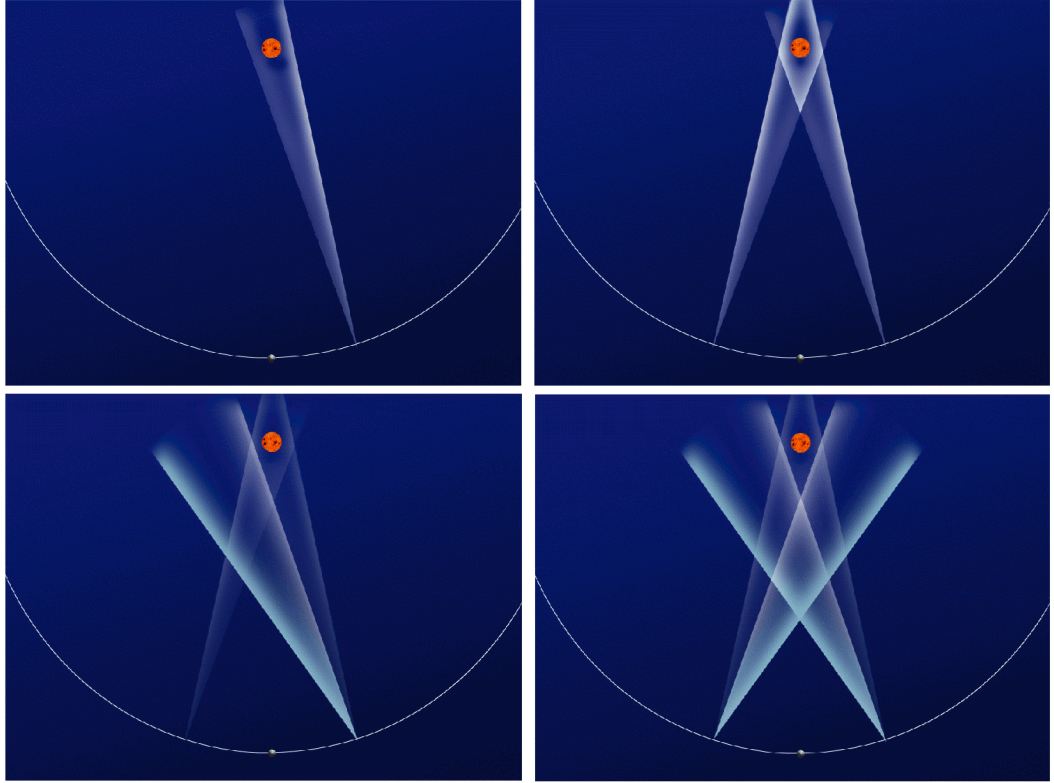


Figure 1.4: Four snapshot images for overlap region from CORs and HI1 STEREO/SECCHI. The orange circle in all four images represents the Sun. The small dot on the arc line represents the Earth. The left of the Earth represent the STEREO B and the right of the Earth represents STEREO A.

Figure 1.4 illustrates the overlap regions of COR2 and HI1. The orange circle in all four images represents the Sun. The small dot on the arc line represents the Earth. The left of the Earth represent the STEREO B and the right of the Earth represents STEREO A. The top left image on figure 1.4 shows the view point of COR2 from STEREO A and the top right panel represents the overlap region of COR2 from both STEREO A and B. The bottom left of figure 1.4 shows the view point of HI1. Finally, the bottom right of figure 1.4 represents the overlap region of COR2 and HI1. This shows the advantage of the STEREO spacecrafts, which are able to detect CMEs evolution in 3D, from two vintages of the spacecrafts.

Another scientific payload on board STEREO is the PLAsma and SupraThermal Ion Composition (PLASTIC) instrument. The objective of PLASTIC is to continuously track the solar wind particles and magnetic field in order to study phenomena including ICMEs, SEPs, and CIRs (Corotating Interaction Region) in the heliosphere as they pass through the spacecraft near 1 AU. (Galvin *et al.*, 2007).

In-situ Measurements of Particles and CME Transients (IMPACT)), another instrument on STEREO, focuses on the particles and magnetic fields that affect Earths space weather (Luhmann *et al.*, 2007). IMPACT is able to measure suprathermal electrons, interplanetary magnetic fields, and solar energetic particles (SEP).

1.3 ICMEs and Their Properties

A CME that propagates in the interplanetary space is called an Interplanetary Coronal Mass Ejection (ICME). ICME had been called driver gas, piston, or ejecta in the past (Hundhausen, 1972). They have been detected by several spacecraft ACE, WIND, and Ulysses. The signatures of ICMEs from in-situ observations are discussed in this section.

Figure 1.5 is taken from Zurbuchen & Richardson (2006). This figure represents the schematic structure of an ICME and the upstream shock, indicating the presence of magnetic field, plasma and solar wind suprathermal electron flows (Larson *et al.*, 1997). This figure illustrates that the CME expelled from the sun into the heliosphere has a flux rope structure containing plasma material from the Sun. The sheath region between the ICME and the shock front, is a heated and turbulent region that contains compressed ambient solar wind plasma (Richardson & Cane, 2010). Krimigis *et al.* (1976) were the first to report the signature of magnetic flux ropes in the interplanetary space using in-situ spacecraft. Many studies of ICMEs then use in-situ data from ACE and WIND, which obtain signatures of ICMEs in near-Earth space.

In-situ signatures of ICMEs include low proton temperature (Richardson & Cane, 1995), magnetic field rotation, low plasma beta, bidirectional suprathermal electron strahls (Zwickl *et al.*, 1983), (Gosling *et al.*, 1987), enhanced plasma helium abundance (Richardson & Cane, 1995), (Borrini *et al.*, 1982), enhanced Fe charge state (Lepri *et al.*, 2001), energetic particle signatures such as bidirectional energetic protons (Richardson & Reames, 1993) and cosmic rays (Dvornikov *et al.*, 2000). The following subsections will briefly discuss the most important signatures for identifying ICMEs: behavior of plasma proton temperature, behavior of magnetic field strength and magnetic field rotation, behavior of plasma beta (β) in magnetic clouds, and behavior of ion ratio in magnetic clouds. These characteristics are useful for identifying the sheaths and ICME ejecta.

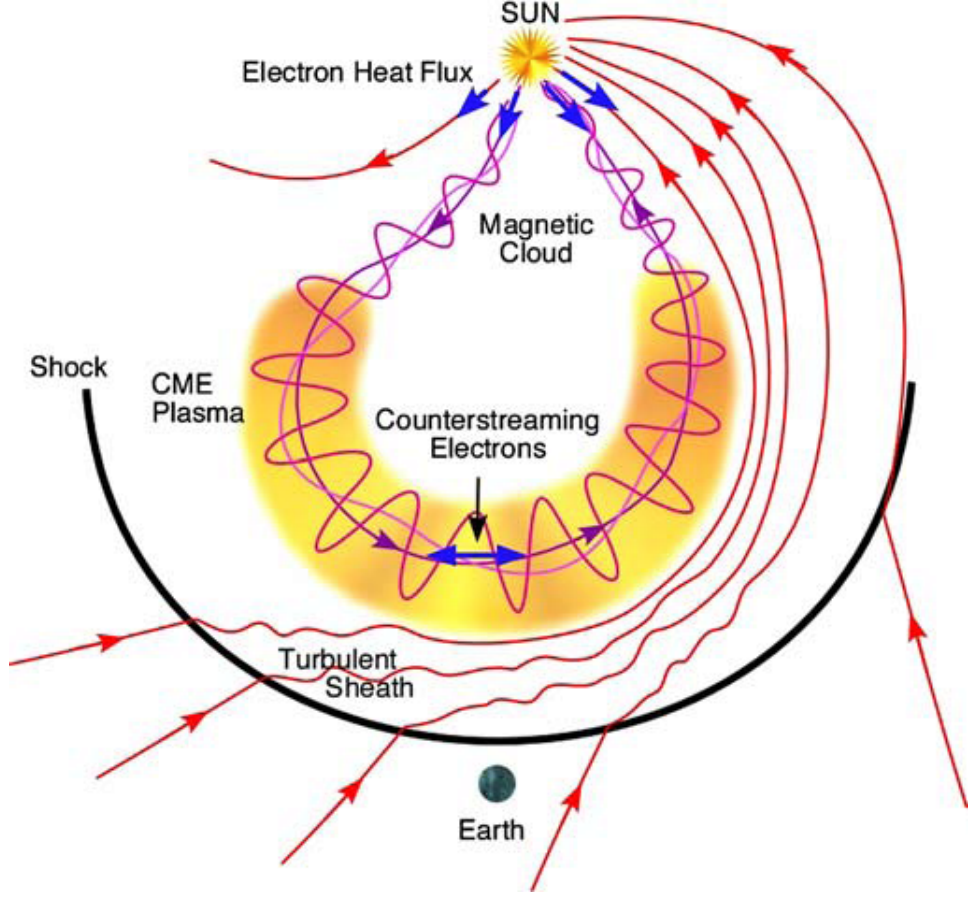


Figure 1.5: Schematic of an ICME and upstream shock indicating magnetic field, plasma and solar wind suprathermal electron flows (Zurbuchen & Richardson, 2006).

1.3.1 Behavior of Proton Temperature, and Solar Wind Velocity

The correlation between ambient solar wind velocity and plasma proton temperature (T_p) was found by Lopez (1987, and references therein). However, this correlation has not been observed in the solar wind that follows interplanetary shock waves or ICMEs; the plasma proton temperature in ICMEs was found to be lower than the temperature in the ambient solar wind (Gosling *et al.*, 1973). This can be explained by ICME expansion, due to the expansion cooling effect Richardson & Cane (1995) developed a good criteria to identify ICMEs signatures by comparing the observed plasma proton temperature and the expected temperature (T_{exp}), which is $T_p < T_{exp}$. The expected temperature formula is an empirical formula and it matches with the data from Helio1. In addition, the expected temperature

is determined from the observed solar wind velocity V_{sw} , and is calculated as follows (Lopez *et al.*, 1986)

$$T_{exp} = \begin{cases} (0.016V_{sw} - 0.278)^3 & V_{sw} < 500 \text{ km s}^{-1}, \\ (0.77V_{sw} - 265) & V_{sw} \geq 500 \text{ km s}^{-1}, \end{cases} \quad (1.1)$$

Another study on the relation between plasma proton temperature and solar wind velocity in ICMEs comes from Neugebauer *et al.* (1997), who presented a thermal index. The equation 1.2 give the equation for thermal index.

$$I_{th} = (500V_p + 1.75 \times 10^5)/T_p \quad (1.2)$$

Where V_p represents the observed solar wind proton velocity, and T_p is the observed proton thermal temperature. If $I_{th} > 1$, the plasma is probably associated with an ICME (Neugebauer *et al.*, 1997).

Cane *et al.* (1997) investigated and found that the ratio between plasma electron temperature and proton temperature is ~ 2 . A decade later, Liu *et al.* (2005) reported that the electron temperature T_e is often larger than the proton temperature within ICMEs with a typical ratio of $T_e/T_p \sim 3$. However, in the opposite, electron temperature is often lower than proton temperature in sheath region (Skoug *et al.*, 2000).

1.3.2 Behavior of Magnetic Field Strength and Rotation

Today it is commonly accepted that "magnetic clouds" (Burlaga *et al.*, 1981), the strongest in-situ evidence of the presence of ICMEs, are actually of a flux rope-like shape. One of the signatures of magnetic clouds or ICMEs at 1 AU, is strong magnetic field (> 10 nT), stronger than the ambient magnetic field in the solar wind (Klein & Burlaga, 1982; Lepping *et al.*, 1990; Richardson & Cane, 1995). In addition, a smooth rotation of the magnetic field occurs because of the passage of the helical magnetic structure of a flux rope.

1.3.3 Behavior of Plasma Beta (β) in Magnetic Clouds

In a magnetic cloud, the magnetic field strength is higher than the ambient magnetic field but the plasma proton temperature and proton density are lower when compared with that of the ambient plasma. This can be explained by the expansion of the magnetic cloud in interplanetary space. Plasma beta is the ratio of the thermal pressure over the magnetic pressure. Since the magnetic field strength in a magnetic cloud is higher and the temperature is lower than the ambient plasma, the plasma beta is then lower within a magnetic cloud. Burlaga *et al.* (1981); Richardson & Cane (1995) used plasma beta to identify the signature of magnetic clouds (or ICMEs) at 1 AU.

1.3.4 Behavior of Heavy Ion Charge Ratio in Magnetic Clouds

In the lower corona, ion charge states tend to "freeze-in" because the ionization and recombination times of ions becomes larger than the solar wind ion expansion time as the coronal electron density decreases with increasing distance from the Sun (Richardson & Cane, 2004b). The ratios of the number of particles of different ionization states then provides information on the coronal electron temperature at the freezing-in altitude (e.g. Hundhausen *et al.*, 1968; Owocki *et al.*, 1983). Henkel T et al 1998 2001 also suggested that the heavy ion charge ratio is another way to classify solar wind structures in interplanetary space.

The above discussions provide the introduction of how to identify ICMEs at 1 AU from in-situ observations. These signatures are used in the study of solar sources of intense geomagnetic storms as reported in Chapter 2 and 3. In the next section, I discuss the evolution of ICMEs in interplanetary space.

1.4 Evolution of Interplanetary Coronal Mass Ejections

Before the STEREO era, continuous tracking of individual CMEs throughout the heliosphere was not possible. Statistical studies of a large number of ICMEs, each of which is

observed in-situ provide clues on possible CME evolution. Many studies have attempted to connect observations of magnetic clouds to their inferred active-region sources (e.g. Webb *et al.*, 2000b; Leamon *et al.*, 2004).

On the kinematic evolution of CMEs near the Sun based on SOHO/LASCO observations, Sheeley *et al.* (1999) reported his empirical formula, which is

$$V^2(r) = V_a^2[1 - e^{-(\frac{r-r_0}{r_a})}], \quad (1.3)$$

V_a is the asymptotic speed, r_0 is the place where V_r equals 0, r_a is the e-folding distance. Also, when $r = r_0 + r_a$, the speed reaches 80 % of its asymptotic value. He also provided an acceleration formula by taking the derivative of the velocity equation 1.3,

$$a(r) = \frac{V_a^2}{2r_a} e^{-(\frac{r-r_0}{r_a})} \quad (1.4)$$

A year later, Gopalswamy *et al.* (2000) presented a correlation between CME velocity at the Sun (projected velocity from LASCO) and the velocity of the counterpart or ICME at 1 AU. The empirical formula of the inferred acceleration between the Sun and the Earth is described as

$$a(m/s^2) = 1.41 - 0.0035 \times u(km/s) \quad (1.5)$$

where a is in unit of m/s^2 and u represents the CME velocity in units of km/s . This result was supported by Reiner *et al.* (2003), who measured the deceleration of fast CMEs between the sun and the Earth using both radio and white light observations.

Liu *et al.* (2005) studied the properties of ICMEs from 0.3 to 5.4 AU using in-situ data from Helio 1 and 2, Advance Composition Explorer (ACE), WIND, and Ulysses. The data from Helio 1 and 2 had been used for the heliocentric distance from 0.3 to 1 AU from December 1974 to 1985. WIND and ACE, launched in 1994 and 1997 respectively, provided the measurements of solar wind in near-Earth space. Ulysses, launched in 1991, provided

solar wind data from 1 to 5.4 AU.

Based on their ICMEs, Liu *et al.* (2005) found the statistical dependence of ICME density $N(R)$, velocity $V(R)$, temperature $T(R)$ and magnetic field on the distance R . The four equations below show the evolution of the plasma and magnetic properties of the statistical-constructed average ICME.

$$N_e(R) = (6.16 \pm 6.27) \times R^{-2.32 \pm 0.07} (cm^{-3}) \quad (1.6)$$

Equation 1.6 describes how electron density decreases with heliocentric distance. It is about $N_e = 6.2$ at 1 AU, which is slightly lower than the typical background solar wind density, 7 cm^{-3} .

$$v(R) = (458.40 \pm 6.27) \times R^{-0.002 \pm 0.02} (km s^{-1}) \quad (1.7)$$

The velocity of an average ICME at 1 AU is about 458 km/s, which is close to the typical solar wind velocity (400 km/s).

$$T(R) = (35401.1 \pm 1328.3) * R^{-0.32 \pm 0.06} (K) \quad (1.8)$$

$$B(R) = (7.35 \pm 0.40) * R^{-1.40 \pm 0.08} (nT) \quad (1.9)$$

Equation 1.8 represents the temperature in the average ICME, which is about 3.5×10^4 Kelvin at 1 AU, below the typical solar wind temperature at 1 AU of 10^5 K. Equation 1.9 shows the magnetic field strength of the average ICME, which is around 7.35 nT at 1 AU. While these formulae are constructed from the average properties of a large number of ICMEs at different distances, we are able to study the evolution of these parameters for each individual CME in this dissertation (refer to Chapter 5).

Furthermore, the physical properties within ICMEs are probably inter-related. Gonzalez *et al* (1998) found a correlation between maximum magnetic field strength ($|B_{max}|$) and maximum velocity V_{max} , which can be described as

$$|B_{max}|(nT) = 0.047V_{max}(km/s) - 1.1 \quad (1.10)$$

Owen *et al.* (2005) found a similar correlation for magnetic field greater than $18nT$,

$$|B_{max}|(nT) = 0.047V_{max}(km/s) + 0.6 \quad (1.11)$$

There is also a possible relationship between CME bulk propagation speed, or cruise speed (i.e. speed at the center of mass, or at the centroid of the CME structure) and the structural expansion speed (i.e. how fast the CME front is moving away from the centroid). Owen *et al.* (2005) worked on a set of ICMEs whose starting time and ending time were identified by Cane & Richardson (2003). They obtained the cruise speed V_{CR} , radial speeds at the leading edge V_{LE} of ICMEs and the trailing edge of ICMEs (V_{TE}). The expansion speed could be then inferred as $V_{EXP} = (V_{LE} - V_{TE})/2$. They found that the leading edge velocity V_{LE} is a function of cruise velocity V_{CR} , as follows

$$V_{LE}(km/s) = (1.30V_{CR} - 57.7)km/s \quad (1.12)$$

All of the above empirical equations provide some insight into how CMEs and ICMEs evolve as they travel from the Sun to the Earth. These relations are important if we are to predict the geoeffectiveness of an event when it leaves the Sun.

1.5 Geomagnetic storms

One practical reason for studying ICME evolution is to predict its arrival time at the Earth, thus to predict the occurrence of geomagnetic storms. A geomagnetic storm is a temporary disturbance of the Earth's magnetosphere caused by transient events in solar wind,

including ICMEs and CIRs (Corotating Interaction Region) originated from coronal holes. Geomagnetic storms near solar minimum often originate from the fast solar wind from the coronal hole, the unipolar magnetic regions of the Sun. On the other hand, near solar activity maximum major geomagnetic storms tend to be nonrecurrent and are predominantly associated with transient disturbances in the solar wind arising from solar activity in magnetically closed regions (Gosling *et al.*, 1990). CMEs are the major link between solar activity and transient interplanetary disturbances, which cause large geomagnetic storms. Moreover, large geomagnetic storms come from large intervals of negative B_Z (the north-south component of magnetic field) (e.g. Dungey, 1961; Gosling *et al.*, 1987).

To measure the occurrence and intensity of a geomagnetic storm, Dst index is often used. Dst stands for Disturbance storm time index. Dst instruments monitor the Earth's magnetic field on the ground near mid-latitudes of the Earth. The negative value of the Dst index represents the strength of the geomagnetic storm. The more negative the Dst index means the stronger the geomagnetic storm. The Dst index has a negative value because of the diamagnetic process due to the enhancement of the ring current in the magnetosphere, which flows from east to west above the equator. Kp and Ap indices are also able to identify geomagnetic storms. The name Kp comes from "planetarische Kennziffer" (= planetary index). Kp and Ap index are indicators of electric currents flowing in the ionosphere of the Earth. In Chapter 2, we present a study of all intense geomagnetic storms in solar cycle 23rd.

1.6 Motivation of My Dissertation

Presently, most studies of CMEs/ICMEs are limited to the two ends: CMEs near the Sun and ICMEs near the Earth, leaving the evolution through the vast interplanetary space unknown. My research focuses on CME evolution in the interplanetary space with the aid of STEREO observations because significant improvement over previous coronal observations would be a stereoscopic view. This would give the information necessary to deduce the

three dimensional structure and motion of CMEs.

The objects of this dissertation are 1) to study both kinematical and morphological evolutions of CMEs from STEREO and SOHO observations, in particular, how they accelerate or decelerate in interplanetary space 2) to understand the dynamical processes of CMEs using a theoretical model, in particular, what are the forces acting on CMEs, and how these forces evolve as CMEs move away from the Sun. In chapter 2 and chapter 3, I discuss my early studies on CME-ICME connections using SOHO observations. In chapter 4, I present the results of CME evolution in interplanetary space from STEREO observations. Chapter 5 shows the model explanation of CME evolution. Conclusions and future work are presented in Chapter 6.

Chapter 2: Observational Study One: Solar and Interplanetary Sources of Major Geomagnetic Storms

2.1 Introduction

Understanding the connection and relation between Coronal Mass Ejections (CMEs) seen in coronagraphs and their interplanetary counterpart is important for predicting space weather. In this chapter, I present one of my early works on identifying CME sources of geomagnetic storms by using data from SOHO/LASCO, SOHO/EIT, ACE and WIND. This work was part of the efforts of the Coordinated Data Analysis Workshop (CDAW) at George Mason in 2005 and at Florida Institute of Technology in 2007. My contribution to this group effort is to utilize the data from SOHO/LASCO, SOHO/EIT, ACE and WIND to identify solar wind signatures and solar source regions of intense geomagnetic storms from 1996 to 2005. This identification is independent. I then compared and discussed my results with many other colleagues. Through cross-validation of the results with multiple workers, we are able to conclude with a high confidence the exact sources and types of the 88 intense geomagnetic storms, which occurred from 1996 to 2005.

2.2 Selection of Geomagnetic Storms

The workshops focused on the major geomagnetic storms that occurred between January 1996 and December 2005. This 10-year period extends from the start to late in the declining phase of solar cycle 23, which had two sunspot maxima in 2000 and 2001. The Dst index is a measure of the strength of the Earth's ring current and is widely used for measuring the intensity of geomagnetic storms. We defined a major geomagnetic storm as a minimum in the hourly Dst index falling below - 100 nT. A similar threshold for major/intense storms

has been used by other authors (e.g. Tsurutani *et al.*, 1997). Other indices may be used, such as the Kp index (Gosling *et al.*, 1991; Richardson *et al.*, 2002). Further, if a period of high activity showed multiple $\text{Dst} \geq -100$ nT minima, we arbitrarily assigned these to a single storm event if the minima were separated by less than 24 hours, rather than define each minimum as a separate storm (except for the two storms that occurred at 1200 UT, 6 August, and 0600 UT, 7 August 1998, which corresponded to two well separated ICMEs). As will be noted later, both single and multiple solar CMEs were found to be responsible for minima within a "single" storm event. We identified 88 major geomagnetic storms in total from January 1996 to December 2005, using the selection criteria described above. The events through 2003 are based on the final Dst index, whereas those in 2004 and 2005 are based on the provisional Dst index, so it is possible that they may be adjusted slightly based on the final index. (Dst data are obtained at <http://swdcd.db.kugi.kyoto-u.ac.jp/dstdir/index.html>).

Figure 2.1 shows the distributions of the storm strength (Figure 2.1a), yearly occurrence rate (Figure 2.1b), and occurrence rate as a function of calendar month (Figure 2.1c). A majority of these events (60 out of 88; 68%) had minimum Dst between -100 nT and -150 nT. A further 10 events (11 %) had minimum Dst between -150 nT and -200 nT. There were 18 "severe" storms (21%) with minimum $\text{Dst} \geq -200$ nT. The largest geomagnetic storm ($\text{Dst} = -422$ nT) occurred on 20 November 2003 (Gopalswamy *et al.*, 2005). The yearly major storm occurrence rate was highest (~ 13 events per year) during 2000 to 2002 around the time of maximum sunspot number (SSN). The occurrence rate was lowest in 1996 at solar minimum. Figure 2.1c shows that the occurrence of major storms in general followed the well-known semiannual variation of geomagnetic activity (e.g. Russell & McPherron, 1973; Cliver *et al.*, 2002) that is higher activity during the equinoctial months and lower activity around the solstitial months. The number of major storms peaked in April to May and in October to November and was lowest in June and in December (when no storms occurred). The number of major storms around the fall equinox was almost twice that at the spring equinox with 55 events during the second half of the year compared with only

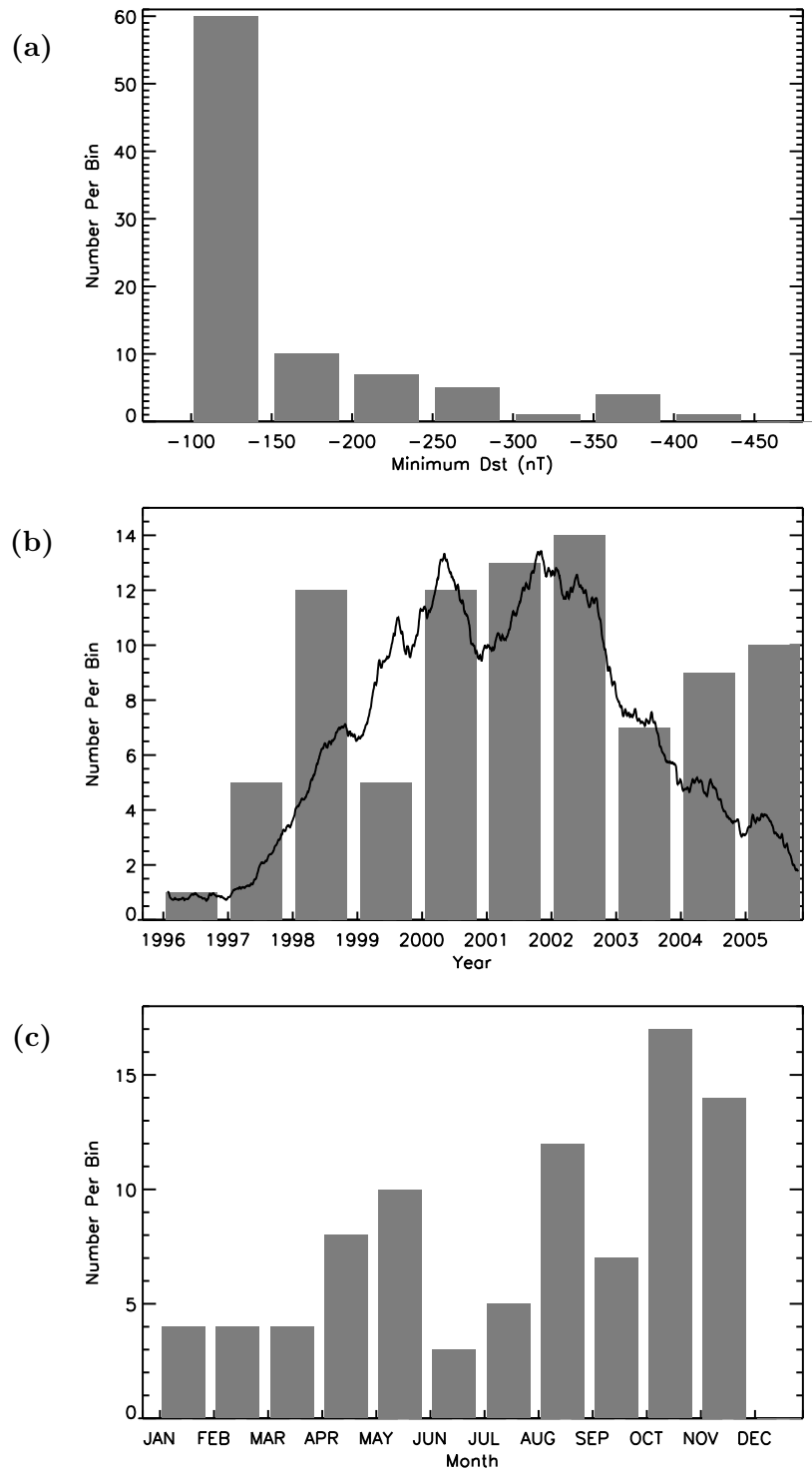


Figure 2.1: (a) Distributions of the minimum Dst (bin size = 50 nT), (b) yearly occurrence rate, and (c) occurrence rate per calendar month for 88 major geomagnetic storms during 1996-2005. The black curve overlaid in Figure 2.1b shows the 180-day-running-average daily sunspot numbers in arbitrary units.

33 during the first half. A similar seasonal asymmetry of the occurrence of "very intense" storms has been reported before Cla de Gonzalez *et al.* (2002).

2.3 Methods of Identifying Solar-IP Sources of Major Storms

2.3.1 Identifying and Characterizing the IP Sources

The primary physical mechanism for energy transfer from the solar wind to the magnetosphere is magnetic reconnection between the IMF and the Earth's magnetic field. The efficiency of this process mainly depends on the strength of the southward IMF, or more accurately, the dawn-dusk (y) component of the electric field ($E = -V \times B$) (e.g. Dungey, 1961; Perreault & Akasofu, 1978; Tsurutani *et al.*, 1997). One formulation for the Dst index (O'Brien & McPherron, 2000) relates the (pressure-corrected) Dst* index to the solar wind driver given by VB_s , where VB_s is the rectified value of VB_z that is positive when B_z is southward and zero when B_z is northward. The equations 2.1 are

$$\frac{d}{dt}Dst^* = Q(VB_s) - \frac{Dst^*}{\tau(VB_s)}, \quad (2.1)$$

$$Q(VB_s) = \begin{cases} \alpha(VB_s - E_c) & VB_s > E_c, \\ 0 & VB_s \leq E_c, \end{cases} \quad (2.2)$$

$$\tau(VB_s) = \tau_\infty \exp\left(\frac{V_0}{V_q + VB_s}\right) \quad (2.3)$$

The rate of change of Dst* is assumed to be proportional to VBs (Q representing injection into the ring current) less a loss term represented by the recovery time τ that depends on the strength of the ring current and is assumed to be proportional to Dst*.

Since storms are driven by the solar wind magnetic fields and plasma impinging on the Earth, we used in situ solar wind plasma and magnetic field observations from the

Advanced Composition Explorer (ACE) and WIND spacecraft to identify the IP sources of the geomagnetic storms in this study. For ACE data, covering events during early 1998 to 2005, 64-s resolution data were examined. We also examined solar wind ion composition data from the ACE/SWICS instrument. ACE is in orbit at the upstream L1 point, so there is typically a ~ 2060 min delay for solar wind structures to transit from ACE to the Earth. For WIND data, 92-s resolution data were used. During the period of this study, WIND spacecraft executed a complicated trajectory in the near-Earth solar wind with a variable solar wind transit time delay of typically less than 1 hour. Because of the near-complete observations provided by the two spacecraft together, we were able to deduce the IP sources for all 88 major geomagnetic storms studied.

On the basis of their plasma and magnetic signatures, we identified various types of structures in the near-Earth solar wind in association with the geomagnetic storms. These include ICME, the upstream ICME-driven shock front, the sheath between the shock front and ICME, and CIR. Note that for the sake of clarity on discussions of solar wind structures, ICME here refers to the coherent magnetic structure originating from solar CMEs and thus does not include the SH part. To assist in these identifications, we referred to several existing catalogs. For shocks, we used the WIND shock list compiled by J. Kasper ([http : //space.mit.edu/home/jck/shockdb/shockdb.html](http://space.mit.edu/home/jck/shockdb/shockdb.html)) and the ACE shock list compiled by C. W. Smith ([http : //www.ssg.sr.unh.edu/mag/ace/ACElists/obslist.html](http://www.ssg.sr.unh.edu/mag/ace/ACElists/obslist.html)). For ICMEs, we referred to an updated version of the "comprehensive" ICME list compiled by Cane & Richardson (2003). In addition, we used lists of MCs and "cloud-like" ICMEs compiled by R. P. Lepping and C.-C. Wu ([http : //lepmfi.gsfc.nasa.gov/mfi/MCL1.html](http://lepmfi.gsfc.nasa.gov/mfi/MCL1.html)) [Lepping *et al.* (2005)] and the magnetic cloud list of Huttunen *et al.* (2005). Considering plasma composition and charge states, we used the list of high Fe-charge state intervals that are frequently associated with ICMEs, compiled by Lepri *et al.* (2001), supplemented by information on compositional and charge state anomalies, also typically associated with ICMEs, based on the study of Richardson & Cane (2004a).

The storm of 27 July 2004 (Event 75 in Table 1 in Zhang *et al.* (2007b)) serves to

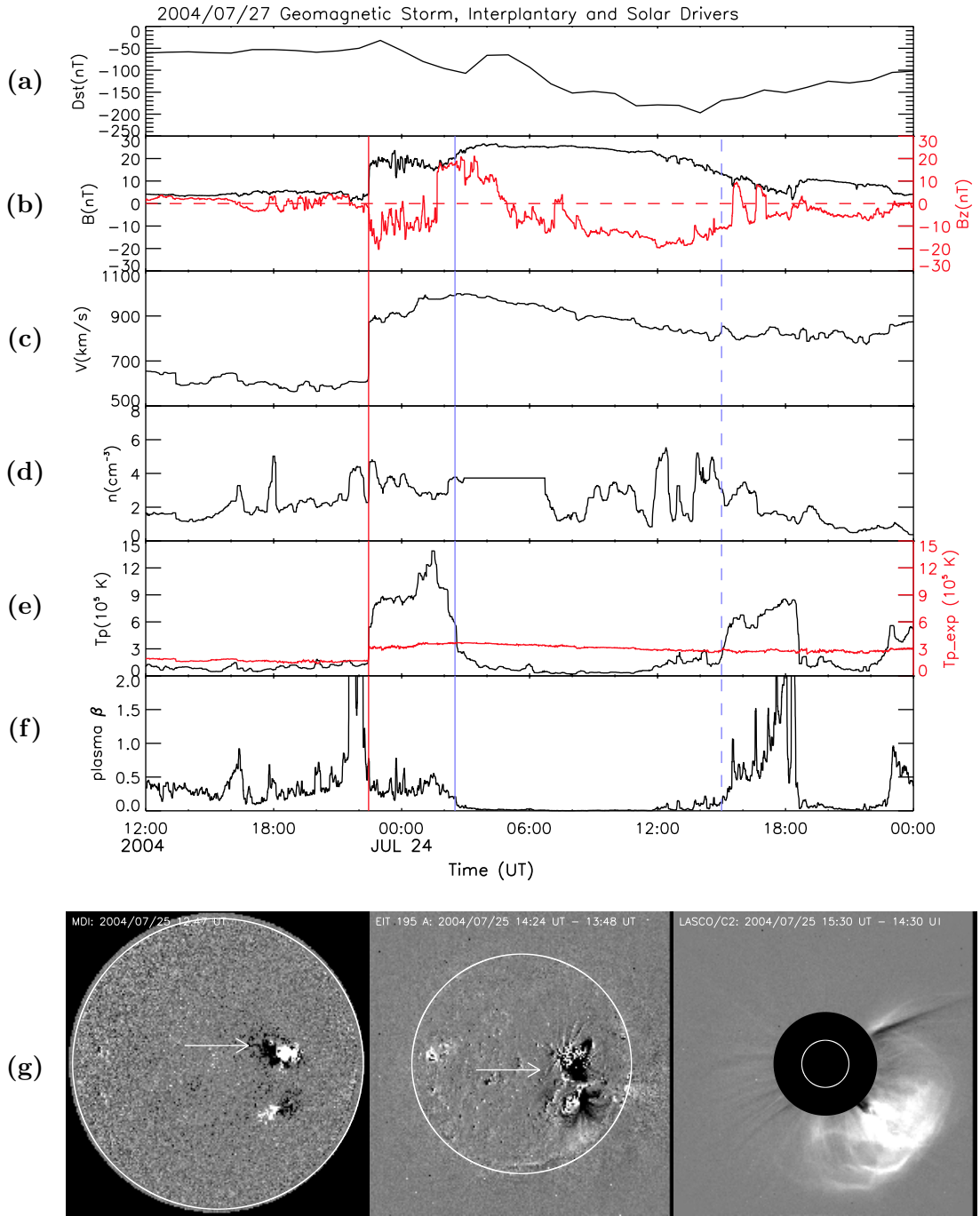


Figure 2.2: (minimum Dst = - 197 nT) on 27 July 2004, showing (a) temporal profiles of the Dst index, (b) solar wind magnetic field intensity (black) with the Bz component (red) overlaid, (c) solar wind velocity, (d) density, and (e) proton temperature (black) overlaid with the expected temperature (red) Richardson & Cane (1995), and (f) the plasma β . The solar wind data are from ACE in GSE coordinates. The solid and dotted blue vertical lines indicate the starting and ending times of the ICME, which in this case is a magnetic cloud. The vertical red line indicates the arrival time of the ICME-driven shock. (g) The three images, from left to right, indicate the source active region in a SOHO/MDI magnetogram, the coronal dimming accompanying the associated CME observed by EIT (running difference image), and this CME shown in a LASCO C2 coronagraph running difference image.

illustrate the method of source identification, as shown in Figure 2.2. Figure 2.2a shows the Dst index, indicating that this storm had a minimum value of $\text{Dst} = -197$ nT at 14:00 UT. Figure 2.2b to figure 2.2f show time profiles of the IMF strength and north-south (z) component, velocity, proton density, proton temperature, and calculated plasma β , respectively. The three solar images in Figure 2.2g will be explained later. The IP driver of the main phase of the storm was evidently the extended interval of southward magnetic field reaching values of ~ 20 nT that started at $\sim 05:00$ UT on 27 July and lasted for about 10 hours. There was also a separate interval of southward field from $\sim 22:00$ UT on 26 July to $\sim 02:00$ UT on 27 July that depressed Dst just below -100 nT at ~ 3 UT. Dst then recovered in response to a northward turning of the IMF; note the ~ 2 hour delay in the Dst response due to the solar wind transit time from ACE and magnetospheric effects.

Examining the broader context of the solar wind driver, we identified the passage of a fast forward IP shock at 22:27 UT (at ACE; 22:25 UT at WIND) on 26 July (indicated by the vertical red line in Figure 2.2, characterized by abrupt jumps in the solar wind magnetic field, speed, density, and temperature. The shock was followed by a "sheath" of shocked IP plasma characterized by enhanced, fluctuating field strength, speed, density, and temperature, extending for about 4 hours.

The interval between the two blue vertical lines is the probable time of passage of the ICME that was driving this shock. The signatures of ICMEs have been discussed extensively (e.g. Neugebauer & Goldstein, 1997; Wimmer-Schweingruber *et al.*, 2006; Zurbuchen & Richardson, 2006). Here, we note the abnormally low proton temperature, depressed below the expected temperature for the normal solar wind [Richardson and Cane, 1995] overlaid in red, together with the enhanced magnetic field, smooth rotation in field direction (evident in B_z), and low plasma beta that is characteristic of a MC. Other signatures (not shown here) include enhanced oxygen charge states observed by ACE/SWICS and bidirectional suprathermal electron flows observed by the ACE solar wind plasma instrument. Thus the extended region of southward field driving the main phase of this storm was associated with the passage of a MC. The short period of southward field producing the initial phase of

the storm was associated with the sheath of shocked plasma ahead of the MC. Compressed magnetic fields in sheath regions may be draped around the approaching ICME (e.g. Gosling & McComas, 1987). This may lead to strong out-of-the-ecliptic fields, perhaps accounting for the initial phase of this storm. Two notable features of this event are the high solar wind speeds, reaching ~ 1000 km/s, in the SH and MC, and the overall low solar wind densities compared to average values.

Considering CIRs, regions of compressed plasma formed by the interaction of high-speed streams from coronal holes with the preceding slower solar wind, these can be recognized by their characteristic variations in plasma parameters, including enhancements in the magnetic field strength, plasma density, temperature, and flow deflections lying at the leading edges of corotating high-speed streams (e.g. Forsyth & Marsch, 1999, and reference therein). Examples of major storms in our study driven by CIRs have been illustrated by Richardson *et al.* (2006), so a sample event will not be discussed in the present chapter. For a recent review of CIRs and associated geomagnetic activity, see the special section in JGR Tsurutani *et al.* (2006).

2.3.2 Identify Solar Source Region

To identify the solar sources of the IP structures such as ICMEs that drive the major storms studied, we predominantly used observations from instruments on the SOHO spacecraft. CMEs near the Sun are observed by the LASCO C2 and C3 coronagraphs (Brueckner *et al.*, 1995), which have fields of view of 2 to 6 Rs and 4 to 30 Rs (measured from the solar disk center in units of solar radius), respectively. There were LASCO observations for 80 of the 88 major geomagnetic storms studied. The eight events with LASCO data gaps occurred mostly in 1998 and 1999 when SOHO lost control for many months. To identify the surface features of CMEs in the source region, observations from SOHOs Extreme-Ultraviolet Imaging Telescope (EIT) (Delaboudinire *et al.*, 1995), which images the Sun's corona over the full disk and up to 1.5 Rs, were used, in particular those in the 195 Å passband which is dominated by Fe XII emission and sensitive to a plasma temperature of

about 1.5 MK. In addition to referring to the LASCO CME catalog generated by NASA and The Catholic University of America in cooperation with the Naval Research Laboratory (Yashiro *et al.*, 2004). ([http : //cdaw.gsfc.nasa.gov/CMElist/](http://cdaw.gsfc.nasa.gov/CMElist/)), we also carefully examined all the LASCO and EIT images in a suitable period prior to each storm to search for any eruption features that might not have been included in the catalog and to confirm the nature of the cataloged events. The Michelson Doppler Imager (MDI) (Scherrer *et al.*, 1995) provided photospheric magnetograms.

In addition to SOHO observations, we used "traditional" synoptic data, such as daily NOAA solar event reports, which include data on soft X-ray flares, filament eruptions, and active regions ([http : //www.sec.noaa.gov/ftpdir/indices/](http://www.sec.noaa.gov/ftpdir/indices/)). These data complement and reinforce the SOHO LASCO/EIT observations. We have also used X-ray coronal images made by the Yohkoh Soft X-ray Telescope (SXT) (Tsuneta *et al.*, 2006) while it was available (Yohkoh was permanently lost in December 2001) to search for possible eruption signatures. X-ray imaging observations made by the Soft X-ray Imager (SXI) on the GOES satellites (Pizzo *et al.*, 2005) have also been used when available. For events from February 2003 onward, observations from the Solar Mass Ejection Imager (SMEI) [Jackson *et al.*, 2004; Webb *et al.*, 2006] were used to help track CMEs to larger distances from the Sun than is possible with LASCO and to aid in the identification and timing of the Earth arrival of the ICME and shock and the storm onset.

The method of identifying the solar source of an ICME is straightforward, though the results are ambiguous in some cases. This method is to find a frontside halo (full or partial) CME at a reasonable earlier time, which depends on the transit time of the CME from the Sun to the Earth (e.g. Webb *et al.*, 2000a; Zhang *et al.*, 2003). The justification of this method is that there must be a cause-and-effect relationship between solar and IP events, even though current observations only cover the near-Sun space, through remote sensing, and the near-Earth space through in situ sampling. Model calculations also show a good correlation between CME structures at the Sun and ICME structures at the Earth (e.g. Krall *et al.*, 2006; Yurchyshyn *et al.*, 2006). However, for the purpose of identification, the

lack of imaging observations in the vast region between the Sun and the Earth through which CMEs can travel for days without direct tracking, contributes to the ambiguity of the association between CMEs and ICMEs.

Among the many CMEs observed at the Sun, halo CMEs, seen as an expanding circular bright feature fully surrounding the coronagraph occulting disk (angular width 360°), are believed most likely to hit the Earth (e.g. Howard *et al.*, 1982). The large angular width observed is attributed both to the projection effect and a large intrinsic width, indicating that the CME axis is likely to be directed along the Sun-Earth line, either toward the Earth if originating from the frontside of the Sun or away from the Earth if originating from the backside of the Sun. In addition to "full" halo CMEs, we also consider "partial halo" CMEs (apparent angular width $\geq 120^\circ$) in the solar source identification. To verify the surface source region of a CME, we mainly use EIT observations, which often manifest the CME origin with several eruptive features, including a large scale coronal dimming (e.g. Thompson *et al.*, 1998) and a posteruption loop arcade (the counterpart of the more familiar postflare loop arcade in H α). These eruptive features are often associated with localized coronal brightenings (the counterparts of flares at EUV wavelengths).

Considering the complexity in associating CMEs with ICMEs, we exploited an iterative process with multiple steps. First, we found all candidate frontside halo CMEs within a 120-hour-long search window before the arrival time of the ICME-driven shock (or other upstream disturbance if there was no fully developed shock, or the ICME arrival if there was no upstream disturbance). The 120-hour-long search window corresponds to a 1 AU transit speed of 347 km/s and is large enough to cover most possible CME sources except for extremely slow events. The large search window may produce several CME candidates, but further steps help to distinguish between likely and unlikely associations. The next step is to reduce the search window by estimating the CME transit time based on in situ solar wind velocities at the location of shock arrival. Since fast CMEs tend to decelerate when moving through the slower solar wind, this method will give an upper estimate for the travel time. This method is not applicable to slow ICMEs because the corresponding,

initially slow, CME may be accelerated by the ambient solar wind. In such cases, the full 120-hour window is used. In some unusual cases where there is no front-side halo CME in the 120-hour window, we extend this window even longer to take into account the extremely slow halo CME (e.g., < 200 km/s) at the Sun (the association of these events is usually problematic as discussed later). The third step is that, for each remaining candidate CME in the search window, we consider whether the CME speed at the Sun is consistent with the 1 AU transit speed implied by an association with the 1 AU shock/ICME and with the in situ solar wind speed.

We recognize that the observed CME speed projected on the plane of the sky may not directly indicate the earthward directed speed. Nevertheless, these speeds tend to be loosely correlated. Comparison with statistical studies of the relationship between CME speeds and 1 AU transit times (e.g. Cane *et al.*, 2006; Gopalswamy *et al.*, 2000; Zhang *et al.*, 2003; Xie, 2004; Schwenn, 2005) can help to indicate whether a given CME-shock/ICME association is plausible or unlikely. We also take into consideration the solar source location implied by the CME/eruptive features. For example a central meridian source might be favored over a near-limb source, in particular if an ICME or magnetic cloud is involved in generating the storm. We should emphasize that the CME-ICME associations were considered by the working group members both individually (often using variations on the approach outlined above and taking into account additional information, such as energetic particle observations which may link solar events and interplanetary shocks) and collectively, to reduce the bias and thus improve the reliability of identification.

We again use the storm on 27 July 2004 (Figure 2.2) as an example to illustrate the process of identifying the solar source. The solar wind speed at shock arrival is ~ 900 km/s. If we simply assume that the CME-driven shock travels from the Sun at this constant speed, a travel time of ~ 46 hour is implied, suggesting (since this is a "fast" event at 1 AU) an CME event after 0000 UT, 25 July as the source. Examining the LASCO CME catalog as well as the related images, there was only one halo CME in the search window, at 1454 UT on 25 July. This had a high projected speed (1333 km/s) which was consistent with the

fast ICME seen at Earth allowing for some deceleration in the inner heliosphere. A direct association can also be demonstrated for this event using energetic particle observations which show an increase commencing at the time of the CME (Cane *et al.*, 2006) that reaches peak intensity in the vicinity of the passage of the ICME-driven shock. This CME was associated with a long duration M1.1 soft X-ray flare located at N04°W30°. The eruption at the surface was accompanied by a coronal dimming as shown in the running-difference EIT image (Figure 2.2g, middle). Both long duration flares and dimmings are well known surface manifestations of CMEs. This CME/flare originated in NOAA AR 0652 as indicated in the MDI magnetogram (Figure 2.2g, left).

We should stress that it is not sufficient to use the time of the storm peak together with a plausible 1 AU transit time to estimate the time of the solar source. Rather, it is important to examine and characterize the solar wind structures within which the geoeffective region is embedded and then estimate the source timing. The effect of this distinction is illustrated by the event in Figure 2.2: the peak of the storm is ~ 16 hours after the arrival of the shock and ~ 12 hours after the arrival of the MC. These intervals are a significant fraction of the 1 AU transit times of the shock and ICME. Another point to note is that the two Dst minima in this storm result from two geoeffective regions, in the sheath and MC, associated with a single solar event. Such so called double-dip or two-step storms could be caused by a single ICME as well as multiple CMEs (e.g. Kamide *et al.*, 1998; Farrugia *et al.*, 2006).

2.4 Storms Involving Complex Solar Wind Structures and Multiples CMEs

We classify the solar-IP drivers of the major geomagnetic storms into three broad categories: S-type, M-type, and C-type. S-type events are storms caused by single CMEs/ICMEs such as the 24 July 2004 storm described above. M-type are caused by multiple CMEs/ICMEs as discussed in this section. The C-type are for storms caused by CIRs Richardson *et al.* (2006). For an M-type event, the storm is associated with complex solar wind structures

that appear to involve multiple SHs and/or ICMEs. Two or more CMEs interact with each other in IP space, producing such complex flows (Burlaga *et al.*, 2002; Zhang *et al.*, 2003; Wang *et al.*, 2003). Direct observations of the interaction between two CMEs near the Sun have been reported (Gopalswamy *et al.*, 2001). The M-type events are treated as a separate category from S-type because of the apparent differences in terms of the propagation/arrival of ICMEs, the resulting IP structures and geoeffective components.

One interesting variety of M-type events that we have noted is when a storm is generated by a faster ICME driven shock propagating into the trailing edge of a slower ICME that originated in an earlier event at the Sun. An example is the storm of 8 November 1998 (minimum $Dst = -149$ nT) shown in Figure 2.3. This storm was clearly generated by the region of southward magnetic field between 2100 UT, 7 November, and 0500 UT, 8 November. The ACE plasma and field data show a weak shock at 0736 UT on 7 November followed by a probable ICME commencing at ~ 2100 UT and indicated, for example, by the low proton temperature (black shading), enhanced magnetic field intensity, and enhancement in the solar wind O^7/O^6 ratio. The southward magnetic field in this structure generated the onset of the storm, reaching levels of $Dst \sim -100$ nT. A second, stronger shock, propagating through the ICME passed ACE at 0421 UT on 8 November. The magnetic field in the first ICME was starting to turn toward the ecliptic at this time. However, the combination of the shock compression, which doubled the magnetic field strength and prevented the southward field strength from decaying, and the increase in solar wind speed, enhanced the y-component of the solar wind electric field, thereby strengthening storm activity and producing the peak of the storm. We suggest that ICME-associated plasma forms the post-shock sheath, at least to the end of the interval shown. Note that the field here turned northward, causing Dst to decline rapidly after the storm peak. We associate the shock on 8 November with a 1119 km/s halo CME with a source at N22°W18° on 5 November. Often in such situations, the source of the slower shock/ICME is less easily established. In the case of the shock on 7 November, however, we suggest that a 523 km/s halo CME at 0754 UT on 4 November

originating from a quiet-Sun region associated with a quiescent filament is a likely candidate. We classify this storm as M-type because, although the arrival of the 8 November shock is clearly associated with the peak of the storm, the presence of the southward fields in the preceding ICME is also required to generate the storm.

Before leaving this event, it is worth commenting on the chance juxtaposition of the 8 November shock, Earth and preceding ICME that generated the storm peak. Had the timing been slightly different, the storm peak strength could have been substantially different. For example, had the shock been delayed relative to the ICME by as little as an hour or so, it would have encountered a region of northward field. Hence the shock-ICME interaction would not have contributed to the storm. If the shock had arrived an hour or two earlier, it would have encountered stronger southward fields in the ICME, and an even more intense storm might have been generated. This clearly illustrates that while for S-type events involving one CME, there may be some hope in the future of predicting the geoeffectiveness using solar observations to infer the CME magnetic field structure, a similar prediction is far more difficult for M-type events.

2.5 Results

On the basis of the methods described above, we have identified the solar and IP sources of the 88 major geomagnetic storms during 1996 and 2005.

In Figure 2.4, we show the distribution of the three solar-IP source types for the 88 major geomagnetic storms during 1996 to 2005. The total numbers of S-type, M-type, and C-type events are 53 (60%), 24 (27%), and 11 (13%), respectively. Hence nearly two thirds of these major storms were generated by single events at the Sun and around another quarter involved multiple solar events. Considering S-type and M-type events together, we conclude that 77 ($\sim 87\%$) of the major storms in our study were driven by ICMEs (including the related upstream SHs) and hence originated from eruptive solar events, the remainder being associated with CIRs and hence with coronal holes. This result agrees with previous studies that have concluded that major geomagnetic storms are predominantly caused by

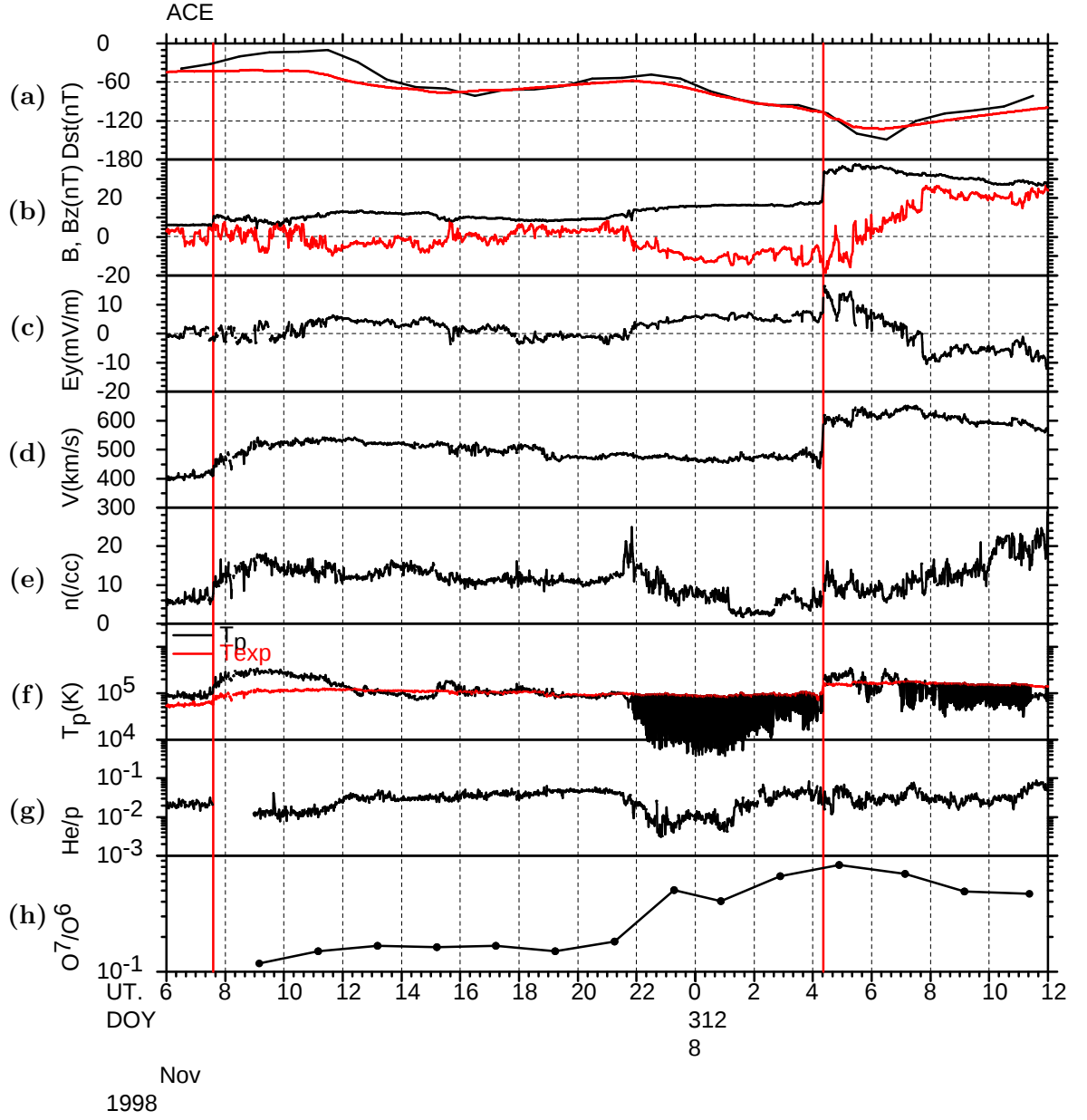


Figure 2.3: Geomagnetic and interplanetary data for the major geomagnetic storm (minimum $Dst = -149$ nT) on 8 November 1998, showing, from top to bottom, (a) the observed Dst (black) with the predicted Dst index using the O'Brien & McPherron (2000) formula overlaid in red, (b) the magnetic field intensity (black) with B_z overlaid in red, (c) the Y-component of the solar wind electric field, (d) the solar wind velocity, (e) density, (f) proton temperature (black) and expected proton temperature (red) with the shaded black shading indicating where the proton temperature falls below the expected temperature, (g) helium/proton ratio, (h) and O^7/O^6 ratio. The two vertical red lines indicate the arrival times of ICME-driven shocks. Here, the peak of the storm is caused by an interplanetary shock (~ 0400 UT on 8 November) propagating through a preceding ICME which has an embedded strong southward magnetic field.

ICMEs and their related structures (Gosling *et al.*, 1991; Tsurutani *et al.*, 1997; Richardson *et al.*, 2001).

Solar-IP Sources of 88 Major Geomagnetic Storms

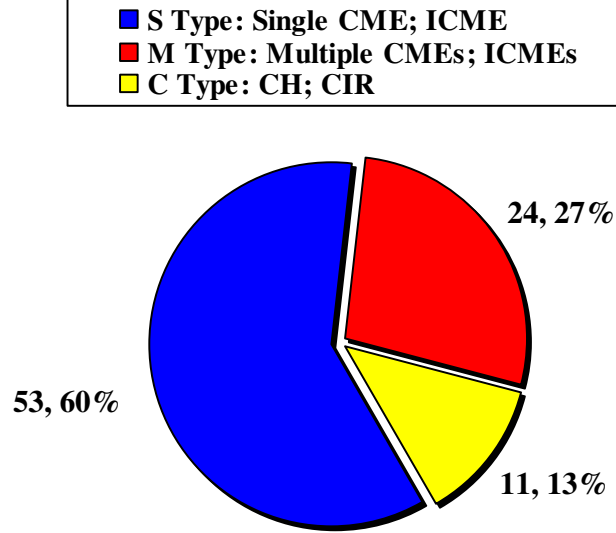


Figure 2.4: Distribution of the three types of solar-IP sources for the 88 major geomagnetic storms during 1996 to 2005.

Nevertheless, we also want to stress the nontrivial fraction ($\sim 13\%$) of these major geomagnetic storms that were driven by CIRs. A detailed analysis of the nine events from 1996 to 2004 has been reported by Richardson *et al.* (2006). This is a somewhat surprising result but it is also a consequence of the -100 nT Dst storm threshold chosen for the workshops; the strongest CIR-associated storm had a Dst minimum of -131 nT so all these events would have been excluded had a lower Dst threshold been chosen. Furthermore, we note that three of the 88 major storms were generated by the interaction of a CIR with an ICME. These were on October 22, 1999; Dst = -237 nT, it also occurs on October 1, 2002; Dst = -176 nT, August 30, 2004; Dst = -126 nT. These three events have been classified as S-type in the table because it is the presence of the ICME that is critical to the generation of the storm.

The year-by-year distribution of event types is shown in Figure 2.5. In 1996, the year of

solar minimum, there was a single major storm driven by a CIR. Otherwise, during the rise, maximum, and declining phases of cycle 23, the major storms were predominantly driven by ICMEs with S-type dominating over M-type. C-type events were observed in 1996 and 1998, were absent during 1999 to 2001 around solar maximum even though low-latitude coronal holes and their associated streams were still typically present (Luhmann *et al.*, 2002), and reappeared in 2002 through 2005 during the declining phase of the cycle. The asymmetry in the number (three versus eight) of CIR-generated storms between the rising and declining phase of the cycle, with more during the declining phase, is typical of other studies (e.g. Richardson *et al.*, 2001). Nevertheless, most major storms were still driven by ICMEs during 2002 to 2005.

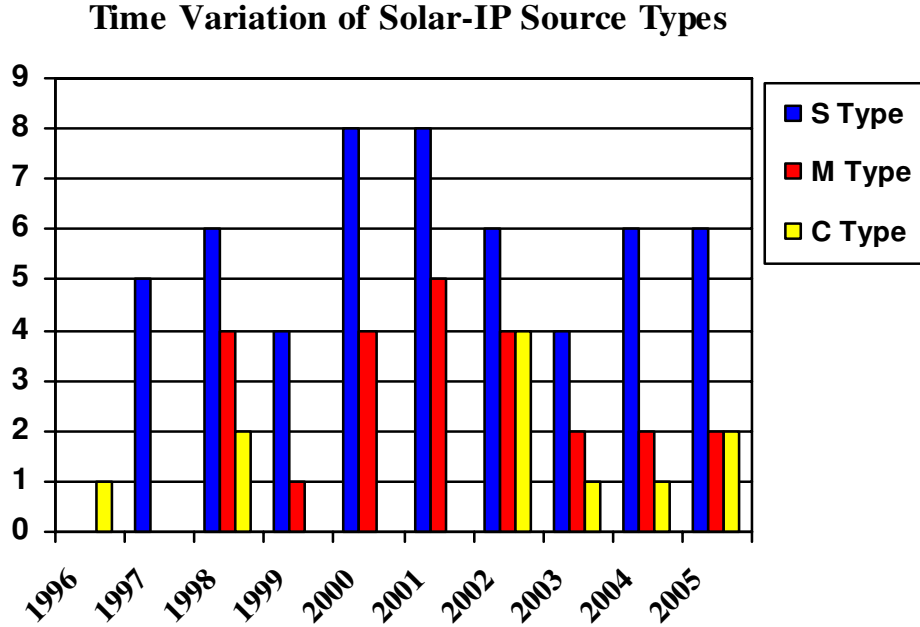


Figure 2.5: Solar cycle variation of the occurrence rate of the three types of solar-IP sources for the 88 major geomagnetic storms during 1996 to 2005.

For the 77 CME-driven storm events, around two thirds (53; 69 %) were S-type and one third (24; 31 %) M-type. The ratio of the numbers of S and M-type events does not show any clear solar cycle variation. Although we might expect M-type events to be more prominent at higher solar activity levels because of the higher CME rate, M-type events

occurred throughout the solar rising, maximum and declining phases, except in 1997, when all five events were S-type. S-type storms are still the most frequent type around solar maximum. The lack of a solar cycle dependence in the occurrence of M-type events may be due to the fact that for at least half of the 24 M-type storms, the responsible multiple CMEs originated from the same active region rather than from separate solar source regions. Such "super" active regions may appear at any phase of the solar cycle.

2.6 Discussions

2.6.1 On Geoeffective Solar Wind Components

For S-type events, the ICME and/or the upstream SH can contribute. We find that the storm peak was driven by the SH in 12 of these events (22 %), by an ICME that is a magnetic cloud in 30 events (57 %) and by a noncloud ICME in 11 events (21 %). Hence a majority of major storms involving a single CME/ICME were driven to storm maximum by a magnetic cloud. For the M-type events, the IP drivers are typically more complex and involve multiple structures. Nevertheless, in most cases the storm driver can be characterized. In rare cases, such as event 10, a single driver among the various structures that pass the Earth (in this case a magnetic cloud) can be identified. A more common situation is that the storm peak is driven by a SH region or an ICME region that appears to include multiple components (indicated by SH(M) and ICME(M), respectively) that presumably reflect the complexity of the solar source. Multi-component SH regions drive nine storms and multi-component ICME or MC regions drive another six storms. The situation illustrated in Figure 2.3 in which a storm is caused by a shock propagating through a preceding ICME, drives the peak of nine M-type storms and hence is responsible for $\sim 10\%$ of all 88 major storms in this study.

Considering the 53 S-type and 24 M-type CME driven storms together, the geoeffective components are MCs in 33 events (43 %), ICMEs without clear cloud signatures in 14 events (18 %), SH regions in 21 events (27 %), and, as noted above, shocks propagating through

preceding ICMEs/MCs in nine events (12 %). Hence consistent with other studies, MCs form the most important class of IP drivers of major geomagnetic storms (Wu & Lepping, 2002; Huttunen *et al.*, 2005). This is despite the fact that only a minority of ICMEs at Earth, in particular around solar maximum, have magnetic cloud signatures (Richardson & Cane, 2004a). The reason is that the magnetic fields associated with magnetic clouds can, if correctly oriented, provide the extended intervals of strong southward fields that drive major storms, such as in Figure 2.2. Other ICMEs typically have less organized, more irregular magnetic fields that may also be less enhanced, and hence noncloud ICMEs are typically less geoeffective. Nevertheless, even if a magnetic cloud is present, it may not drive the peak of the storm if the cloud field orientation is not conducive for storm generation. For example, in event 5, it is the sheath ahead of the magnetic cloud that drives the peak of the storm. More than half of the major storms are associated with other structures which have less organized magnetic structure, and hence in principle have less "predictable" geomagnetic consequences (Huttunen & Koskinen, 2005).

2.6.2 On Solar CMEs Associated With Major Geomagnetic Storms

Except for the ~ 10 % of events driven by CIRs, all the other major geomagnetic storms in our survey were caused by IP transients following solar CMEs. After excluding events that occurred during LASCO data gaps, we were able to identify 68 CMEs that were the likely solar sources of these storms. Apparently, these 68 CMEs were the most effective in producing geomagnetic storms among thousands of CMEs observed during 1996–2005. When summarizing the properties of these CMEs, only the presumed principle CME (shown as the first CME in the list of possible multiple sources in the event table) was included for M-type events.

Considering the apparent angular size of these CMEs, 46 (68 %) were full halo CMEs and 22 (32%) were partial halo CMEs. Clearly, partial halo CMEs should be considered when searching for the solar drivers of major geomagnetic storms. During the same period, LASCO observed 1187 halo CMEs of which 378 (32 %) were full halos and 809 (68 %) were

partial halos. Comparing with the number of similar CMEs that produced major storms, we estimate that about one out of eight full halo CMEs (or one out of four frontside full halo CMEs, assuming that around half of halo CMEs originate on the backside of the Sun) will cause a major geomagnetic storm, and about 1 in 36 partial halo CMEs will do so. If all LASCO CMEs, 10,410 in total in the period of interest, are considered, on average only 1 out of ~ 150 CMEs will cause a major storm. Since halo CMEs comprise only a small fraction of all CMEs observed, it is practical to use these relatively rare events to predict the interception of an ICME by the Earth, and hence the possible generation of a geomagnetic storm. However, there is certainly not a one-to-one association between halo CMEs and ICMEs at Earth. About 15 % of frontside halo CMEs may not intercept the Earth, and some 20 % of ICMEs are not preceded by identifiable frontside halo CMEs (Schwenn, 2005). Furthermore, when an ICME does intercept the Earth, the magnetic field configuration still has to be conducive for the generation of a major storm. The ICME rate at Earth (Cane & Richardson, 2003), far exceeds the rate of major storms, for example by a factor of ~ 4 around solar maximum.

In Figure 2.6, we display the speed distribution of the 68 CMEs associated with major geomagnetic storms. Remarkably, the distribution has a wide range from ~ 60 km/s to ~ 2800 km/s with evidence of a peak at about 900 km/s. The average (median) speed of the 68 CMEs is 945 km/s (875 km/s). A similar average speed (855 km/s) was obtained by Gopalswamy (2006) for a set of 55 geoeffective CMEs. For comparison, the average (median) speed of all 10410 CMEs in the study period is 472 km/s (410 km/s), and the average (median) speed of all 1187 halo CMEs is 767 km/s (636 km/s). The difference between the speeds of halo CMEs and the general population of CMEs is probably due to the relatively low detection rate of slow halo CMEs; a slow CME tends to be narrower and thus may fall below the LASCO detection threshold when it expands beyond the occulting disk as it has to propagate further from the Sun to become a visible halo (Webb & Gopalswamy, 2006). The major storm-associated CMEs are on average around twice as fast as the all-CME average, in agreement with recent results (Webb, 2002; Yashiro *et al.*, 2004). Forty-five (66

%) of the 68 major storm-associated CMEs have speeds in the LASCO C2/C3 fields of view that exceed 600 km/s. These properties are consistent with the expectation that major geomagnetic storms are usually due to fast halo CMEs.

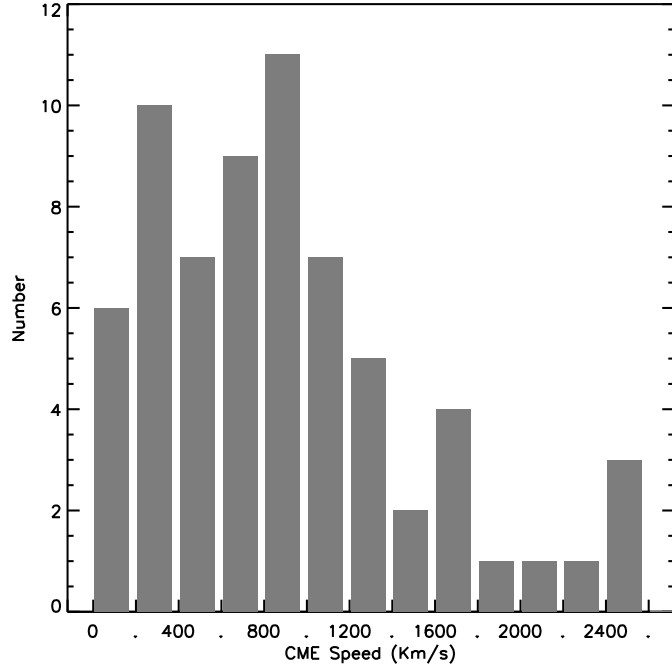


Figure 2.6: Distribution of the plane of the sky speeds for the 68 CMEs observed by SOHO/LASCO that resulted in major storms.

Nevertheless, the relatively small difference (~ 200 km/s, compared with the breath of the distributions) between the average speeds for all halo CMEs and major storm-associated CMEs suggests that strongly geoeffective halo CMEs cannot necessarily be distinguished from other halo CMEs on the basis of their speed alone, as discussed earlier by Zhang et al. [2003]. Further, some very slow CMEs, though a small faction, can also generate major storms. Twelve (18 %) of the 68 storm-associated CMEs had apparent speeds of less than 300 km/s. These results emphasize the fact that speed alone is not the major factor determining geoeffectiveness. Rather, the configuration of the embedded magnetic fields is also important, as exemplified by the fact that most of these storms associated with slow CMEs resulted from slow magnetic clouds at the Earth with speeds comparable to the ambient solar wind.

Considering the association of major storms with GOES soft X-ray flares, we find that among the 77 CME driven storms, 19 (25 %) were associated with X-class flares, 17 (22 %) with M-class flares, 19 (25 %) with C-class flares, and 22 (28 %) with either minor (B or A-class), or with no evidence of a flare. We conclude that major (M or X-class) flares were associated with about one half of our major storms and that around a third of the storms were not accompanied by a flare or only by a minor flare. Therefore using flares, the traditional indicator of solar activity, to predict geomagnetic storms is often far from satisfactory (Gosling, 1993).

2.6.3 On the Solar Surface Source Regions Associated With Major Geomagnetic Storms

Figure 2.7 summarizes the nature of the solar surface source regions where the major storms in our study originated. For three of the 88 events, there were insufficient data (e.g., data gap in LASCO/EIT observations, and no major flares reported in a plausible time window) for the source to be inferred. In the case of Mtype events, we only include the source of the principle CME. We find that 54 storms (~ 63 %) originated in active regions, 11 (13 %) originated in quiet Sun regions, and 11 (13 %) were associated with coronal holes. Here, quiet Sun region is a general reference to any coronal region other than active regions or coronal holes. It should be noted though that even when a CME originates outside an active region, it is usually associated with a quiescent filament or filament channel overlying a magnetic inversion line in the photosphere. For the remaining nine (11 %) events we were unable to identify any solar surface signature and hence the nature of the source region is unknown. Thus while half of the major geomagnetic storms originated in active regions, a similar number originated outside active regions.

Nevertheless, active regions remain the source of the largest storms. The 10 largest storms (minimum Dst ≤ -271 nT) during 1996 to 2005 were all associated with active regions. For comparison, the largest storm that originated from a quiet Sun region reached Dst = - 237 nT. Furthermore, the largest storm with an unknown surface source attained

Solar Surface Source Regions of Storms

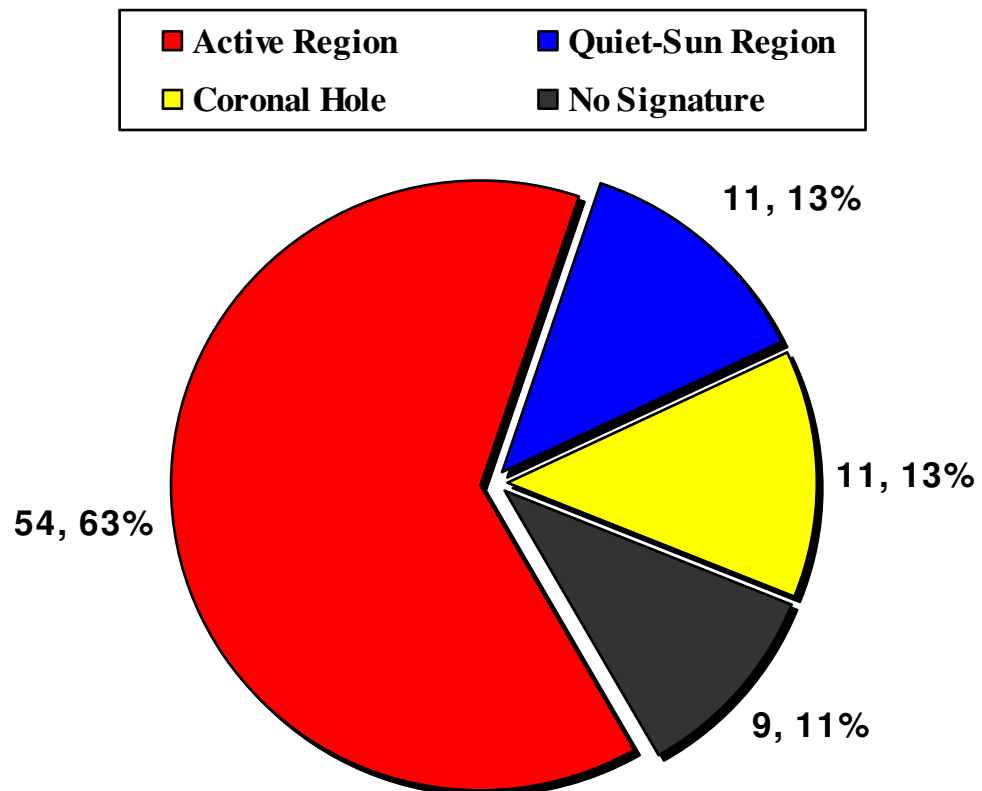


Figure 2.7: Types of solar surface source regions for the 88 major geomagnetic storms during 1996-2005.

Dst = - 182 nT, and the largest storm from a coronal hole source had a minimum Dst of only - 131 nT.

In Figure 2.8, we show the heliographic distribution of the source regions (Column 10 of Table 1). This distribution includes the 65 CMEs with identified surface sources. The other 23 events are excluded because they were associated with coronal holes (11 events), or unidentified sources (nine events), or occurred within solar data gaps (three events). The source locations lie within 35°N to 58°S latitude for active region (red symbols) and quiet Sun sources (blue symbols), and 61 of the 64 source regions (95 %) lie within 30 ° from the equator. A possible explanation is that CMEs originating from higher latitudes propagate into the high latitude region of the heliosphere and do not intercept the Earth.

Considering the longitudinal distribution, 56 of the 65 source regions (86 %) lie within 45 from central meridian, 49 (75 %) within 30°, and 34 (52 %) within 15°. Hence the vast majority of major storms arise from solar sources that are close to central meridian. The sources also show an east-west asymmetry that favors the western hemisphere and reinforces the similar result from the study of Zhang *et al.* (2003). Specifically, the sources extend to 85°W, but only to 58°E, and 43 lie on the western hemisphere, compared with 20 on the eastern hemisphere (two events are at the central meridian). Hence the ratio of number of western to eastern sources is $\sim 2:1$. The average (median) longitude of all the 65 events studied is 12°W (8°W). Geoeffective CMEs could be from far western regions but not from far eastern regions. This east-west asymmetry seems to be a general feature of the ICMEs that intercept the Earth, regardless the strength of geoactivity (Wang *et al.*, 2002; Cane & Richardson, 2003). One possible explanation is that this asymmetry results from the deflection of CME trajectories by the spiral IP magnetic field (Wang *et al.*, 2004).

2.6.4 Implication for Forecasting Major Geomagnetic Storms

What are the implications of this study for forecasting major geomagnetic storms using solar observations? First, there may be a misconception that a major geomagnetic storm must be caused by an unusually fast halo CME from a strong active region accompanied by

Surface Source Regions of Major Geomagnetic Storm

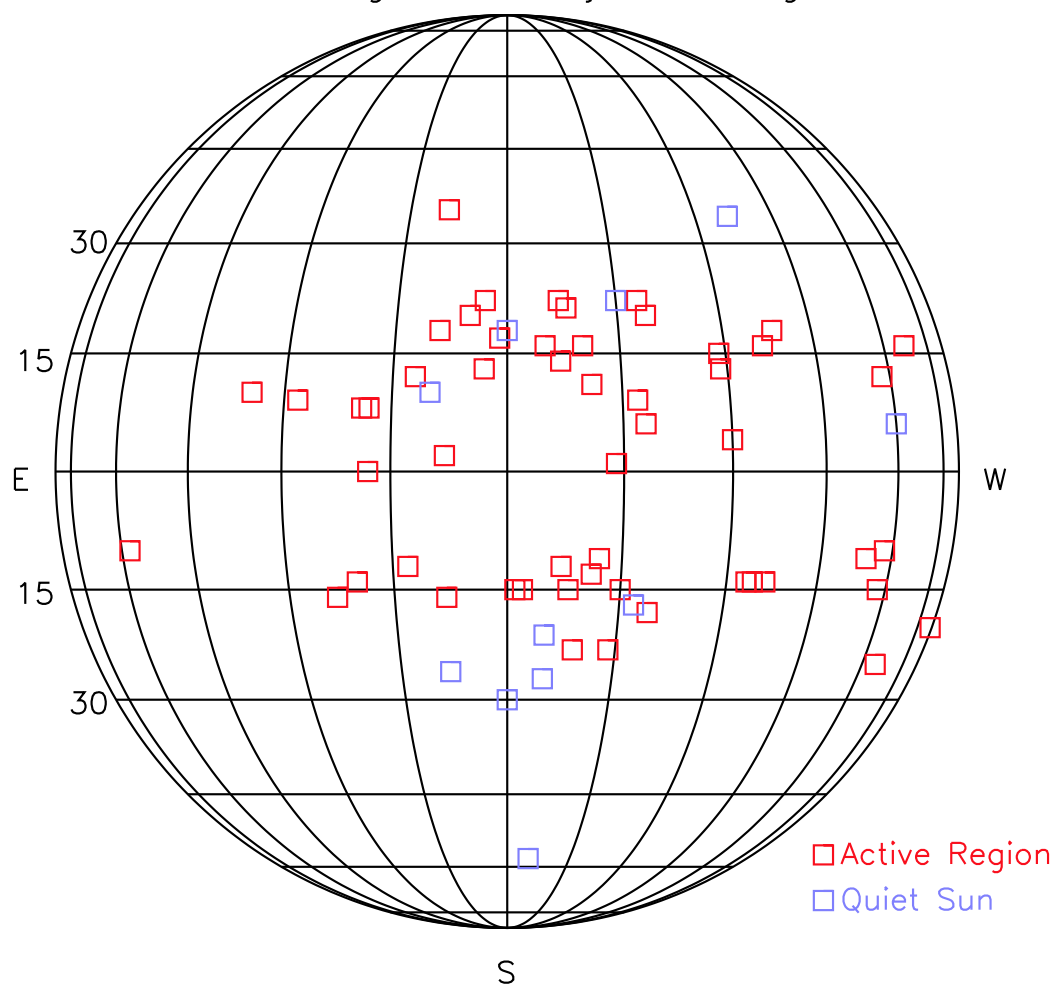


Figure 2.8: Heliographic locations of the 65 identified surface source regions for the CMEs that resulted in major geomagnetic storms during 1996 to 2005.

various energetic eruptive signatures (e.g., major solar flares). Except for the largest storms, this was not the case for many of the major storms ($Dst \leq -100$ nT). In fact, some of these storms were caused by moderate speed CMEs that may have originated outside of active regions, as well as by CIRs associated with coronal holes as described earlier. A central reason is that the driving electric field y -component depends on both the solar wind speed and B_s , but the variation of the size of B_s is greater than that of the solar wind speed. Furthermore, activity is suppressed when the IMF is northward, so a fast ICME with a predominantly strong northward field will not generate a major storm. The size of a storm also depends on the time variation of the southward field component. Thus a relatively slow moving MC with an extended region of enhanced southward field (such as event 15) can generate a major storm. Hence the speed of a halo CME alone is an inconsistent predictor of a major geomagnetic storm. Nevertheless, faster CMEs at the Sun are more likely to generate stronger storms because of their tendency to be associated with stronger magnetic field strengths and hence southward field components. It has been found that faster CMEs are statistically better correlated with parameters characterizing the geoeffectiveness (e.g. Yurchyshyn *et al.*, 2004; Kim *et al.*, 2005; Moon *et al.*, 2005). A combination of CME speed and magnetic field in ICMEs seem to have a high correlation with Dst index (Gopalswamy, 2006). A major advance would be to be able to "predict" the interplanetary magnetic field configuration at 1 AU, in particular for S-type storms involving only one CME/ICME, based on solar observations.

In the case of storms that involve more than one CME/ICME, a complicating factor for forecasting is that it is the details of the magnetic structures formed by the interaction of these transients (and their associated shocks), both with each other and with the ambient solar wind, that determine the resulting level of geomagnetic activity. The precise path of the Earth through the structure is also a factor. Even with a relatively complete MHD simulation of two CMEs launched toward the Earth, it would be difficult to model the resulting fields at 1 AU on the necessary few hour timescales. Information from upstream spacecraft would help to assess the likely geomagnetic impact, but the interacting structures

may still evolve before reaching the Earth.

2.7 Summary

We have investigated the solar and IP sources of the 88 major geomagnetic storms ($\text{Dst} \leq -100$ nT) that occurred during 1996 to 2005 with the aim of providing a list of associations that is as reliable as possible and is intended to provide a basis of future studies by the LWS CDAW participants and others. By combining remote sensing solar observations, in situ near-Earth solar wind observations, and the wide range of experience of the Working Group members, we were able to identify with reasonable confidence the chain of sources for about 83 % (73) of these events, although the detailed one-to-one association could not be established for those complex events involving multiple CMEs and ICMEs. We are uncertain of the origin of the other 17 % (15) of the storms, mainly because their driving CMEs were not associated with noticeable eruption signatures at the solar surface. Detailed parameters of the solar and IP sources for each of the 88 major geomagnetic storms have been provided. The main results are as follows:

On the basis of the overall solar and IP properties, the sources can be divided into three broad categories: S-type, driven by single CMEs and their IP counterparts; M-type, associated with multiple CMEs/ICMEs, and C-type due to CIRs driven by high speed streams from coronal holes. The total numbers of S-type, M-type, and C-type events are 53 (60 %), 24 (27 %), and 11 (13 %), respectively.

Of the 68 identified LASCO CMEs associated with major storms, 46 (68 %) were full halo CMEs, and 22 (32 %) were partial halo CMEs. Their speeds have a wide range (60 km/s to 2800 km/s). The average speed (945 km/s) is about twice as fast as the average for all LASCO CMEs. About half (47 %) of these storm-associated CMEs were accompanied by major (X and M-class) flares.

For the 85 storms for which we could identify the solar surface source, we find that 54 (~ 63 %) originated in active regions, 11 (13 %) in quiet Sun regions associated with

quiescent filaments, and 11 (13 %) were associated with coronal holes. The other 9 (11 %) events originated from unknown surface source regions.

Major geomagnetic storms predominantly originated from sources near central meridian (e.g., 86 % from within 45° , and 75 % from within 30° of central meridian) but showed an east-west asymmetry with around twice as many storm sources originating on the western hemisphere than on the eastern hemisphere.

The content of this section has been published in the Journal of Geophysical Research (Zhang *et al.*, 2007b). Some of our work, relevant but not included here, is also published in Zhang *et al.* (2007a, 2008)

Chapter 3: Observational Study Two: Sizes and relative geoeffectiveness of interplanetary coronal mass ejections and the preceding shock sheaths

3.1 Introduction

Following the work presented in Chapter 2, we made statistical studies of the size property of geo-effective ICMEs. My contribution to this study to identify (1) the starting time of the sheath, (2) the starting time of ICMEs and (3) the ending time of ICMEs for all the events used in the statistics. I developed the algorithms and programs to read and analyze data from ACE and WIND spacecrafts. The result of this study provides a better understanding of the relative importance of sheath regions and ICME regions in producing geomagnetic storms. This new result is published in the Journal of Geophysical Research Letter (Zhang *et al.*, 2007a)

Following initiation and acceleration close to the surface of the Sun, coronal mass ejections (CMEs) propagate through and expand in the heliosphere, where the ambient solar wind affects their subsequent kinematic and morphological evolution. These CMEs, also called ICMEs (interplanetary CMEs) in interplanetary space, often drive an upstream shock or wave and form a compressed sheath region between the shock/wave front and the driving ICME (Gosling *et al.*, 1990; Bothmer & Schwenn, 1996). The magnetic and plasma properties of ICMEs and the associated sheaths, in particular the strength and duration of the dawn-dusk solar wind electric field, determined by the southward magnetic field component (B_s), regulate the geoeffectiveness of these structures (Akasofu, 1981). We study the basic dimensional properties (duration and radial size) of both ICMEs and sheaths, and their relative geoeffectiveness. A statistical knowledge of these important parameters will help

us understand the fundamental processes of CME evolution in interplanetary space.

Because of the higher internal magnetic pressure with respect to the background solar wind, ICMEs expand with heliocentric distance (Bothmer & Schwenn, 1998; Liu *et al.*, 2005; Wang *et al.*, 2005; Forsyth *et al.*, 2006). The pre-eruption CME structure, which lies close to the surface of the Sun, is usually only a fraction of a solar radius in size, e.g, the size of an active region or a filament. During eruption, a CME accelerates to hundreds of km/s and reaches a height of several solar radii in tens of minutes, driven by strong internal forces. The radial size of a CME is about a few solar radii at the end of the acceleration phase. This is followed by the so-called propagation phase, with relatively small changes of velocity and almost constant angular extension, whose small variations are largely influenced by the interaction with the ambient solar wind (Zhang & Dere, 2006). Previous studies suggest that the average radial size of ICMEs at 1 AU is about 0.25 AU (Liu *et al.*, 2005; Forsyth *et al.*, 2006; Lepping *et al.*, 2006). While a great deal has been learned about the size of ICMEs, the size distribution of the preceding sheath region is relatively less well studied. Nevertheless, it is known that the sheath size is equivalent to the standoff distance of a shock in front of an obstacle (in this case, the ICME itself) that depends on the shape of the obstacle and Mach number of the flow relative to the obstacle (Russell & Mulligan, 2002). Furthermore, little is known about the relationship between these sizes and the properties of their solar drivers.

3.2 Observations

The ICMEs used in this study are a subset of the 88 events that produced intense ($Dst \leq -100$ nT) geomagnetic storms during 1996 to 2005 (Zhang *et al.*, 2007a). The interplanetary drivers of these intense geomagnetic storms fall into three broad categories: (1) "S-type" (53 events), in which the storm is associated with a single ICME and a single CME at the Sun; (2) "M-type" (24 events), in which the storm is associated with a complex solar wind flow which may include multiple ICMEs and sheaths, and may be the result of multiple halo

CMEs launched from the Sun in a relatively short period which happen to interact with each other; and (3) "C-type" (11 events), in which the storm is associated with a corotating interaction region formed at the leading edge of a high speed stream originating from a coronal hole (Richardson *et al.*, 2006). Note that a 5-category classification of solar wind drivers of geomagnetic storms, including moderate storms, has been made by Bothmer and Zhukov [2006, cf. Figure 3.53]. For the purpose of this study, we have used only the S-type events, because of the simplicity of the interplanetary driver, and because their size and driver structure are not affected by any preceding and/or trailing transients. Of the S-type storms, we here study the 46 events for which data are available from the ACE spacecraft.

For each of these events, we identified three critical times: (1) The arrival time of the ICME-driven shock (or wave), giving the start time of the sheath; (2) The ICME arrival time, also indicating the trailing edge of the sheath, and (3) The ICME ending time. The shock/wave arrival time is obtained from examining the solar wind data upstream of the ICME for sharp discontinuities or more gradual increases in the solar wind speed, temperature, density and magnetic field intensity. We also referred to the ACE shock list (<http://www.ssg.sr.unh.edu/mag/ace/ACElists/obslist.html>). Note that preceding disturbances driven by slower ICMEs may not have steepened into shocks at 1 AU. To identify the start and end times of the ICME and hence estimate the duration of the ICME, we have used a combination of ICME signatures, including an enhancement of the magnetic field with a smooth rotation through a large angle, low field variance, abnormally low proton temperature and enhanced oxygen and iron charge states Wimmer-Schweingruber *et al.* (2006); Zurbuchen & Richardson (2006). We find that, although most of the signatures generally indicate a consistent starting time for a CME, the ending time may be less well defined. In this situation, for consistency, we use the trailing edge of the enhanced and smooth magnetic field to define the ending time of the ICME. Once the ICME region boundaries are identified, it is straightforward to calculate the linear size of the ICME features by integrating the observed solar wind speed with time during ICME passage (ACE data with 16-second resolution are used in this calculation). The size of the sheath

can be determined in a similar manner.

3.3 Results

3.3.1 Duration and Size of Sheaths and ICMEs

The distributions in Figure 3.1 and figure 3.2 show, respectively, the durations and radial sizes of the sheaths, ICMEs and the sheath-ICME combined, for the 46 events studied. The total duration of the sheath and ICME has a wide variation from 12.9 to 66.2 hr with an average (median) value of 41.2 hr (41.6 hr). Most events (34/46, or 74 %) have durations between 30 and 60 hours. The total sizes range from 0.12 to 0.73 AU with an average (median) value of 0.51 AU (0.51 AU). Most events (39/46, or 85 %) have sizes between 0.3 and 0.7 AU. There are some events with remarkably long durations and/or large radial sizes. In particular, there are two events with durations of more than 60 hr, and four events with sizes larger than 0.7 AU.

Considering the two components separately, the ICME durations range from 8.0 to 62.0 hr with an average (median) value of 30.6 hr (28.0 hr). The corresponding sizes range from 0.08 AU to 0.63 AU with an average (median) size of 0.37 AU (0.37 AU). The sheath durations range from 2.6 to 24.5 hr with an average (median) value of 10.6 hr (11.0 hr). Sheath sizes range from 0.03 AU to 0.31 AU, with an average (median) value of 0.13 AU (0.14 AU). The distributions of these sizes are not regular enough to allow a good functional fit to the profiles, mainly because of the limited number of events considered. Nevertheless, the average sizes calculated represent well the most probable sizes of these components as can be seen in Figure 3.1 and Figure 3.2. The average size (duration) of the ICMEs is 2.8 (2.9) times as large as that of the sheaths. We do not find a correlation between ICME and sheath sizes or durations; the correlation coefficient is 0.06 for radial size and 0.21 for duration.

We have also investigated the relations between the properties at 1 AU and close to the Sun. However, the results obtained are generally of marginal significance. The ICME size

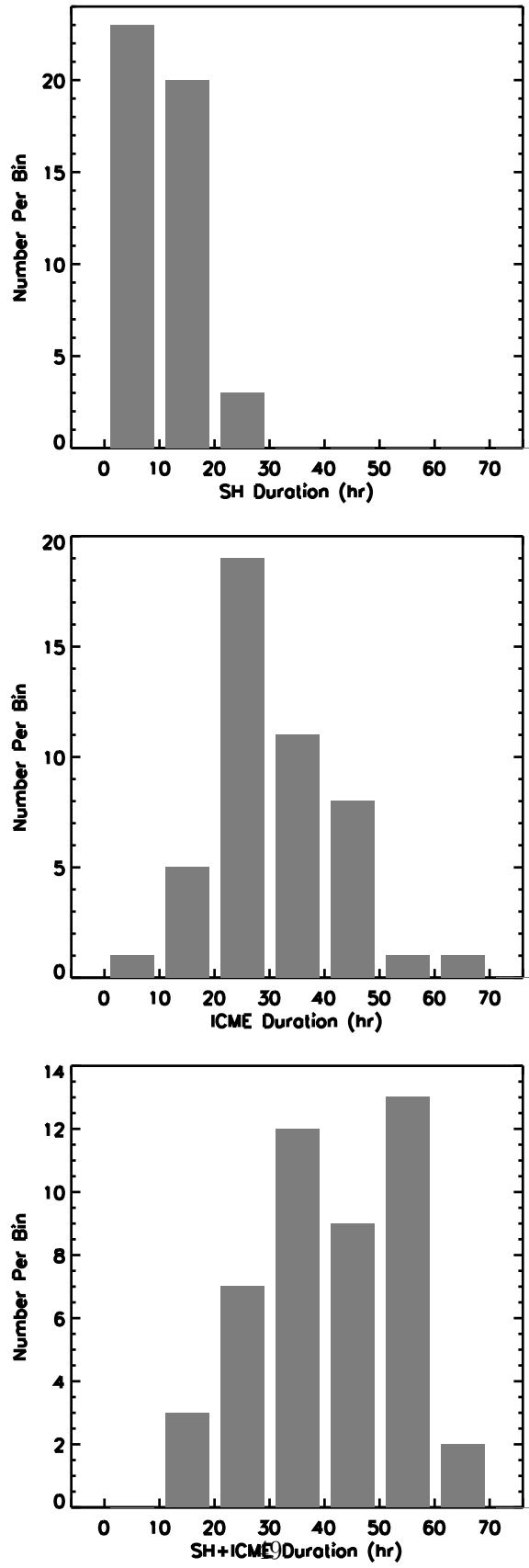


Figure 3.1: Distributions of the durations of (top) the shock sheaths preceding ICMEs, (middle) ICMEs, and (bottom) the entire transients (combined sheath and ICME) for the 46 single type solar-interplanetary drivers leading to intense geomagnetic storms in 1996 to 2005.

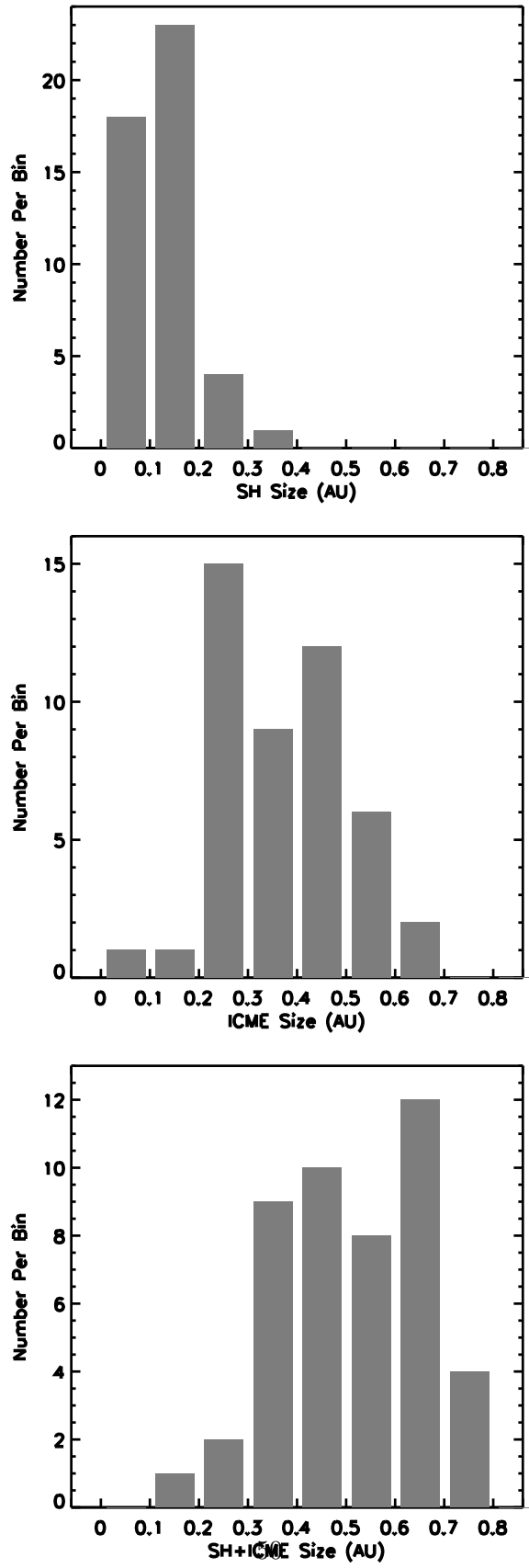


Figure 3.2: Distributions of (top) the radial sizes of sheaths, (middle) ICMEs, and (bottom) the entire transients.

has no correlation with the speed of corresponding source CME (correlation coefficient = 0.06). Furthermore, there is no correlation between the sheath size and the speed of the source CME at the Sun (correlation coefficient = - 0.12). Considering the geometric effects, we might have expected some relationship between ICME or sheath size and the longitude of source region, assuming this is a reasonable proxy for the direction of motion of the CME/ICME through the heliosphere. In particular, we might expect a spacecraft to pass through the nose of the sheath and central part of the ICME for an event originating near central meridian, and through the flanks of the shock and ICME for an event originating some distance from central meridian, potentially giving larger sheath and ICME durations and sizes. However, we find no correlation between ICME size and the longitude of the source CME (correlation coefficient = 0.09). A similar result is found between the sheath size at 1 AU and the longitude of the source CME (correlation coefficient = 0.11). There is a very weak negative correlation between the sheath radial size and the solar wind speed within the sheath (correlation coefficient = - 0.26).

3.3.2 Relative Geoeffectiveness of Sheaths and ICMEs

To estimate the geoeffectiveness of the sheaths and ICMEs, we use the well-known ε parameter, which is a good proxy of the rate of energy input to the magnetosphere (Akasofu, 1981). This parameter is given by

$$\varepsilon = VB^2 \sin^4(\theta/2) l_0^2 \quad (3.1)$$

where V , B , θ , and l_0 denote the solar wind speed, the solar wind magnetic field magnitude, the polar angle of the magnetic field vector projected onto the Y-Z plane, and $l_0 = 7$ RE (Earth radius). The solar wind parameters used here are in GSE coordinates rather than the usual GSM coordinates, in order to remove the seasonal effect due to the orientation of the Earth's dipole and thus focus on the intrinsic geoeffectiveness of the structure of

interest. The total energy input during a certain period is obtained by integrating ε during the period of interest. In Figure 3.3, we show the distribution of the total energy input provided by the sheath and ICME combined for 44 of the events studied (the plasma data are corrupted for the other events). The total energy inputs range from 6.0×10^{18} J to 6.4×10^{19} J with an average (median) value of 1.4×10^{19} J (1.3×10^{19} J). Evidently, 6.0×10^{18} J is the lower cut-off of the energy distribution for these intense geomagnetic storms. There is a good correlation between the total energy and peak (minimum) Dst value (correlation coefficient = - 0.68). Such a correlation between the peak Dst value and the integrated input is expected since Dst is determined by parameters similar as ε .

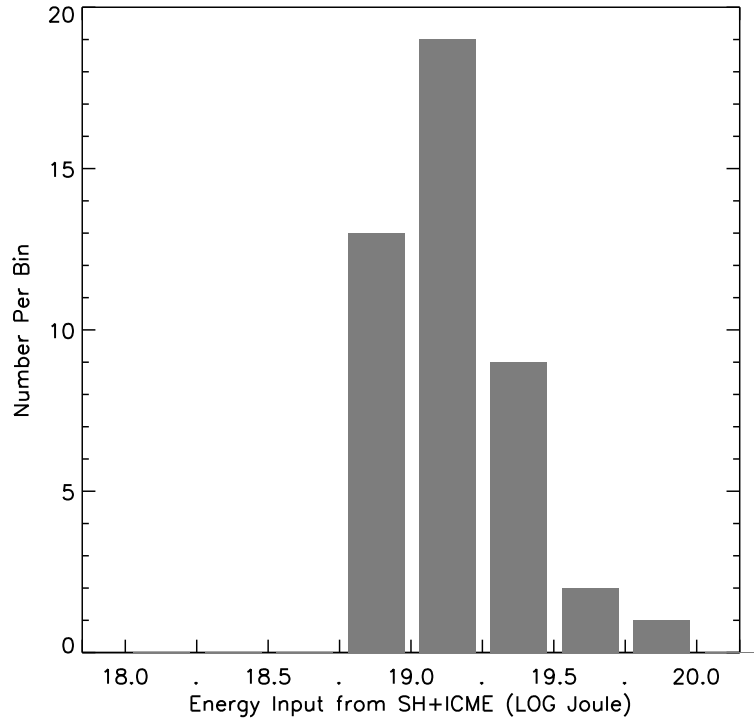


Figure 3.3: Distribution of the calculated total energy input into the Earth's magnetosphere from the entire interplanetary transients or sheath and ICME combined.

In Figure 3.4, we show the distribution of the percentage of the total energy input into the magnetosphere contributed by ICMEs during these intense storms. The percentage due to ICMEs ranges from 2% to 99% with an average (median) value of 71% (80%). For about half of the events studied (23 out of 44), the ICME contributes more than 80% of

the total energy input, whereas for only 2 events, the sheath contributes more than 80%. Evidently, the ICME usually dominates energy input into the magnetosphere during these storms. Nevertheless, sheaths remain an important energy source for these geomagnetic storms, contributing about 29% of the total energy input on average. It turns out that the relative contribution is mainly caused by the amount of the time spent within each of the structures. The power input, averaged with time, is almost equal in the sheath and ICME. It is about 1.6×10^{14} W in both components.

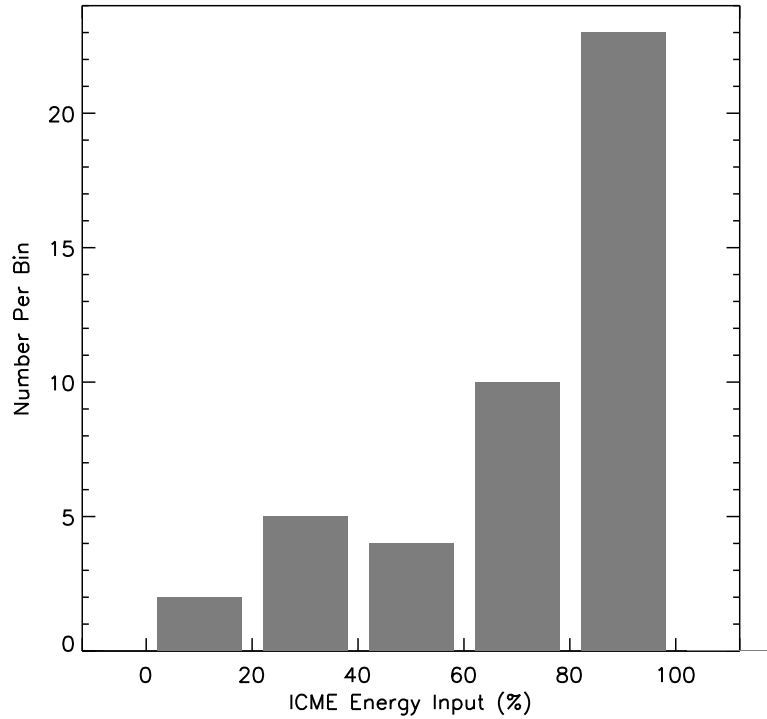


Figure 3.4: Distributions of the percentage of calculated energy input into the magnetosphere from ICMEs with respect to that from the sheath and ICME combined.

3.4 Summary and Discussion

This study shows that there is a wide distribution in the radial sizes of both ICMEs (0.08 to 0.63 AU) and sheaths (0.03 to 0.31 AU), as well as the entire transients combining the two components (0.12 to 0.73 AU), associated with S-type intense geomagnetic storms.

The average ICME size we obtain is 0.37 AU, which is significantly larger than, but not inconsistent with, the ~ 0.25 AU size reported by other researchers (Forsyth *et al.*, 2006; Lepping *et al.*, 2006). The difference may be a selection effect due to the fact that all the 46 events used in this study produced major geomagnetic storms, and thus may possess different properties, including perhaps a larger physical size that may help to sustain geoeffective solar wind conditions, than the general population of ICMEs. While ICMEs are the dominant transient features producing major geomagnetic storm, sheaths are also important, contributing about 29 % of the total energy input into the magnetosphere during these storms.

The solar drivers of these transients are usually CMEs launched from the front-side of solar disk and with one part moving along the Sun-Earth line. However, we find that there is almost no correlation between ICME radial size and CME speed, even though CME speed is moderately correlated with the original CME size close to the Sun (Yashiro *et al.*, 2004). Further, there is also no correlation between ICME size and the CME source longitude relative to central meridian, even though it might be expected that the spacecraft trajectory through the structures will influence the inferred size along this trajectory. Therefore, it seems that the size of ICMEs determined from observations at 1 AU is not well related to the CME speed and/or size observed by SOHO/LASCO coronagraphs close to the Sun. Several factors may be involved. The ICME size at 1 AU may be largely determined by its evolution in interplanetary space, for example, by the expansion rate, which depends on the pressure imbalance between the interior of the ICME and the ambient solar wind. The trajectories of the observing spacecraft may vary in latitude relative to the axis of the ICME, and this axis may also be inclined to the ecliptic.

There is also almost no correlation between sheath and ICME sizes. This may not be too surprising since the dynamics controlling the evolution of ICMEs (e.g., expansion) (Forsyth *et al.*, 2006) and sheaths (e.g., compression, field line draping over the ICME) (Russell & Mulligan, 2002; Kaymaz & Siscoe, 2006) are totally different. We would expect the standoff distance between the shock front and ICME leading edge to increase as the angle

between the nose of the shock and the observer increases, but this requires multiple-point observations of the same event.

The content of this chapter has been published in the Journal of Geophysical Research (Zhang *et al.*, 2007a)

Chapter 4: Observational Study Three: STEREO Observations of CME Evolution

4.1 Introduction

This chapter presents my main observational study in this dissertation, which focuss on the CME evolution in interplanetary space based on STEREO observations. As mentioned before STEREO spacecraft are the most suitable to study the kinematical and morphological evolution of CMEs because they provide not only a global view of CMEs through a much larger field of view, but also the 3-D perspective from two vantage points in space. The result in this chapter will provide a better understanding of the acceleration or deceleration of CMEs. In particular, our study is the first of its kind to study both acceleration and expansion of CMEs in interplanetary space. Thus, our result will be useful for creating realistic space weather prediction models using solar observations.

4.2 Observations

In this chapter, I use the data from SECCHI/COR2, and SECCHI/HI1 to measure CME parameters from 5 solar radii to about 80 solar radii. Further, I use other instruments, including ACE, STEREO/IMPACT, and STEREO/PLASTIC to study the corresponding ICMEs in-situ. From SECCHI images, the position of CMEs can be obtained. When the positions are measured in both A and B, the 3-D position can be calculated by using the basic triangulation method. Then, the 3-D velocity and 3-D acceleration can be calculated by taking the first and second derivative of the position versus time respectively. The 3-D position, 3-D velocity and 3-D acceleration from SECCHI are thus free of projection effect, which are of significant improvement over previous studies using SOHO observations. In

this dissertation, I have studied four such events. A detailed observational study of each of these events will be presented later.

Figure 4.1 shows one example of such observations: the snapshot images of a CME on March 25, 2008. This event occurred in the eastern hemisphere. SECCHI detected this event from EUVI to HI 1. Therefore, this CME is one good event for studying the kinematical and morphological CME evolution from the sun through interplanetary space.

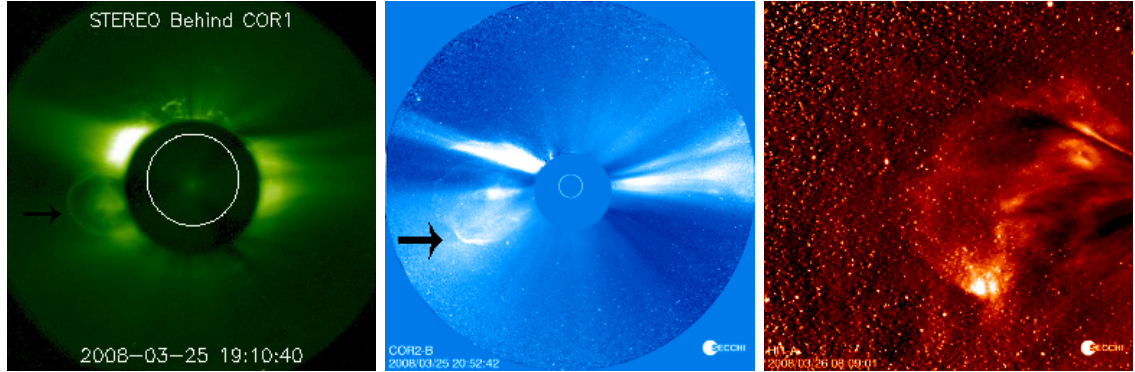


Figure 4.1: Three snapshots of the 2008 March 25 CME taken by COR1 B(*left*), COR2 B (*middle*) and HI1 A (*right*), respectively. Credit: NRL

In the next section, I present the methodology in measuring and characterizing CMEs from STEREO/SECCHI.

4.3 CME Measurement Using the Circular Fitting Method and Its Limitation

The simplest way to measure a CME is the circular fitting method. Dere *et al.* (1999) reports that CMEs show circular pattern based on LASCO and EIT from SOHO spacecraft. One simple method of measuring CMEs in 3-D is to assume that the CME has a spherical shape. The circular fitting method can be applied to STEREO A and B images to calculate the following parameters: the centroid of the CME (Z), and the radius of the CME (a). The radius means the distance from the centroid of the CME to the leading edge. In this model,

the velocity at the leading edge has two components: the first one is the propagation velocity or bulk velocity as measured at the centroid, the second one is the expansion velocity of the leading edge with respect to the centroid. The expansion velocity can be calculated by taking the derivative $\frac{da}{dt}$, where a is the radius of the CME. The bulk or propagation velocity can be found from the first derivative of Z , $\frac{dZ}{dt}$, where Z is the height of the CME.

The images in Figure 4.2 show the circular fitting of the CME on April 26, 2008. Circular fitting is easy to implement and works well in the lower corona in EUVI, and COR1 images. However, the circular fitting method can not get an accurate measurement from COR2, HI1 and HI 2, because the spherical assumption likely breaks down there. Therefore, I have to use a different method in the outer corona in order to better fit the CME geometry at large distances. The method, which I am going to apply in tracking CMEs at large distances, is the Raytrace or Graduated Cylindrical Shell model developed by Thernisien *et al.* (2006, 2009). This model will be described in the next section.

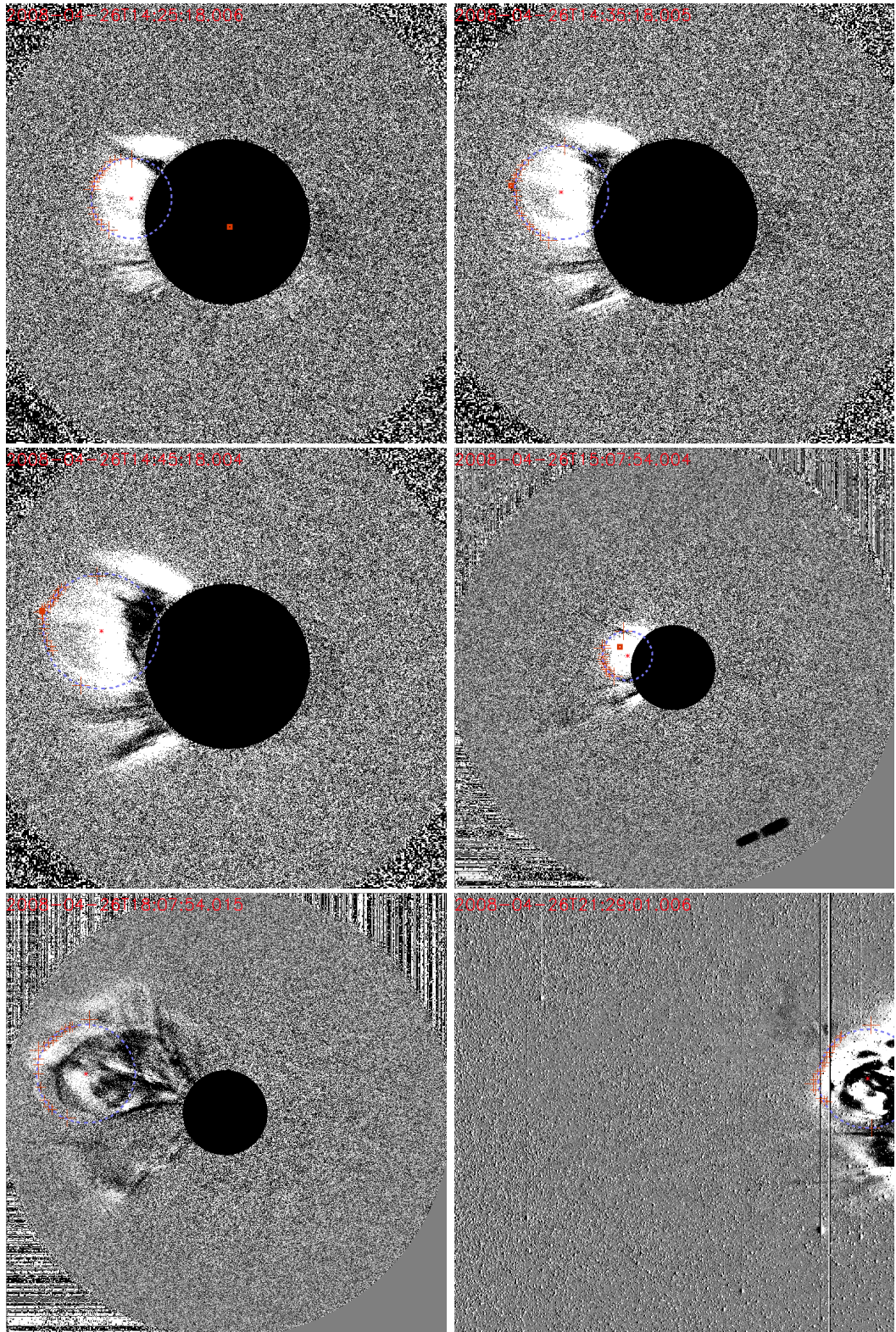


Figure 4.2: Six snapshot images of the 2008 April 26 CME taken by COR1, COR2, and HI1, respectively. The first two images in the first row show the circular fitting in COR1, the two images in the second row represent the circular fitting in COR2. The circular fitting in HI 1 shows in the last image of the third row.⁵⁹ This event is hard to be seen in HI2 because the CMEs was too faint.

4.4 CMEs Measurement Using Graduated Cylindrical Shell (GCS) Model

The GCS model assumes a flux rope-like structure of CMEs. This model can measure both the major and minor radius of the flux rope by using STEREO A and B observations simultaneously.

The geometry and the characterizing parameters of the GCS model or Raytrace model also called "croissant" model are well illustrated in Figure 4.3. This sophisticated model can be applied as a tool to make measurements of CME structure. This is done by projecting the 3-D structure of the model onto the FOV of the instruments. Since the views from the two vantage points will be different, it is possible to constrain the parameters of the model by varying them until the model best approximates the image of the CME as seen in the FOV of the STEREO instruments. The resulting structure is then thought to approximate the true 3-D geometrical shape of the CME. By applying this method to a series of images taken simultaneously by STEREO A and B, it is possible to reconstruct the kinematic and morphological evolution of the CME.

As shown in Figure 4.3, the Raytrace model represents a CME as a 3-D flux rope-like structure. The geometry of this model splits into two parts, the upper portion as a tubular semi-circle that represents the main body and the lower portion as two cone-shaped legs. This model has six free parameters: Carrington longitude (ϕ) and latitude (θ) of the source region (SR), height or leading edge of CME (r) along the central axis that joins the Sun center and the leading edge, tilt angle (γ) of the major axis with respect to the equator, half angle (α) between the two CME legs anchored on the surface, and aspect ratio (κ) scales the minor radius w (or cross section) of the flux rope with the leading edge distance.

Additionally, even though the Raytrace model has six free parameters, Carrington longitude (ϕ) and latitude (θ) of the source region (SR) can be easily constrained by observations from EUVI. Further, the angular width of CMEs may rapidly increase in the lower corona,

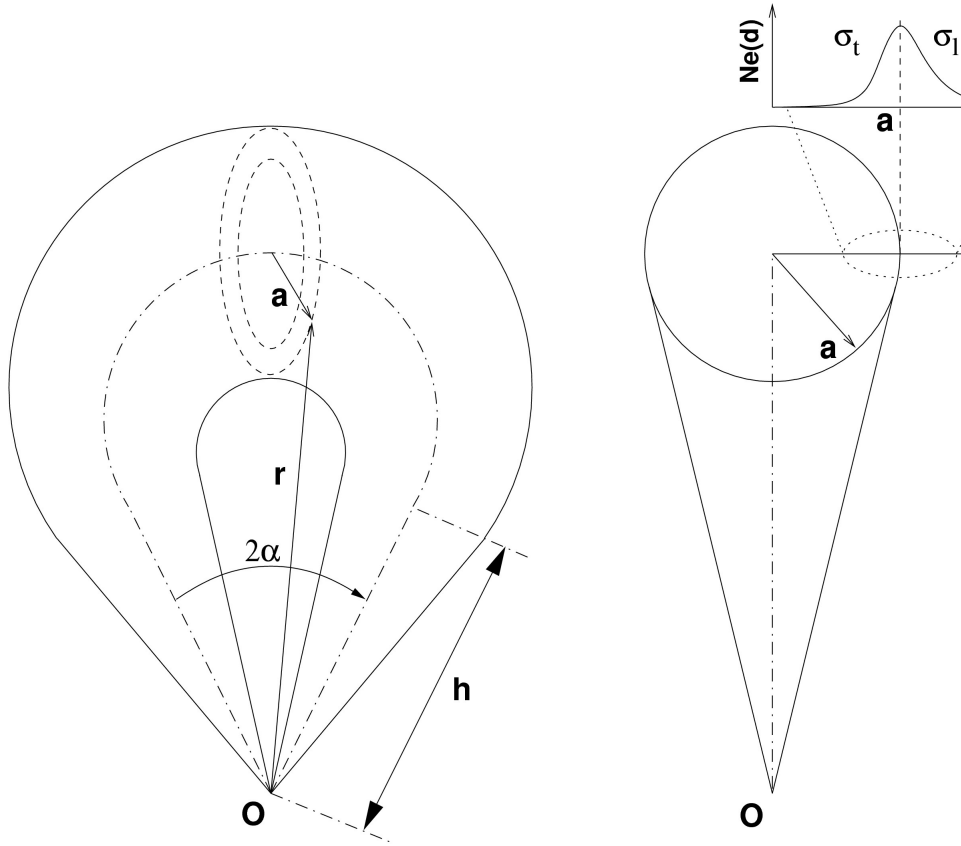


Figure 4.3: Graduated Cylindrical Shell Model. This Figure shows the face-on and edge-on of the flux rope-like model or Graduate Cylindrical Shell model. The dash-dot line shows the axis through the center of the model. The solid line represents the plane cut through the cylindrical shell and its origin (adopted from Thernisien *et al.* (2006))

but it does not have a large variation in the outer corona, where is the height range of concern in this dissertation. I therefore assume that the angular widths in the higher corona in COR 2 and HI 1 are constant. I also assume that the tilt angle from this model is constant, which is to assume that there is no significant rotation of CMEs in the outer corona. These assumptions are physically reasonable, and significantly simplify the process of model fitting.

The Raytrace model is a powerful tool to measure CMEs in 3D. I will present the measurements later. But I would like first to introduce the formula to fit the time evolution of the CME's parameters from Raytrace model measurements.

4.5 Exponential Velocity Fitting

With the Raytrace model, we are able to directly measure the leading edge distance (the major radius), and the aspect ratio (κ). Since the aspect ratio scales with the minor radius w (or cross section) of the flux rope with the leading edge distance, as described in the following equation 4.1 below.

$$w(r) = \kappa r \quad (4.1)$$

Three velocities can be derived from above the measurements, using the first-order numerical derivative method that is free of assumption of any functional curve (e.g. Zhang *et al.*, 2001). From the height time measurement of the LE, which characterizes the foremost location of the CME in the interplanetary space, the familiar CME LE velocity can be calculated. The CME expansion velocity, which characterizes the cross-section size of the flux rope, is the rate of change of the minor radius. Further, the bulk velocity, which is useful in theoretical modeling of CMEs in terms of overall propagation or translation, is defined as the velocity of the apex (Z) of the axis of the flux rope. Z can be simply inferred from the LE (r) minus the minor radius (w)

$$Z = r - w. \quad (4.2)$$

Therefore, the leading edge, bulk and expansion velocities are calculated from r , Z , and w respectively,

$$V_L = \frac{dr}{dt}, V_B = \frac{dZ}{dt}, V_E = \frac{dw}{dt}. \quad (4.3)$$

Further, we find that the leading edge velocity of the events studied seems to approach an asymptotic value (details will be given in next section). The velocity profile can be fitted by the following empirical formula,

$$V(r) = V_a + (V_i - V_a)e^{-\left(\frac{r-r_i}{r_a}\right)}, \quad (4.4)$$

where V_a is the asymptotic velocity, V_i is the initial velocity at $r = r_i$ (the height of the first data point used in the fitting) and r_a is the e-folding constant from the fitting. Note that the formula fitting starts with the derived velocity profiles, but not the height profiles. This functional form of velocity is a modified version of Sheeley *et al.* (1999), which is given in equation 1.3

Our new formula is able to describe events that are either decelerating or accelerating to an asymptotic value. If $V_i > V_a$, the event is decelerating, and if $V_i < V_a$, the event is accelerating. In both cases, the acceleration, or the velocity rate of change, goes to approximately zero as r becomes large; in the mean time, the velocity goes to V_a . It is straightforward to derive the acceleration as

$$a(r) = -V(r) \frac{(V_i - V_a)}{r_a} e^{-\left(\frac{r-r_i}{r_a}\right)}. \quad (4.5)$$

The effectiveness of this fitting is tested by using the coefficient of determination R^2 , which is the square of the sample correlation coefficient between the observed values and their fit values. R^2 will produce values between 0 and 1 depending on how well the empirical formula fits the observation. If the value of R^2 is near 1 the formula fits the observations closely.

4.6 Events Studied

Using the methods described above, we have carefully examined four CME events, including both fast and slow events. Table 4.1 shows the list of events that we studied. The first three events on the table 4.1 are impulsive events, and the last event is a gradual event.

Table 4.1: List of CMEs observed by SECCHI

Events list			
Event date	Onset time	Vel	Acc
2008-03-25	2008-03-25 18:47	1126.8	-30.6
2008-04-26	2008-04-26 13:53	741.0	1.4
2008-05-17	2008-05-17 10:02	986.5	13.1
2008-12-12	2008-12-12 10:22	350.0	11.5

4.6.1 Event: March 25, 2008

The first sign of solar activity for this event was found on the solar disk at 18:00 UT on March 25 2008 by EUVI A and B at Carrington longitude $\sim 199^\circ$ and latitude $\sim -11^\circ$. The source active region is NOAA AR 0988 with a heliographic coordinate at about S09°E59°. In Figure 4.4, we show the measurement of the CME's LE, minor radius and apex height with time (top panel), $\diamond$ represents the CME leading edge and the orange and blue lines show the bulk and expansion velocities respectively. The derived velocities and acceleration with distance from the center of the Sun are shown in the middle and bottom panels. The velocity of this event at 20 solar radius is about 1500 km/s, the velocity then decreases to about 500 km/s after 65 solar radius. The bulk velocity after 45 solar radius is around 350 km/s and the minor radius expansion velocity is about 150 km/s. The first three points in the top and middle panel of figure 4.4 came from COR2 and the remaining from HI1. The values of uncertainty in the height time plot for LE, minor radius and apex height (top panel) are approximated as $0.12 R_S$ in COR2 and $1.0 R_S$ in HI1 respectively. This uncertainty corresponds to about 8 pixels in both COR2 and HI1 images. We believe that this is a conservative estimation for events with shapes of sharp contrast, but a reasonable one for more diffusive events. Detailed discussions of the sensitivity of model parameters

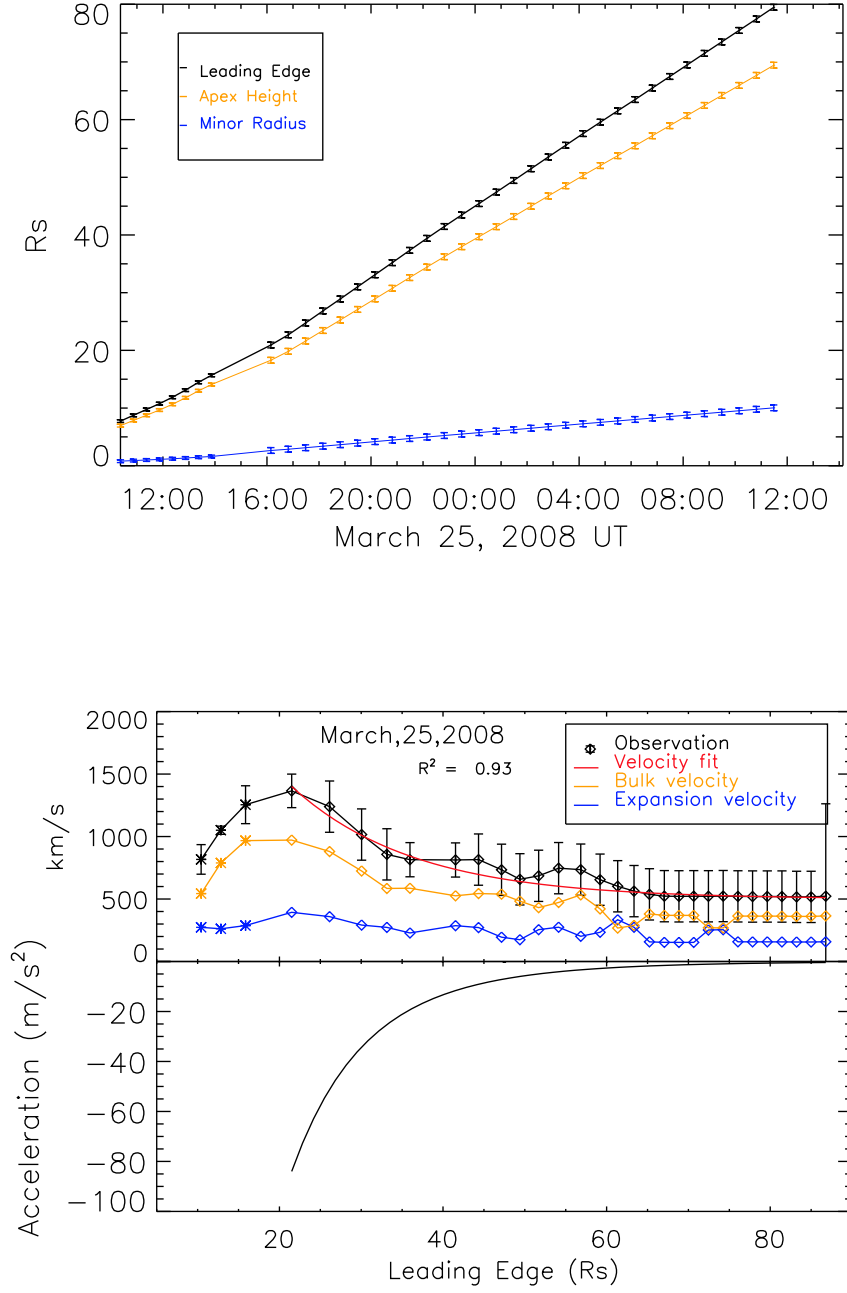


Figure 4.4: The distance-time (upper panel), velocity-distance (middle panel) and acceleration-distance (lower panel) plots for the CME on March 25, 2008. In the first (second) plot, the three curves (from top to bottom) represent the LE (nominal velocity), the apex (bulk velocity), and the minor radius (expansion velocity), respectively. The red line in the velocity plot show the functional fitting to the observed LE velocity starting from the peak velocity time. The acceleration curve is derived from the fitted velocity curve. The first three data points are from COR2, and the rest from HI1

are carried out by Thernisien *et al.* (2006, 2009).

Figure 4.8 shows one sample (event on 2008 March 25) of the model measurements overlaid on the observations: EUVI (left column), COR2 (center column) and HI1 (right column); images in the top row are from STEREO A observations, while those in the bottom row from STEREO B. EUVI observations are used to locate the CME source region, the preliminary values of longitude and latitude, which are indicated by transient features such as bright flare patches, post-flare loop arcades, and extensive dimming on the disk. In this case, the source region was near the eastern limb in both A and B images. The central location of the source region is indicated by the asterisk symbol (red color in B represents the front-side origin, while white color in A represents the behind-the-limb or backside origin). The footpoints of the CME legs are indicated by the plus symbols, while the orientation of these footpoints indicate the tilt angle of the flux rope center axis. The COR2 images (center column) are used to constrain CME leading edge, tilt angle, half angle and aspect ratio. The appearance of the model is sensitive to the variation of these parameters, in particular, when a pair of images from two perspectives are used to make the constraint simultaneously. The images are further used to fine tune the longitude and latitude because of the non-radial motion of CMEs in the inner corona. In HI1 (right column), we usually vary only the leading edge, while keeping all other parameters the same as in the last measurement in COR2. Since the CME on 2008 March 25 originated on the eastern limb, it appeared in HI1 A images only and was absent in HI1 B, which is expected from the geometric projection.

This CME erupted on the eastern limb and is able to be detected in both COR 2 A and B. However, when it propagates further from the sun, only the HI 1 A camera is able to follow its evolution in interplanetary space. Figure 4.6 and 4.7 shows the plots of the solar wind parameters from STEREO/PLASTIC and STEREO/IMPACT instruments for the A and B spacecraft respectively. The signatures of the ICME are not able to be detected because this ICME propagated towards the east and might not hit both STEREO spacecrafts. The first panel in Figure 4.6 is the velocity plot. The apparent increase of the

velocity starting from the middle of March 28 does not mean the signature of an ICME. The proton temperature on the second panel does not change from March 29 to March 31. The proton density in the third panel shows a jump on March 28 but the density enhancement is not a CME signature, which come from the source occurs on March 25, 2008. Further, there are no CME signatures in the magnetic field measurements as shown in the fourth panel (total magnetic field), fifth (magnetic field X-direction), sixth (Y-direction) and seventh (Z-direction). The last panel is the plasma beta plot. Figure 4.7 is the plot from PLASTIC and IMPACT on STEREO B, which does not show any signature of an ICME. The velocity, proton temperature, plasma proton density and magnetic fields strength plots do not have any sudden change in the time period, which confirms that the ICME does not get close to STEREO B.

Figure 4.5 shows the solar wind data from the ACE spacecraft, which is located at the L1 point. The first panel is the magnetic field profile and the red plot in the first panel represents the north-south component of the interplanetary magnetic field or B_Z . The second plot is the velocity profile. The third and the forth panels are proton density and the proton temperature; moreover, the red plot on the forth panel is the expected proton temperature. The next panel is the ratio of the expected temperature and proton temperature. The last two panels are the plasma beta and the total energy, respectively. The ACE spacecraft is not able to detect any ICME signature, coming from the source region of March 25,2008. However, it has some signatures of a CIR present in the solar wind, but it is out of the scope of this dissertation.

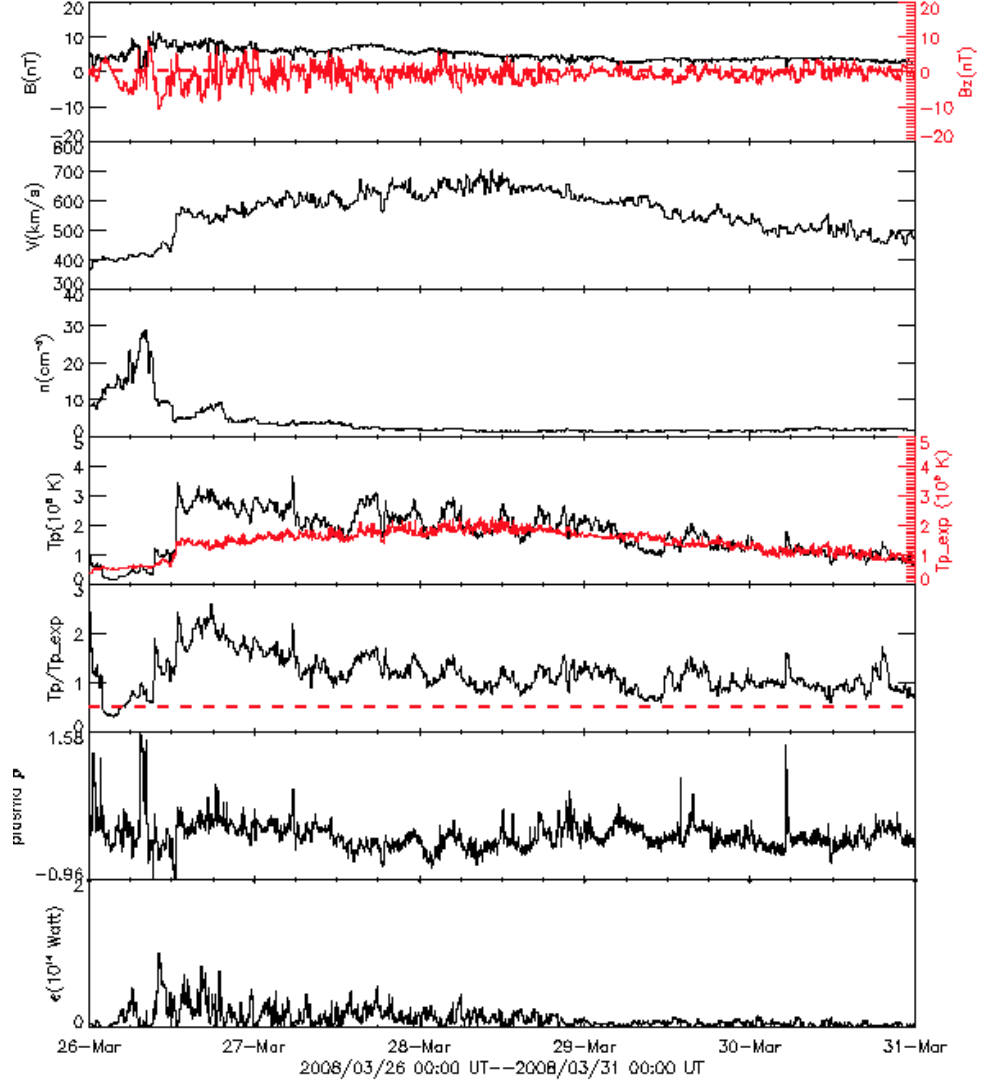


Figure 4.5: Solar Wind plot from ACE spacecraft on March 26, 2008. The starting time is 00:00 UT on March 25 2008, and the ending time is on 00:00 UT March 31, 2008. The first panel shows the CME magnetic field strength and the red plot is B_z . The second panel is velocity. Proton density and proton temperature are the third and forth plots respectively. The ratio of expected temperature and proton temperature are presented in the fifth panels. The next two panels present the plasma beta and the input energy to the magnetosphere, respectively. No ICME signatures found in in-situ spacecraft.

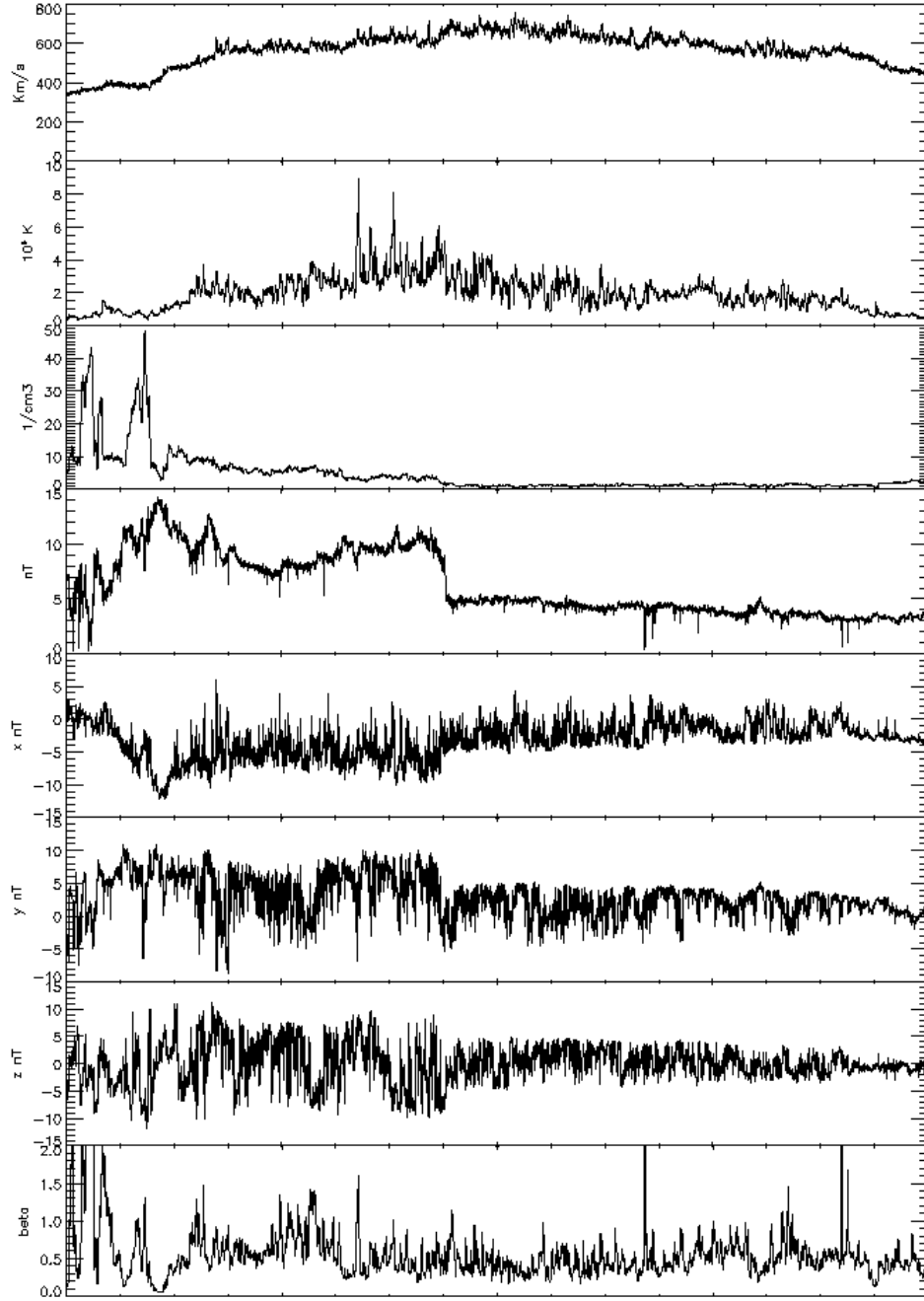


Figure 4.6: Solar Wind plot from STEREO A/PLASTIC and IMPACT. The starting time is 00:00 UT on March 28 2008, and the ending time is on 00:00 UT March 31 2008. The first panel shows the CME velocity. The second panel is plasma proton temperature. Proton density and magnetic field strength are on the third and fourth panels. The next three panels present the direction of magnetic field in the x, y and z directions, respectively. The last panel is the plasma beta. This plot does not show any signature of an ICME on IMPACT and PLASTIC/STEREO-A

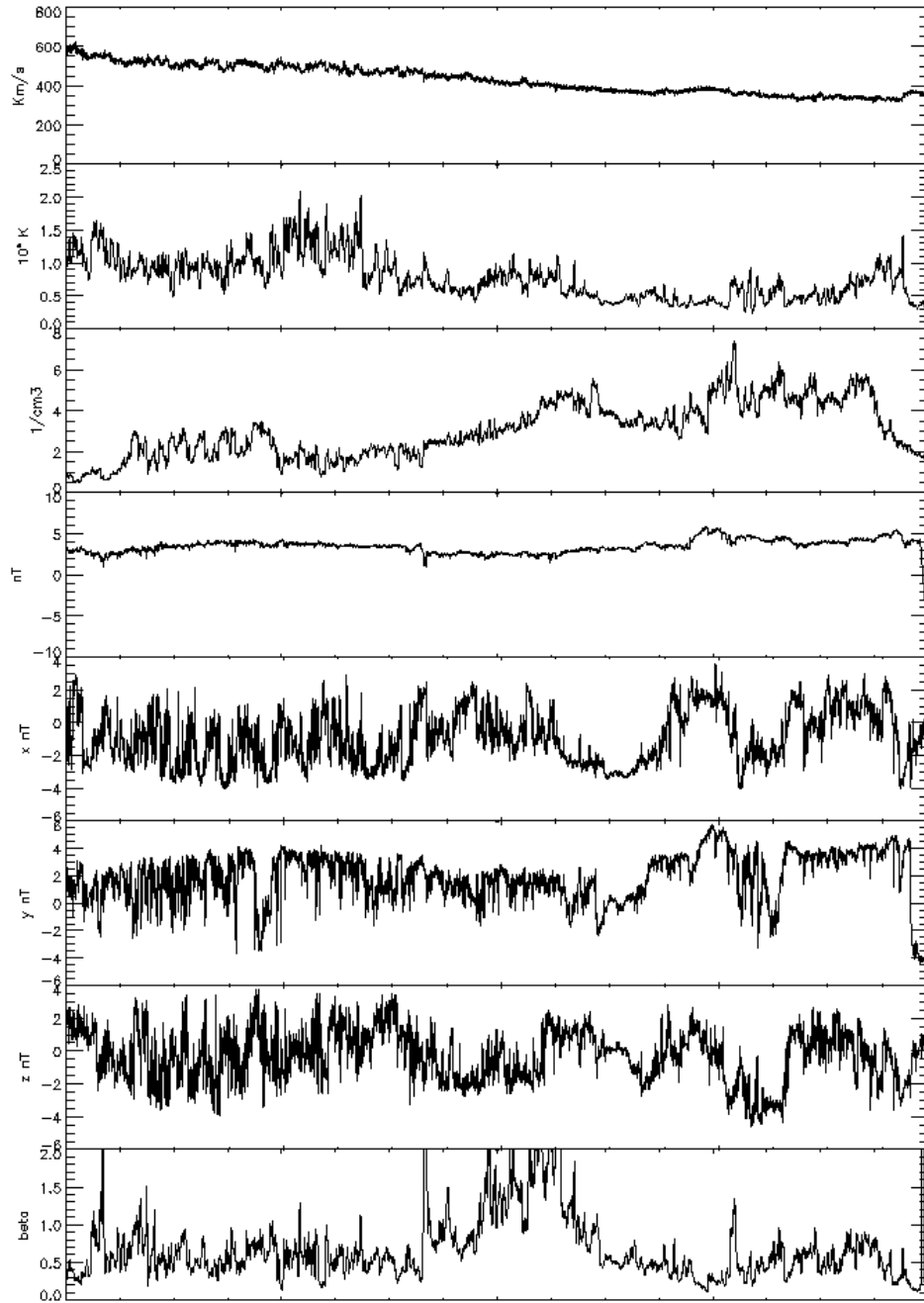


Figure 4.7: Solar Wind plot from STEREO A/PLASTIC and IMPACT. The starting time is 00:00 UT on March 28 2008, and the ending time is on 00:00 UT March 31 2008. The first panel shows the CME velocity. The second panel is plasma proton temperature. Proton temperature and magnetic field strength are on the third and forth panels. The next three panels present the direction of magnetic field in the x, y and Z direction, respectively. The last panel is the plasma beta. This plot does not show any signature of an ICME on IMPACT and PLASTIC/STEREO-B

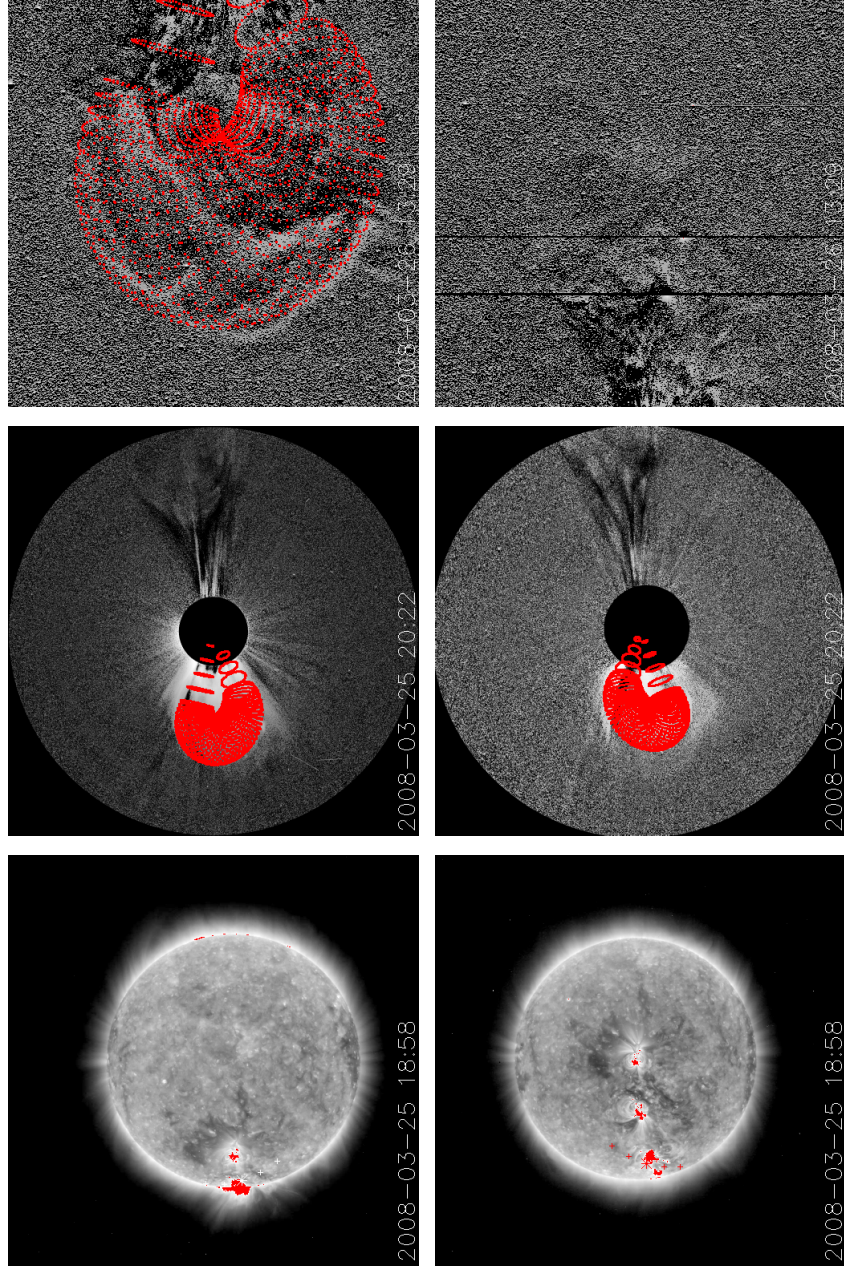


Figure 4.8: Raytrace model measurements (red wire lines) overlaid on the observed images (gray scale) for the March 25, 2008 CME event. From left to right, the three columns are of EUVI, COR2 and HI1 images respectively. The top row is for STEREO A and bottom row STEREO B.

4.6.2 Event: April 26, 2008

This event originated at NOAA AR 0992 with heliographic coordinate N13°W32° and Carrington longitude $\sim 204^\circ$ and latitude $\sim 3^\circ$. Figure 4.9 shows the raytrace measurement in EUVI, COR2 and HI 1. This CME is a partial halo from the point of view of STEREO B, which is able to see in the second row of figure 4.9. The evolution of the velocities of this CME is shown in Figure 4.19 (top panel). The LE velocity of this event at $13 R_S$ is about 720 km/s and the velocity decreases to about 640 km/s at $40 R_S$ and after. Additionally, the minor radius expansion velocity converges to about 140 km/s and the bulk velocity to about 500 km/s at large distances. The initial and final LE velocities we obtain are consistent with those of previous studies of this event (Thernisien *et al.*, 2009). The goodness of the velocity fitting R^2 for this event is 0.66. The low value is probably due to the fact that, between 20 and $28 R_S$, this event was only seen by HI1A and had not yet reached the FOV of HI1 B. This means that in the height range (20 - $28 R_S$) the geometrical fitting had to be done with only one vantage point. Therefore, the uncertainty in the measurement during this height range is expected to be higher than if the geometrical fitting were done with two vantage points.

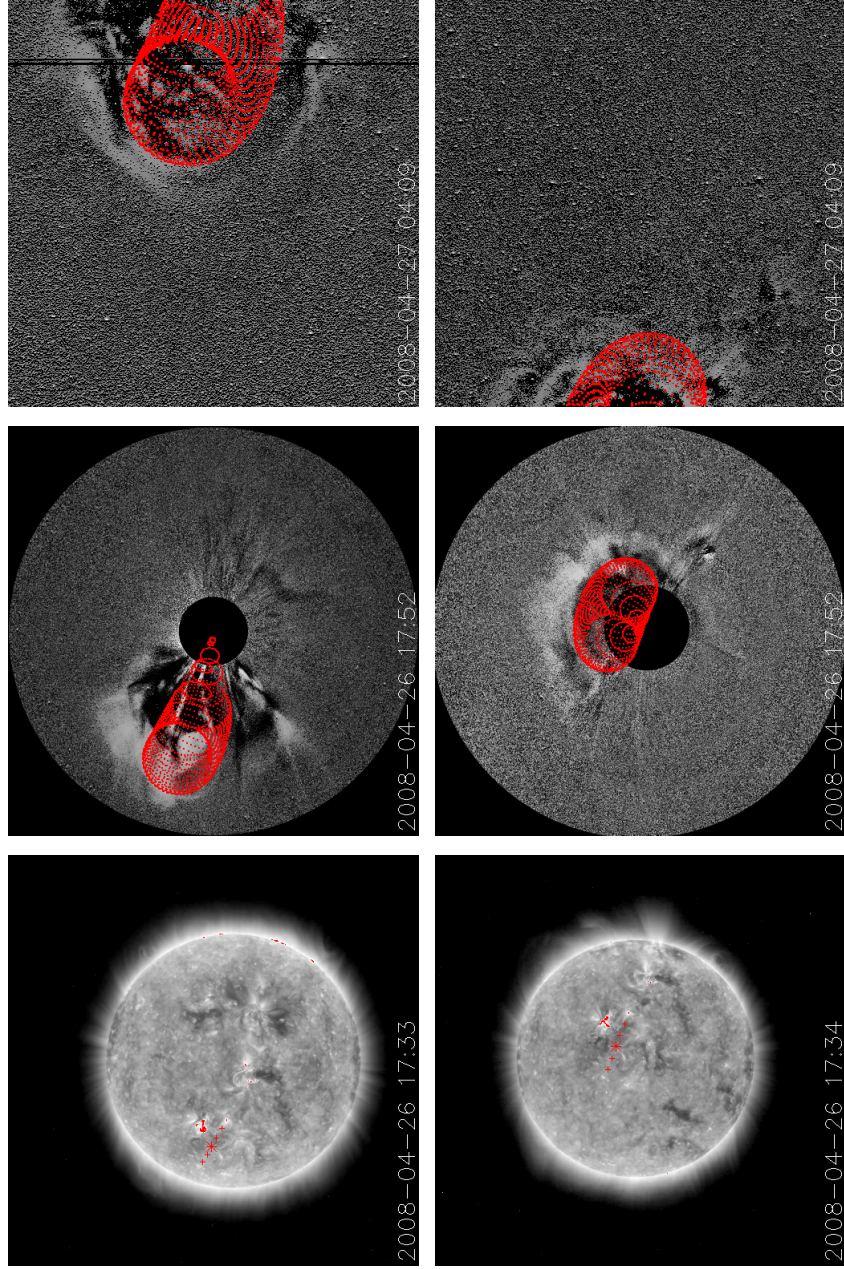


Figure 4.9: Raytrace Model measurements (red wire lines) overlaid on the observed images (gray scale) for the April 26, 2008 CME event. From left to right, the three columns are of EUVI, COR2 and HI1 images respectively. The top row is for STEREO A and bottom row STEREO B.

Figure 4.10 and figure 4.11 show the solar wind plot from STEREO/IMPACT and PLASTIC. The first panel shows the CME velocity. The second panel is plasma proton temperature. Proton temperature and magnetic field strength are presented on the third and forth panels. The next three panels present the magnetude of magnetic field in the x, y and Z direction, respectively. The last panel is the plasma beta.

This event does show clear signatures of an ICME on STEREO B (see figure 4.11); however, it does not show any sign on STEREO A (see 4.10). When the CME erupted from the sun, it was a partial halo CME on STEREO B (see the second row of Figure 4.9). The signatures showing on STEREO B/IMPACT and PLASTIC are spikes of proton velocity, proton temperature and plasma proton density at 14:00 UT on April 29, 2008. The magnetic field strength and rotation B_Z also show in the fourth and seventh panels. The plasma beta is lower than 0.5 at the arrival time of this event. However, this CME does not show a signature on ACE spacecraft, which is in figure 4.12. No signatures on ACE confirms that the evolution of this CME is directed on the eastern of the Sun and it will not have any impact on the Earth.

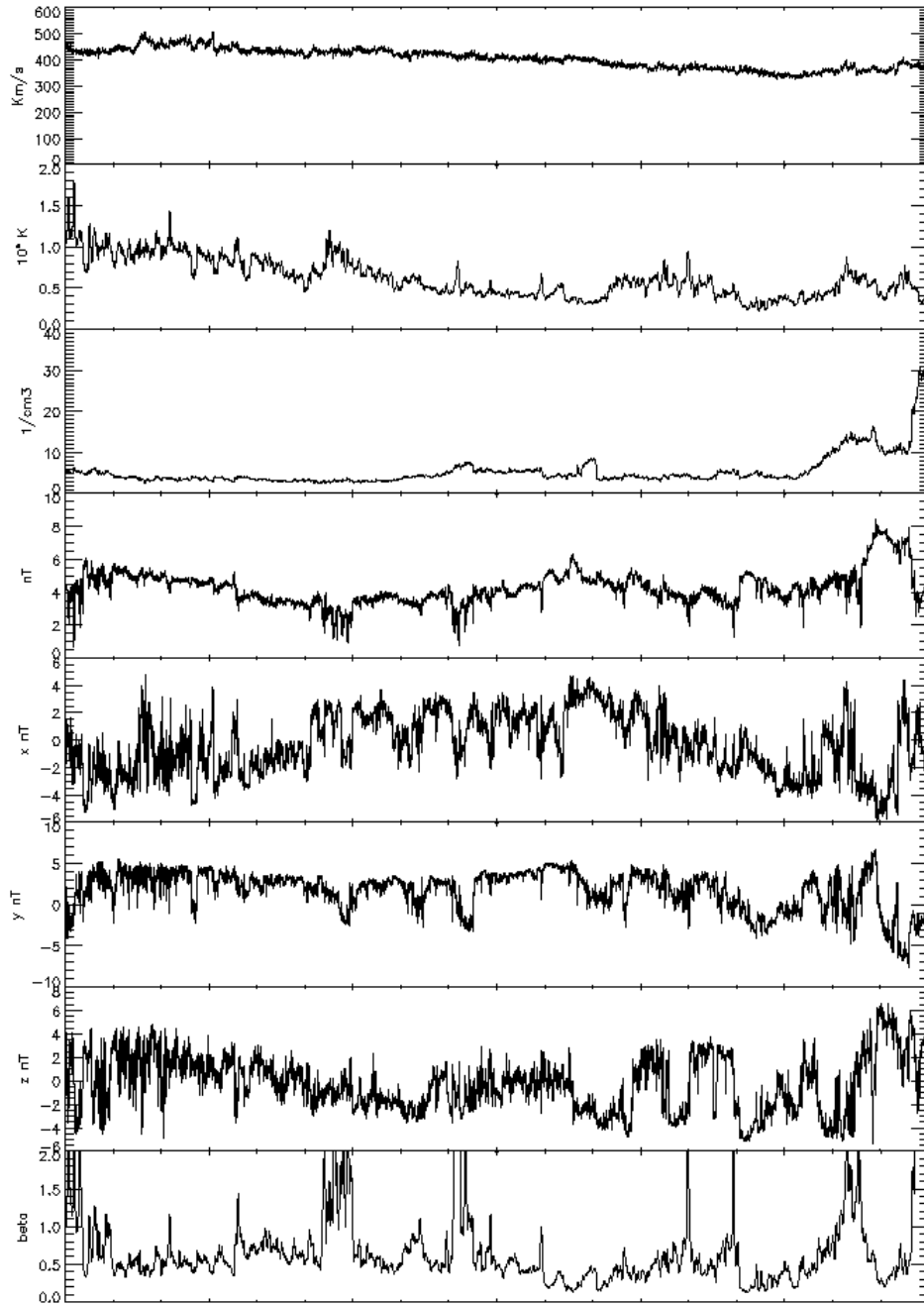


Figure 4.10: Solar Wind plot from STEREO-A / PLASTIC and IMPACT . The starting time is 00:00 UT on April 29 2008, and the ending time is on 00:00 UT May 1 2008. The first panel shows the CME velocity. The second panel is plasma proton temperature. Proton density and magnetic field strength present on the third and forth panels. The next three panels present the direction of magnetic field in the x, y and Z direction, respectively. The last panel is the plasma beta. This plot does not show any signature of ICME on IMPACT and PLASTIC/STEREO-A

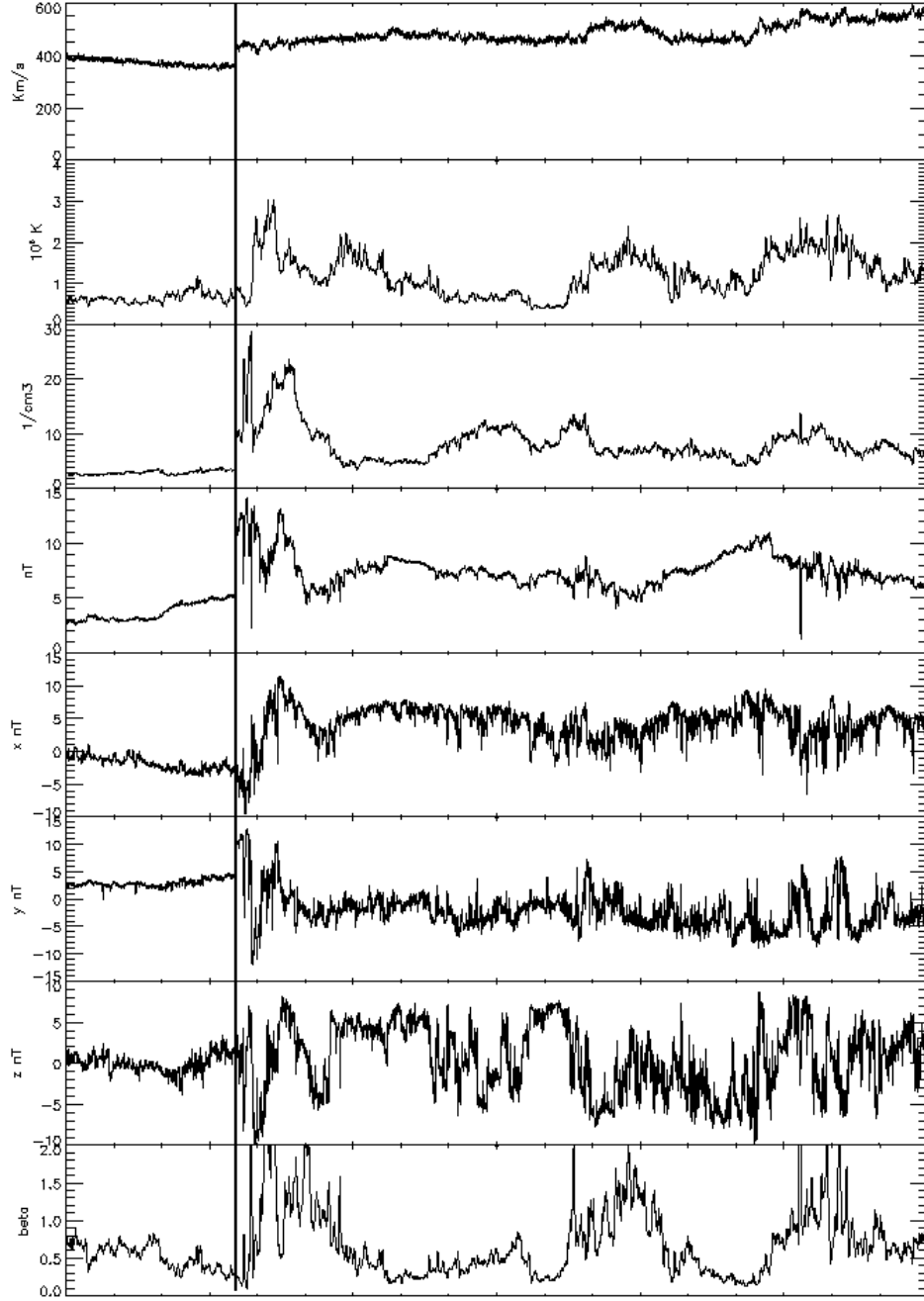


Figure 4.11: Solar Wind plot from STEREO-B/PLASTIC and IMPACT . The starting time is 00:00 UT on April 29 2008, and the ending time is on 00:00 UT May 1 2008. The first panel shows the CME velocity. The second panel is plasma proton temperature. The proton density and magnetic field strength present on the third and forth panels. The next three panels present the direction of magnetic field in the x, y and Z direction, respectively. The last panel is the plasma beta. The dark solid vertical line represents the velocity jump, which is only signature of ICME can see in the plot but other signatures do not show in this plot.

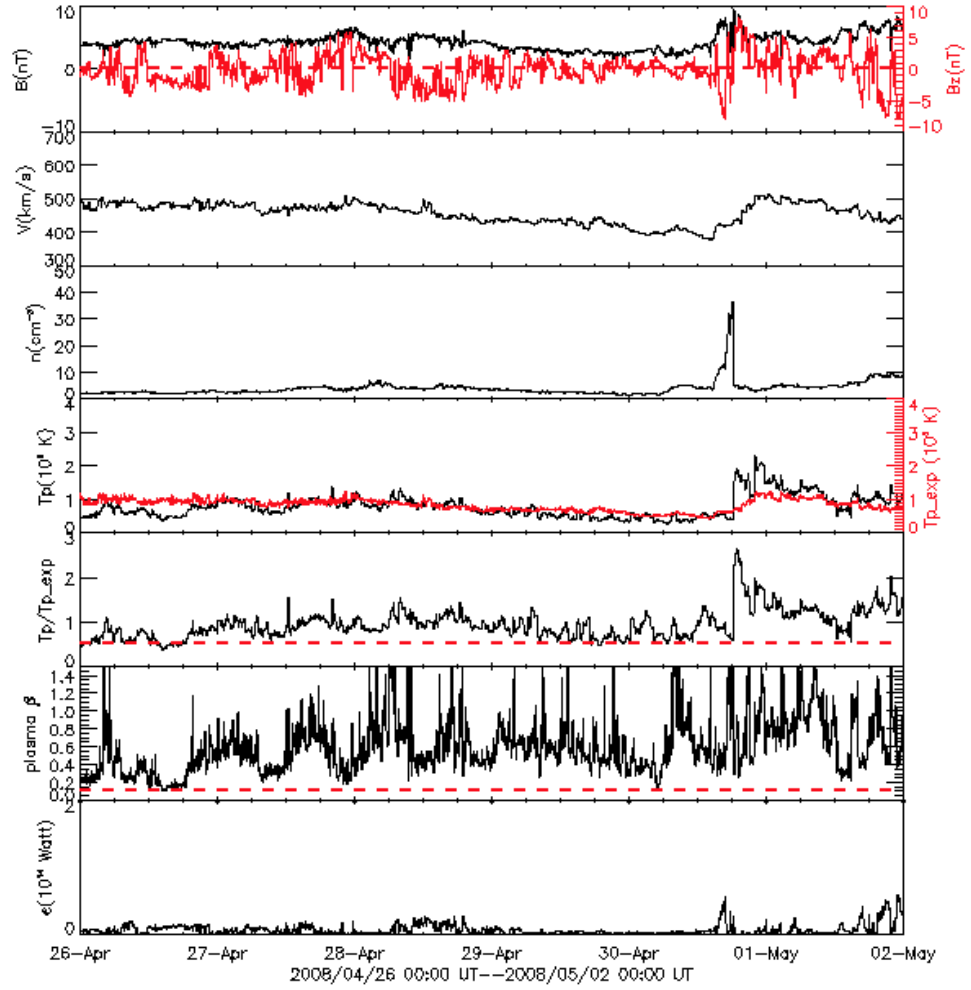


Figure 4.12: Solar Wind plot from ACE spacecraft on April 26, 2008. The starting time is 00:00 UT on April 26, 2008, and the ending time is on 00:00 UT May 2, 2008. The first panel shows the CME magnetic field strength and the red plot is B_Z . The second panel is velocity. Proton density and total magnetic field are the third and forth plots respectively. The ratio of expected temperature and proton temperature present on the fifth panels. The next two panels present the plasma beta and the input energy to magnetosphere, respectively. No ICME signatures found in in-situ spacecraft.

4.6.3 Event: May 17,2008

The active region associated with this event is seen on the northeastern limb by STEREO A and close to the center of the solar disk by STEREO B on May 17,2008 at 11:52 UT. It is located at Carrington longitude 261° and latitude 11° . We measured the velocity of this event at $20 R_S$ to be about 1000 km/s. The velocity then decreases to approximately 720 km/s after $40 R_S$ and remained approximately constant up to $50 R_S$ where we stopped making measurements. In addition, the value of goodness of fitting for this event is 0.81. This number indicates that the fitting LE velocities are fairly close to the observations. The minor radius expansion velocity and bulk velocity for this event are 150 km/s and 670 km/s respectively in the region between 40 and $50 R_S$. This result is in close agreement with a previous study done by Wood & Howard (2009), who showed that the initial velocity at $6 R_S$ is about 900 km/s and the final velocity is about 600 km/s as measured from in situ data at STEREO-B. One could then come to the conclusion that after the deceleration, which occurred before $40 R_S$, this CME propagated with an almost constant velocity through interplanetary space up to 1 AU.

Figure 4.13 shows signature of an ICME from STEREO/PLASTIC and IMPACT. However, the signature, velocity jump, does not come from the source region because the CME is going opposite direction and it is really faint in STEREO B. In addition, the signature is not able to be detected by ACE (see Figure 4.15).

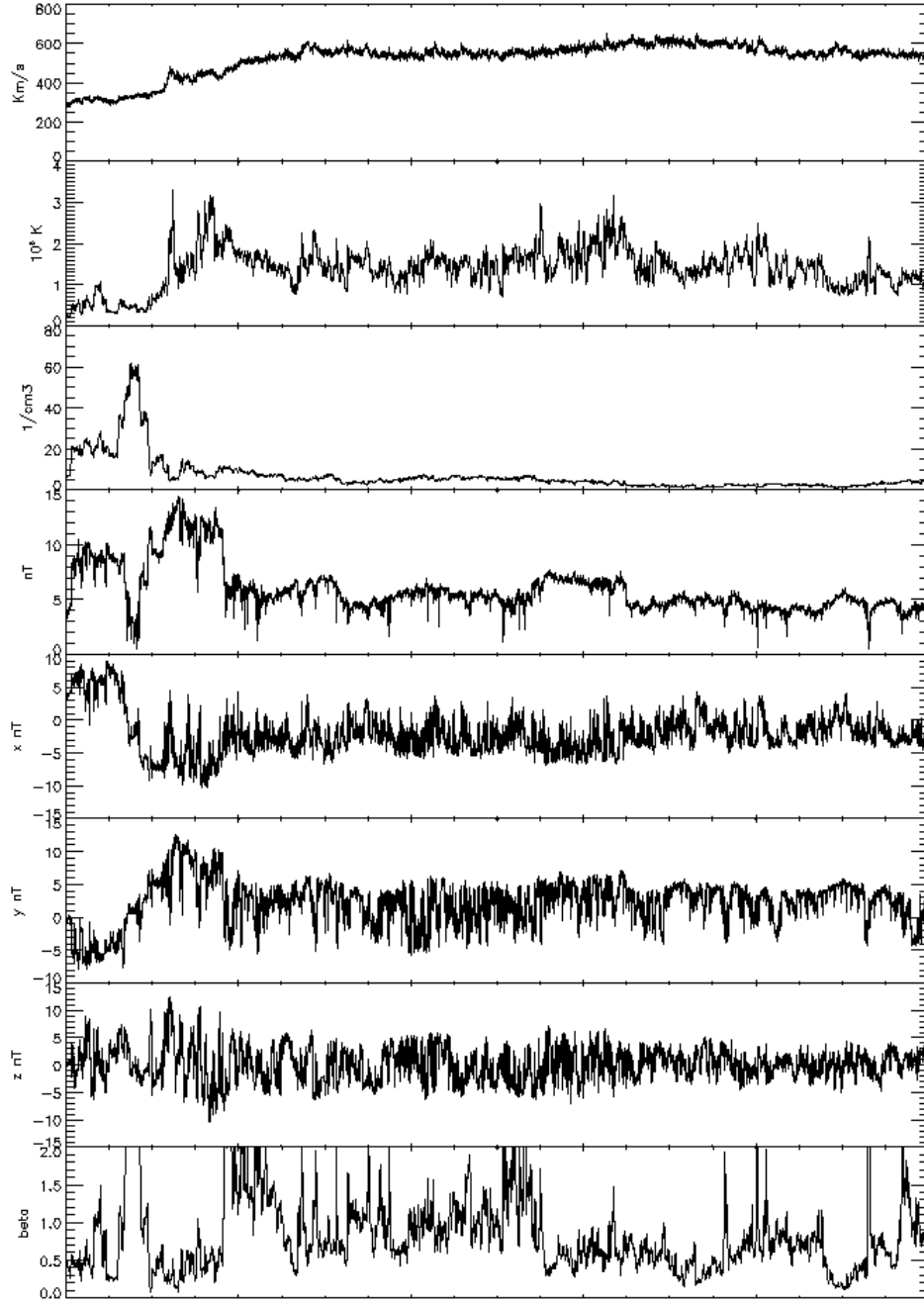


Figure 4.13: Solar Wind plot from STEREO-A/PLASTIC and IMPACT. The starting time is 00:00 UT on May 21, 2008, and the ending time is on 00:00 UT May 25, 2008. The first panel shows the CME velocity. The second panel is plasma proton temperature. Proton density and magnetic field strength present on the third and forth panels. The next three panels represent the direction of magnetic field in the x, y and Z direction, respectively. The last panel is the plasma beta. This plot does not show any signatures of the ICME on IMPACT and PLASTIC/STEREO-A

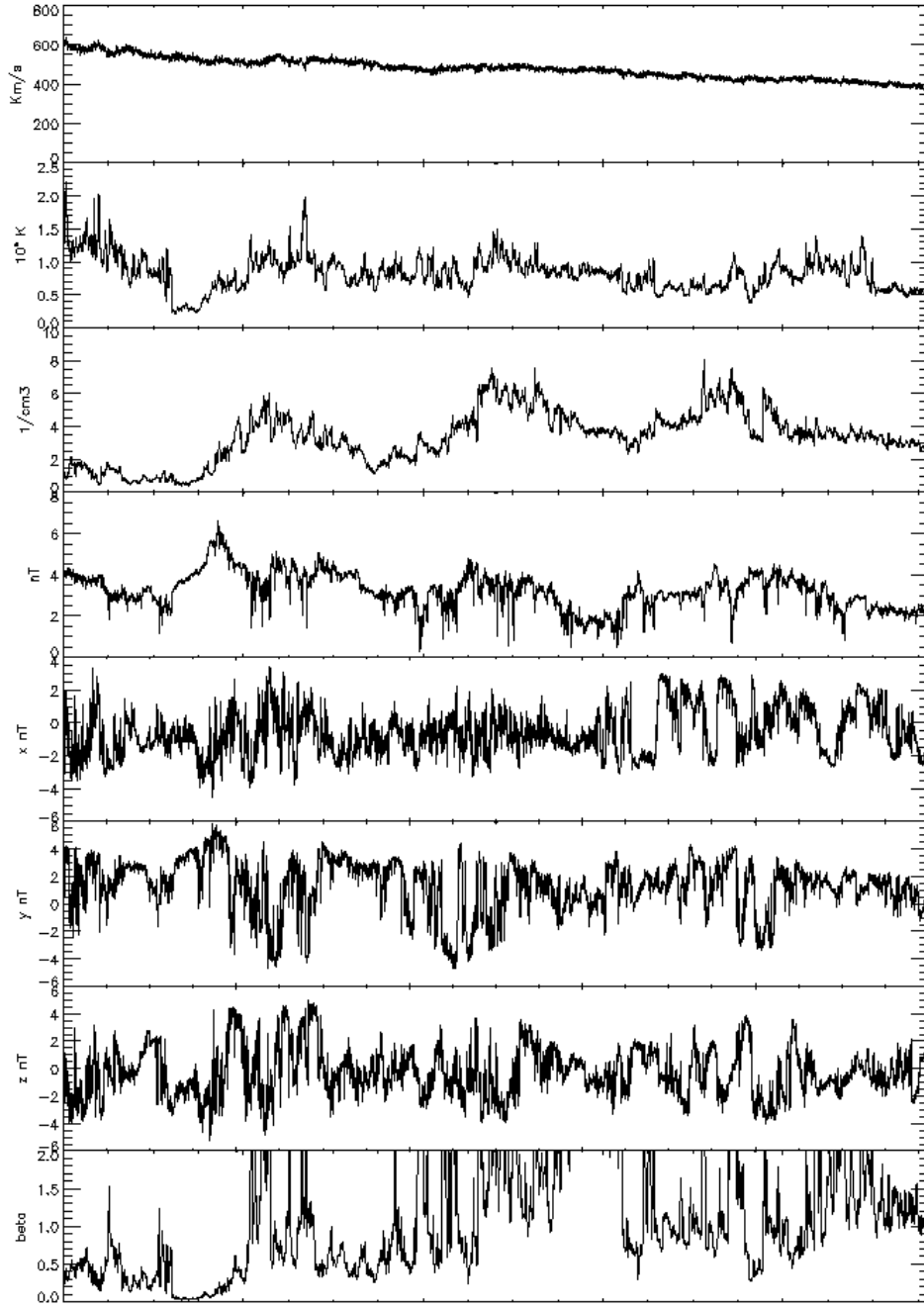


Figure 4.14: Solar Wind plot from STEREO-B/PLASTIC and IMPACT. The starting time is 00:00 UT on May 21 2008, and the ending time is on 00:00 UT May 25 2008. The first panel shows the CME velocity. The next panel is plasma proton temperature. Proton density and magnetic field strength present on the third and forth panels. The next three panels represent the direction of magnetic field in the x, y and Z direction, respectively. The last panel is the plasma beta. This plot does not show any signatures of the ICME on IMPACT and PLASTIC/STEREO-B

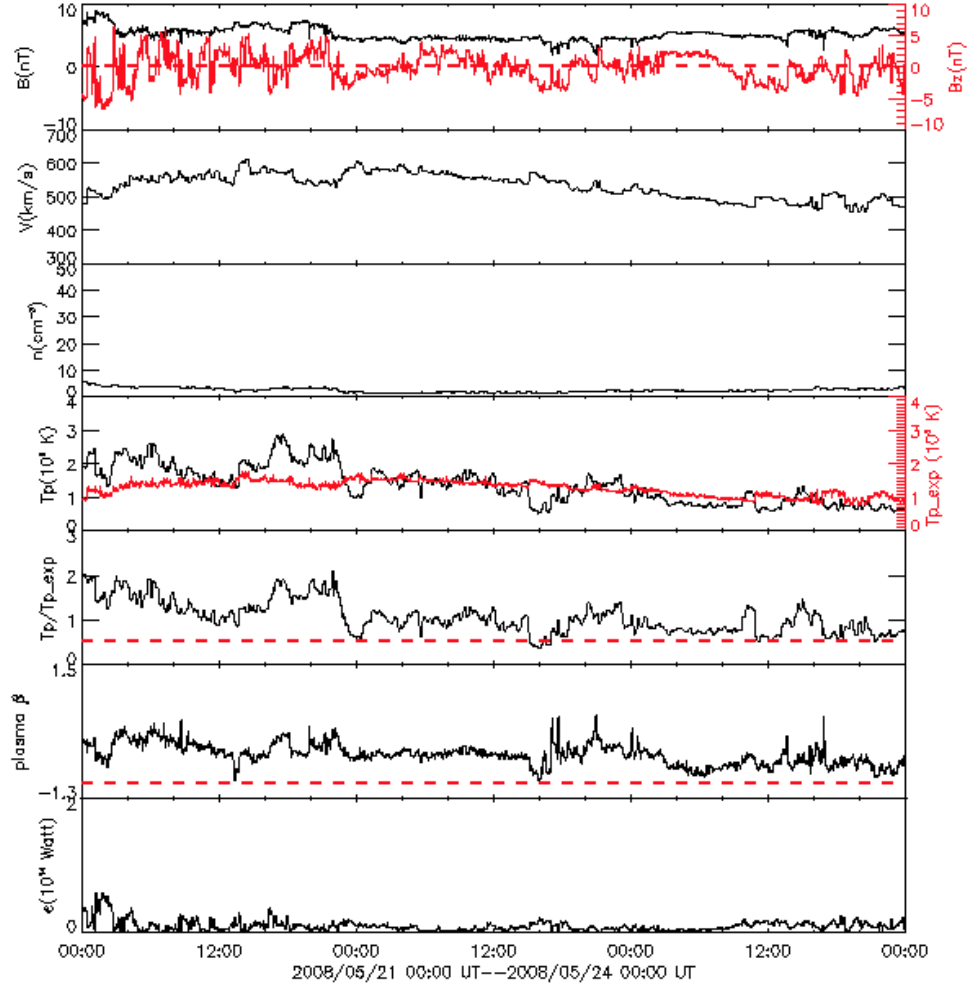


Figure 4.15: Solar Wind plot for May 17, 2008. The starting time is 00:00 UT on May 21, 2008, and the ending time is on 00:00 UT May 24, 2008. The first panel shows the CME velocity. The next panel is plasma proton temperature. Proton temperature and magnetic field strength present on the third and forth panels. The next three panel present the direction of magnetic field in x, y and Z direction, respectively. The last panel is the plasma beta. No ICME signatures found in in-situ spacecraft.

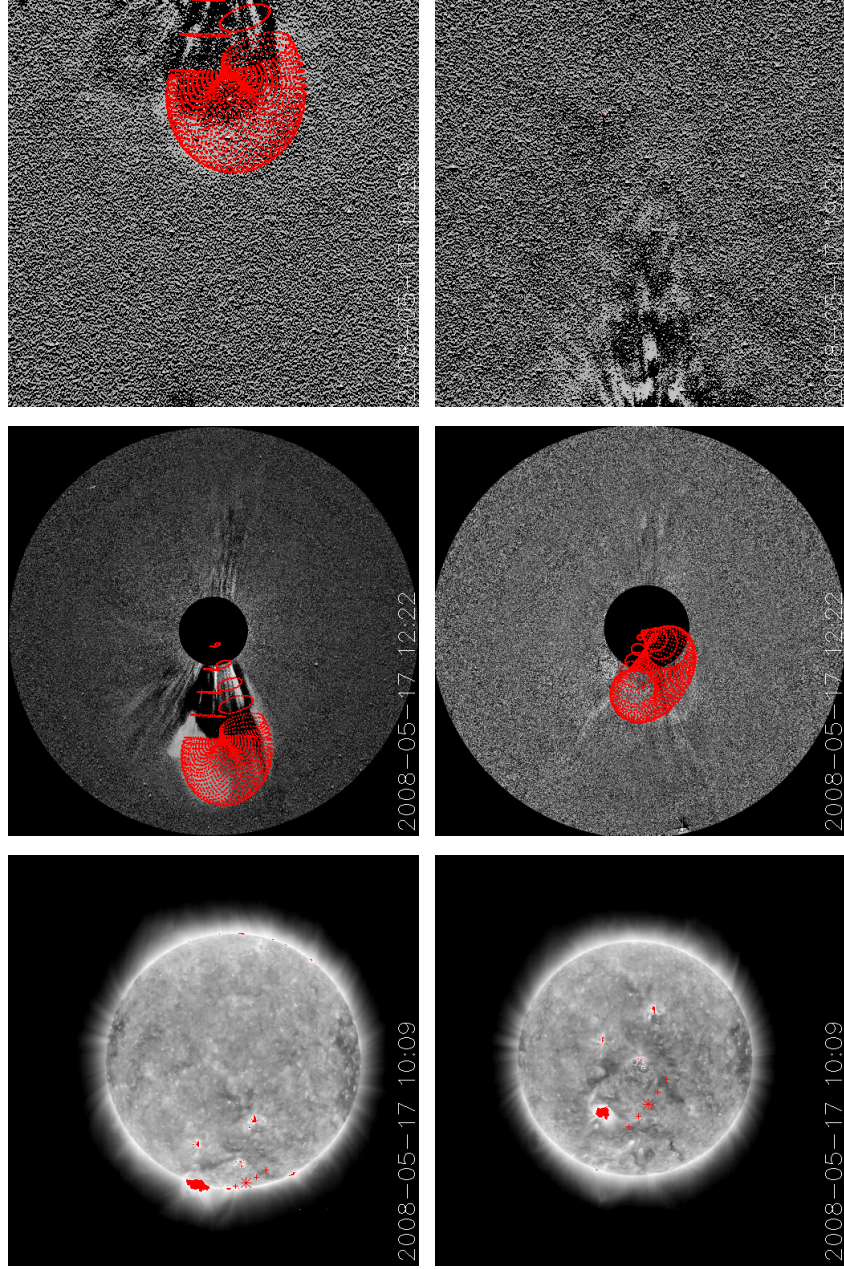


Figure 4.16: Raytrace Model measurements (red wire lines) overlaid on the observed images (gray scale) for the May 17, 2008 CME event. From left to right, the three columns are of EUVI, COR2 and HI1 images respectively. The top row is for STEREO A and bottom row STEREO B.

4.6.4 Event: December 12,2008

This event is considered to be a gradual event because the initial velocity is found to be ~ 350 km/s and the final velocity is about 590 km/s, indicating a gradual acceleration from a low initial velocity. The source region was at 72° in Carrington longitude and 11° in latitude on December 12,2008 at 10:22 UT. The minor radius expansion and bulk velocity at about $80 R_S$ were found to be 90 km/s and 500 km/s respectively. This CME manifested as a magnetic cloud in near-Earth space from in situ measurements (Williams *et al.*, 2009; Davis *et al.*, 2009; Liu *et al.*, 2010; Byrne *et al.*, 2010). The speed of the magnetic cloud is about 350 km/s, indicating a deceleration of the CME from $80 R_S$ to 1 AU. Nevertheless, this average deceleration is about -1.1 m/s^2 , which is rather small compared with the acceleration close to the Sun in the COR2 FOV. Therefore, the asymptotic assumption of the fitting is still valid as a good approximation of CME evolution in the inner heliosphere. In addition, we found the value of goodness of fitting for this event is 0.89.

The ACE plot for this event has data gap on the proton density and proton temperature data. Therefore, we used the WIND data to show the solar wind. The Figure 4.17 is taken from Byrne *et al.* (2010). There is a clear enhancement and smooth rotation of magnetic field, indicating the presence of a magnetic cloud. Another signatures those can identify the magnetic cloud is the low proton density as shown in the first panel.

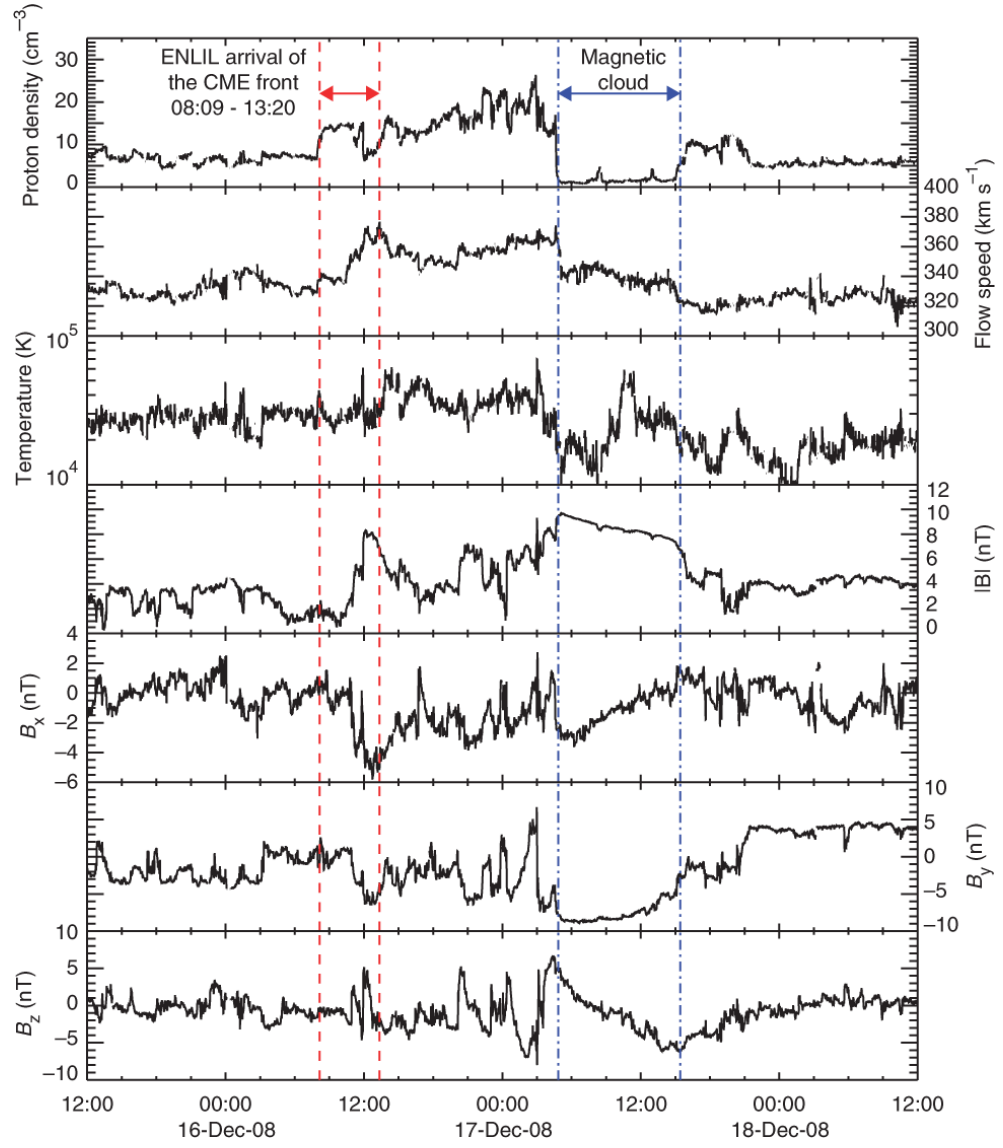


Figure 4.17: Solar Wind plot from WIND on December 12, 2008. In situ solar wind plasma and magnetic field measurements from the WIND spacecraft. From top to bottom, the panels show proton density, bulk flow speed, proton temperature and magnetic field strength and components. The red dashed lines indicate the predicted window of CME arrival time from our ENLIL with Cone Model run (08:09 - 13:20 UT on 16 December 2008). We observed a magnetic cloud (flux rope) signature behind the front, highlighted by the blue dash-dotted lines. Byrne *et al.* (2010)

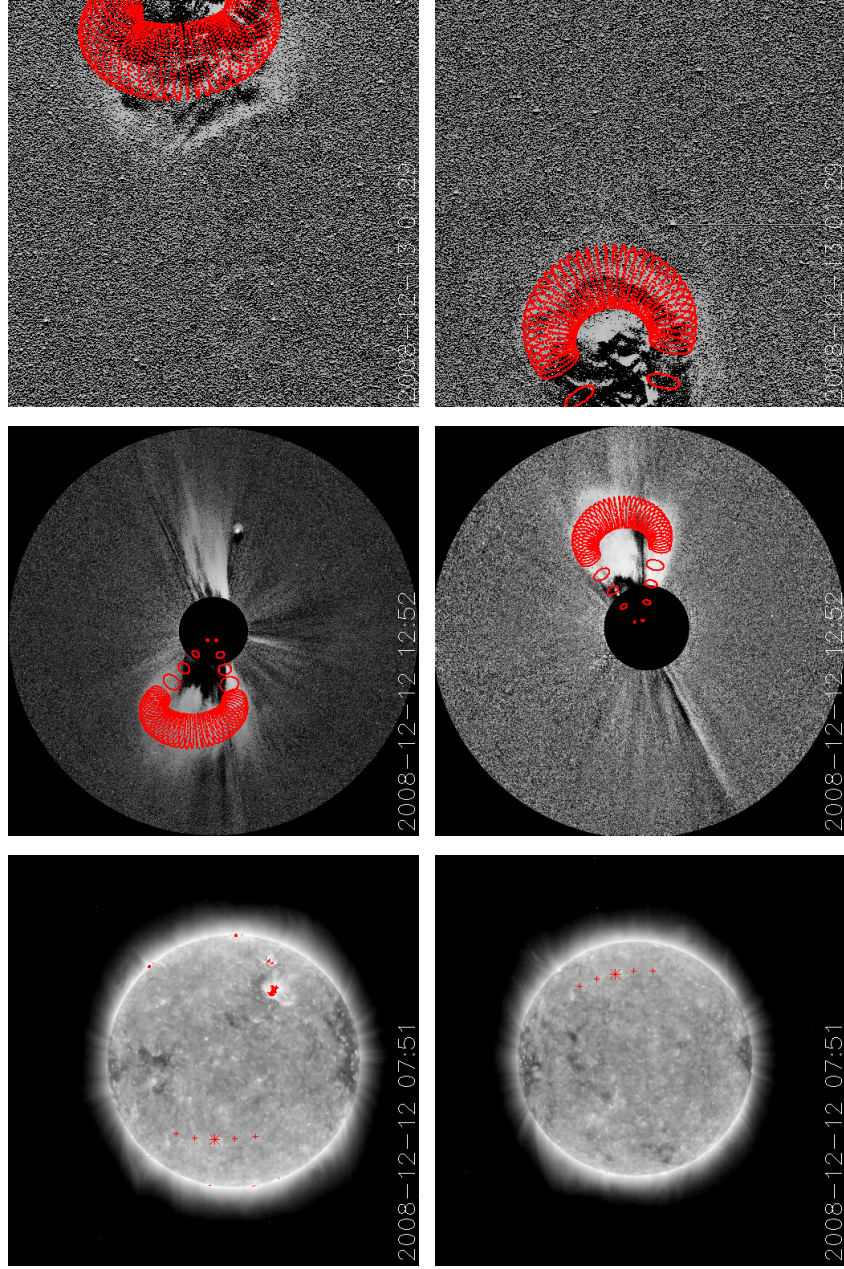


Figure 4.18: Raytrace Model measurements (red wire lines) overlaid on the observed images (gray scale) for the December 12, 2008 CME event. From left to right, the three columns are of EUVI, COR2 and HI1 images respectively. The top row is for STEREO A and bottom row STEREO B.

4.7 Results

Table 4.2 summarizes the geometric-fitting parameters (column 2-7) and the kinematic-fitting parameters (column 8-12) for the four events studied. There are two rows of parameters for each event: the first row indicates the initial parameters at the time when the CME was first observed by COR2, and the second row indicates the final parameters at the time when the CME was last observed by HI1. Except for the LE, the other five geometric parameters of any individual CME in the six-parameter flux-rope model do not change significantly during its evolution in the heliosphere, i.e. from about 10 to 90 R_S . Nevertheless, there are sometimes noticeable changes in order to best fit the observations. For instance, the heliographic latitude of the apex of the CME on March 25, 2008 gradually moved toward the equator from about $S12^\circ$ to $S6^\circ$. The heliographic longitude of the gradual CME on December 12, 2008 shifted from 73° to 61° . The angular width of CMEs on March 25, 2008 and Apr. 26, 2008 also increased by more than 10° when they traveled across the COR2 and HI1 FOVs. While there are uncertainties associated with the model fitting (See Thernisien *et al.*, 2009, for details), we believe that these changes are larger than the fitting errors and thus are true changes of CMEs. Note that our results are generally in agreement with Thernisien *et al.* (2009) who are based on COR2 data only. We now focus on the kinematic evolutions of the CMEs studied.

We show in Figure 4.20 the composite plots of the fitted velocity profiles (upper panel) and the acceleration profiles of the four CMEs studied. It is seen that the leading edge velocities converge to a narrow range between 500 - 750 km/s after about 50 R_S , even though the beginning velocities of these CMEs have a much larger range from 350 km/s to 1500 km/s. For any individual CME, the velocity is almost constant after 50 R_S ; the change is too small to be appreciated by the method employed in this chapter. This observation justifies the choice of the velocity function to be exponential, in order to quickly converge into an asymptotic value.

Further, the rate of change of the velocity, the acceleration, is far from constant with distance (Figure 4.20, lower panel). The acceleration function is also exponential, because

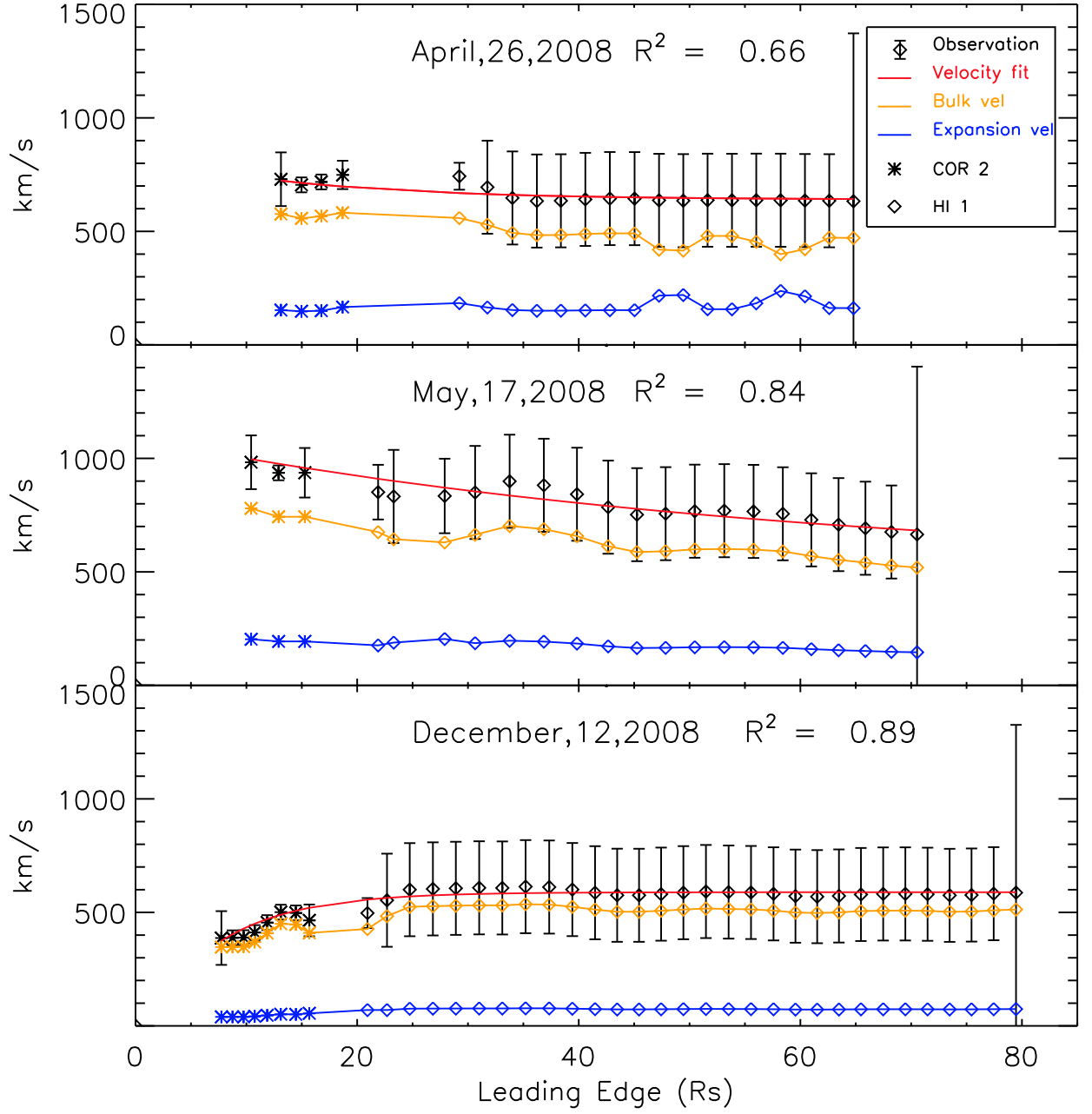


Figure 4.19: Velocity-distances profiles for three CMEs (in the three panels respectively). In each panel, the three curves from top to bottom represent the LE velocity, bulk velocity and expansion velocity respectively. The red line shows the functional fitting to the observed LE velocity. Error bars are only shown for the LE velocity, and they are similar for the other two velocities (not shown to avoid clutter)

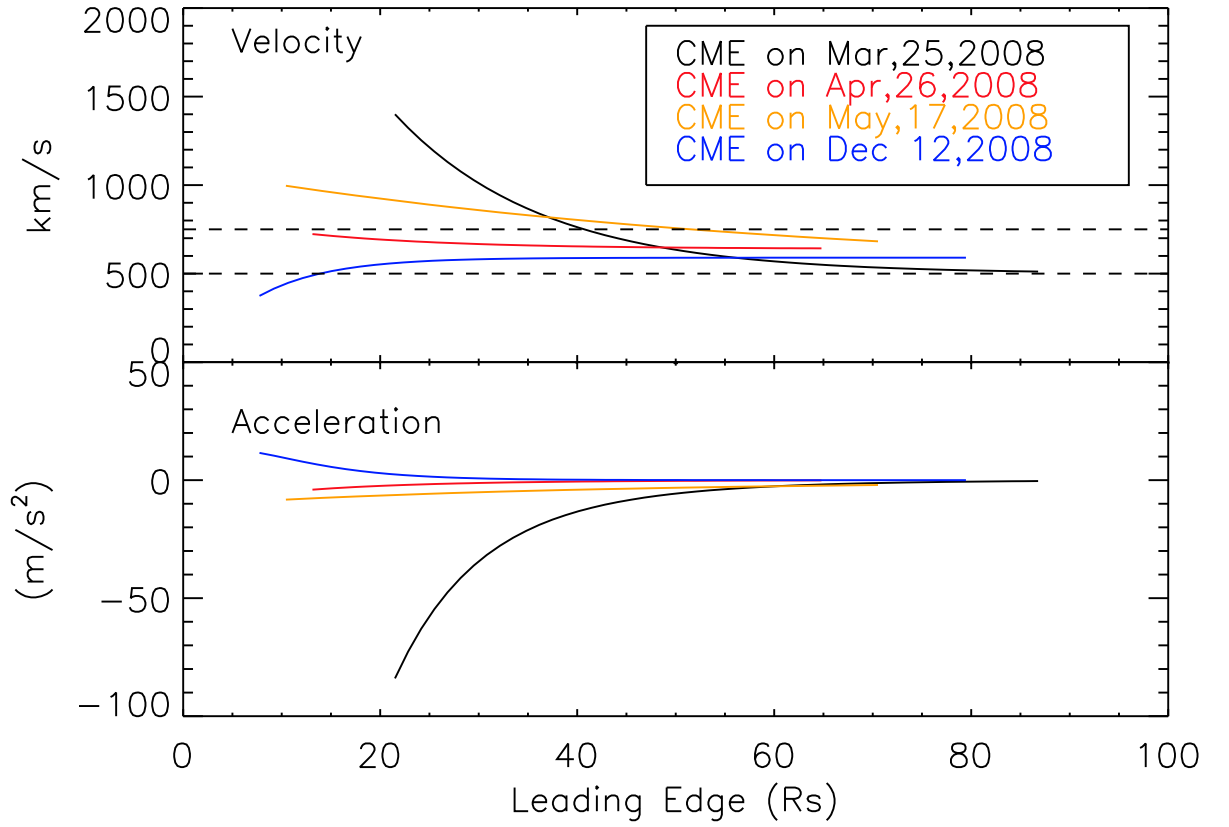


Figure 4.20: The fitted velocity profiles (top panel) and acceleration profiles (bottom panel) for the four events studied. These profiles are described by an exponential function approaching an asymptotic value with distance. Note that the velocities and accelerations quickly converge toward a narrow range as CMEs move out.

of the choice of the velocity function. As seen in the Figure 4.20, the acceleration profiles decrease to a very small value after $50 R_S$, as small as $\pm 5 \text{ m/s}^2$. The acceleration (or deceleration for a fast CME) is much stronger when it is close to the Sun. The initial acceleration of March 25, 2008 CME has a value of -83.9 m/s^2 when the CME is at $15 R_S$. This value is -8.3 m/s^2 for May 17, 2008 event. For the gradual and slow CME on Dec. 12, 2008, the initial acceleration is $+11.5 \text{ m/s}^2$ at about $8 R_S$. On the other hand, the Apr. 26, 2008 CME shows very small acceleration in the entire FOV studied: the acceleration is only -4.0 m/s^2 at the distance of $13 R_S$ from the Sun.

Another interesting result is that the expansion velocity is largely proportional to the LE velocity (Figure 4.19). This is true for both decelerating fast events and the accelerating slow event. When the LE velocity decreases, the expansion velocity decreases. Similarly, when the LE velocity increases, the expansion velocity also increases. The parameter of the aspect ratio (κ) measured in the geometric model (column 6 in Table 4.2) is equal to the ratio between the expansion velocity and the LE velocity. For the three fast events studied, the ratio is between 0.2 and 0.3, indicating that the LE velocity is about three to five times larger than the expansion velocity. For the gradual and slow event, the expansion velocity is about 10 times smaller than the LE velocity. Further, the expansion velocity may become relatively smaller compared to the LE velocity as the distance from the Sun increases, since the aspect ratio seems to increase with the distance (Nevertheless, the study of the quantitative change of the aspect ratio with distance is difficult, because of the limited accuracy of the measurement).

4.8 Conclusion and Discussions

There are several new findings in this study. First, the leading edge velocity of CMEs converges rather quickly in interplanetary space, e.g., from an initial range between 400 km/s to 1500 km/s at 5 to $10 R_S$, to a narrow range between 500 km/s to 750 km/s at about $50 R_S$. Expansion velocities are also found to converge into a narrow range between

75 km/s and 175 km/s. Secondly, both leading edge and expansion velocities for any individual CME are nearly constant after $50 R_S$. Third, the acceleration of CMEs in the inner heliosphere from ~ 10 to $90 R_S$ can be modeled by an exponential function. Fitting the leading edge velocity to an exponential function has been done before Sheeley *et al.* (1999). However, we show in this chapter that this functional form is valid for a large distance in interplanetary space.

It seems that the kinematic evolution profile in the inner heliosphere is probably attributed to the drag force between the CME and the ambient solar wind. The observed initial deceleration for fast events, which is in the order of tens of m/s^2 , cannot be explained by the gravitational force and the slow-down effect of mass pile-up in front of CMEs (Sheeley *et al.*, 1999). The solar wind drag force is proportional to the square of the velocity difference between the CME and the solar wind (e.g. Chen, 1996; Cagill, 2004). Therefore, the acceleration is the largest when the velocity difference is the largest, and goes to almost zero when the two velocities are close to each other. The asymptotic value of the CME velocity seems to be constrained by the ambient solar wind speed.

The close correlation between the expansion velocity and the LE velocity of individual CMEs indicates that, to the first order of approximation, the CME evolution can be treated as a self-similar expansion superposed on the bulk outward motion. The expansion contributes a non-trivial component to the overall velocity at the leading edge, e.g., 30% for fast events and 10% for slow events. It is likely that this expansion is driven by the CME internal thermal pressure overcoming the ambient solar wind pressure (Wang *et al.*, 2009). We have carried out a detailed theoretical study of the CME expansion, as well as the bulk propagation in the inner heliosphere. This theoretical study is presented in the next chapter.

Table 4.2: Geometric and kinematic parameters of CMEs in the inner heliosphere.

Date/time	ϕ ¹	θ ¹	γ ¹	LE ¹	κ ¹	α ¹	r_i ¹	r_a ¹	V_i ¹	V_a ¹	a ²
YYMMDD HH:MM	(°)	(°)	(°)	R_S	(°)	R_S	R_S	R_S	km/s	km/s	m/s ²
³ 20080325 20:22	199	-12	-44	10	0.20	21	15.0	-	1400.0	-	-83.9
⁴ 20080326 16:49	199	-5	-44	86	0.30	28	-	21.5	-	500.0	-
20080426 17:22	204	3	-16	13	0.20	12	13.7	-	720	-	-4.0
20080427 08:09	204	-4	-16	79	0.27	23	-	15.0	-	640	-
20080517 11:52	261	-12	-35	10	0.20	15	10.0	-	1000	-	-8.3
20080518 00:49	261	-11	-35	70	0.21	15	-	60.0	-	500	-
20081212 10:22	73	7	87	7	0.10	18	6.0	-	350	-	11.45
20081213 11:49	61	6	87	79	0.12	19	-	9.0	-	590	-

¹: The meanings these parameters are as indicated in the text.

²: The initial acceleration rate at r_i .

³: The first time of the CME appearing in COR2 FOV with effective measurement.

⁴: The last time of the CME appearing in HI1 FOV with effective measurement.

Chapter 5: Model Explanation of CME Evolution

5.1 Introduction

As mentioned in chapter one, the major causes of geomagnetic activities are CMEs and ICMEs, which are considered to be of a flux rope-like structure by the solar community (Goldstein, 1983; Farrugia *et al.*, 1993; Chen & Garren, 1993; Lynch *et al.*, 2008). The idea of flux rope is supported by many observational studies of CMEs from Wood *et al.* (1999); Dere *et al.* (1999); Chen *et al.* (2000); Plunkett *et al.* (2000); Krall *et al.* (2001); Vandas *et al.* (2001); Thernisien *et al.* (2006). When a flux rope CME propagates into the interplanetary medium it becomes an ICME, it usually conforms to the six defining characteristics of a magnetic cloud (MC). The six signatures that define a magnetic cloud in interplanetary space are a strong magnetic field (Klein & Burlaga, 1982), a large rotation of the magnetic field (Klein & Burlaga, 1982), low proton temperature (Richardson & Cane, 1995), high ratio of oxygen charge state ($O^{+7}/O^{+6} > 1$) (Zurbuchen *et al.*, 2003), low plasma beta (Zurbuchen & Richardson, 2006), and low ratio of proton temperature to the expected temperature (Gosling *et al.*, 1973).

Many existing studies provide useful but limited knowledge on CME dynamic evolution in interplanetary space. The solar community still has many important unanswered questions from both scientific and practical points of view. How does the velocity of a CME change enroute to the Earth? Apparently, the assumption of constant acceleration is an over-simplification, yielding poor results in predicting the arrival time of an ICME at 1 AU. This issue is practically important in forecasting space weather. How does a CME expand while it propagates through interplanetary space? A good understanding of this issue helps predict the possibility of a CME impacting the Earth. How do the physical states of a

CME evolve with time, such as internal magnetic field, density, temperature and pressure? Understanding physical state can clarify all forces acting on the flux rope evolution.

In this chapter, I address these problems through model calculation of CME evolution in the interplanetary space. In previous studies, Chen (1996) used these equation 5.2 and equation 5.10 and their variation with distance for a set of CMEs observed by COR2 and HI1. The novel approach in my study is that I start to evolve the Eruptive Flux Rope (**EFR**) model from a few solar radius above the solar surface without worrying about the detailed initiation mechanism of CME close to the surface. In the next section, some existing CME evolution models are introduced. Several existing simulations showed that one model can produce different kinematic profiles by simply varying the initial conditions and magnetic environment (Chen, 1989; Lynch *et al.*, 2008; Schrijver *et al.*, 2008). Therefore, observational constraints of theoretical models are important. In section 5.3, I discuss the theoretical model used in my simulation. The numerical methodology for solving the flux rope model is introduced in the appendix. The parameter space study of key model parameters will be discussed in section 5.4. Section 5.5 presents the flux rope fitting and compares the model results with observational data from STEREO/SECCHI spacecrafts. Discussion are presented in Section 5.6.

5.2 Existing Models of CMEs Evolution

Studies of CME evolution have produced a few theoretical models. The first CME evolution model is the eruptive flux rope model or **EFR** by Chen (1996) and the other is Melon-Seeds-Overpressure-Expansion or MSOE model by Siscoe *et al.* (2006). The MSOE uses the same external density function as the **EFR** model (Chen, 1996). However, the MSOE does not consider internal magnetic structure such as the effect of internal magnetic pressure, which cause the expansion of CMEs. In addition, the MSOE model does not include the solar wind profile, which is important for calculating the drag force. Therefore, this dissertation will largely follow Chen's flux rope model, which takes into account the internal magnetic

field.

5.2.1 Eruptive Flux Rope Model

The Eruptive Flux rope or **EFR** by Chen (1989) assumes a torus-geometry. Figure 5.1 from Chen (1996) shows the schematic of a toroidal flux rope embedded in the corona. The current loop has a major radius R , minor radius (a), footpoint separation (S_f) and Z is a center of mass of the apex height from the chromosphere. Figure 5.1 is the view from the side and the plane of the flux rope is on the plane of the paper. The arrow on the upper right is the end-on viewing perspective. In addition, the current density consists of two components, the toroidal and the poloidal. J_t flows along an axial field of the flux rope and J_p goes around the flux rope. Two other important components in the flux rope are toroidal and poloidal magnetic fields, which twist along the axial field and flow around the flux rope, respectively. Another parameter in this model is B_c , which is an ambient magnetic field. The ambient field is assumed to be perpendicular to the plane of the flux rope. The angular position θ is the angle measured from the footpoint ($\theta = \theta_f$). F_R is the net force acting on the major radius of the flux rope as shown in equation 5.2.

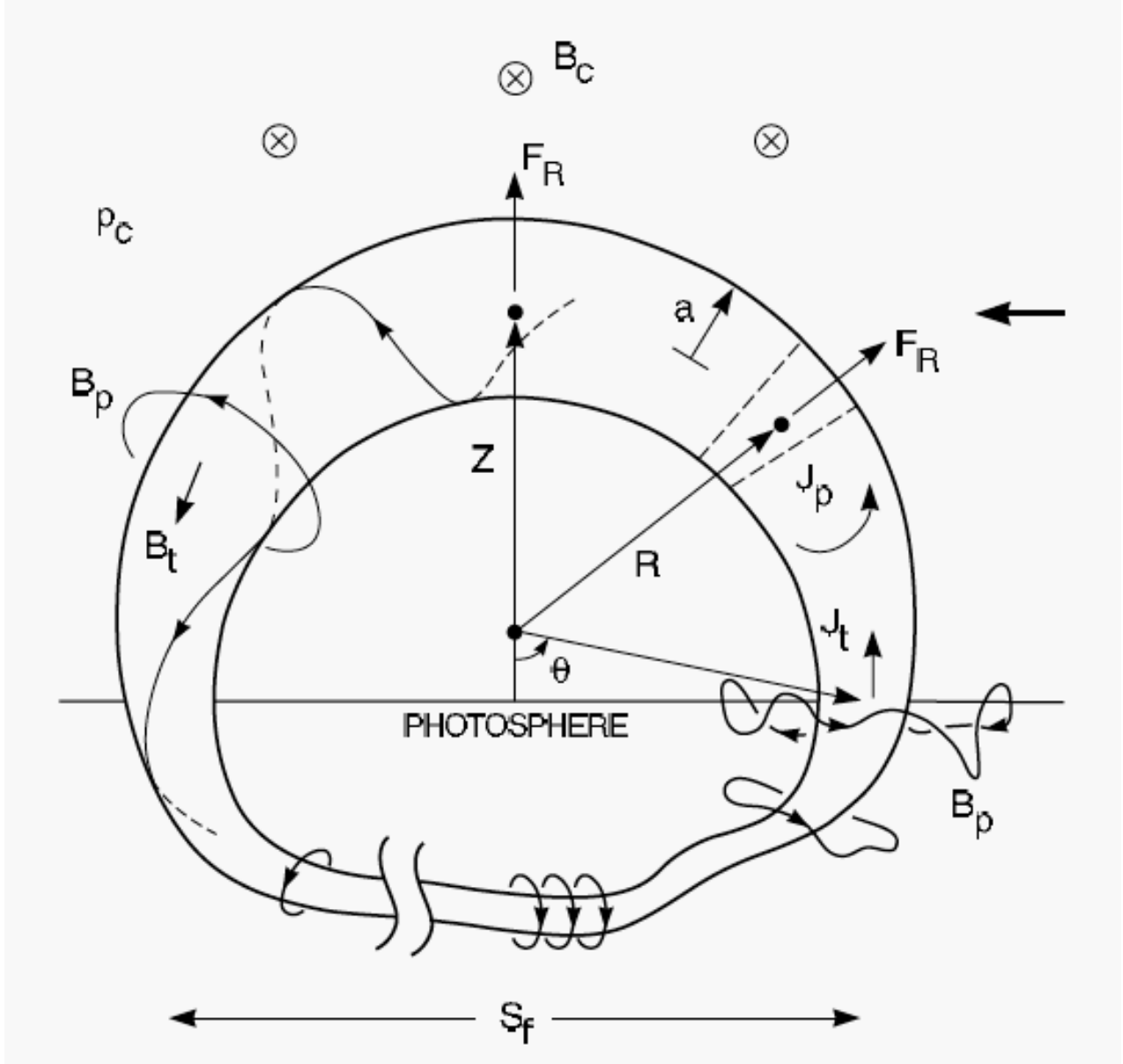


Figure 5.1: The schematic of the Eruptive Flux Rope model. The current loop has a major radius R and minor radius a and footpoint separation (S_f). Z is a center of mass of the apex height from the photosphere. The current density consists of two components, the toroidal and the poloidal. J_t flows along an axial field of the flux rope and J_p goes around the flux rope. Two other important components in the flux rope are the toroidal and poloidal magnetic field, which twist along the axial field and flow around the flux rope, respectively. The figure 5.1 is the views from the side and the plane of the flux rope is the plane of the paper. The arrow on the upper right is the end-on viewing perspective (Chen, 1996).

The **EFR** model assumes a torus-geometry. The torus major radius, apex height, and distance between the two footpoints are related as

$$R(t) = \frac{Z^2 + \frac{S_f^2}{4}}{2Z(t)} \quad (5.1)$$

In the **EFR** model, major radial and minor radial equations control the bulk propagation motion and expansion motion respectively and are driven by a set of different forces. The major radial equation is controlled by four kinds of forces: Lorentz force, thermal pressure force, gravity force and drag force. The net force per unit length in the major radius can be calculated by the first derivative of inductance and energy equations, and the net force on the major radius is shown in equation 5.2

$$F_R = \frac{I_t}{C^2 R} \left[\ln\left(\frac{8R}{a}\right) + \frac{1}{2}\beta_p - \frac{1}{2}\frac{B_t^2}{B_{pa}^2} + 2\frac{R}{a}\frac{B_s}{B_{pa}} - 1 + \frac{\xi_i}{2} \right] + F_g + F_d \quad (5.2)$$

B_t is the toroidal field component. $B_{pa} = B_p(a)$ represents the poloidal field component on the surface of the torus. B_s , or external magnetic field, is perpendicular to the toroidal field, and $\xi_i = 2 \int \frac{r B_p^2(r) dr}{a^2 B_{pa}^2}$ is the internal inductance. Part of the internal inductance is related with current distribution. $\beta_p = 8\pi(\bar{P} - P_a)/B_{pa}^2$, where $\bar{P}$ is the average pressure inside the flux rope, P_a is the ambient coronal pressure.

The first, fifth, and sixth terms ($\ln(\frac{8R}{a} - 1 + \frac{\xi_i}{2})$) in the equation 5.2 come from $J_t X B_p$ force that push the CME outward. The third term in the equation is the $J_p X B_t$ force ($-\frac{1}{2}\frac{B_t^2}{B_{pa}^2}$), which always pulls the CME down toward the surface of the Sun. Ratio of pressure is $+\frac{1}{2}\beta_p$, which usually pushes the CME outward. The forth term is the overlying field Lorentz force, which prevents CME eruption.

The following equation is the gravitational force per unit length, which is given by

$$F_g = \pi a^2 m_i g(Z) (n_a - \bar{n}_T) \quad (5.3)$$

Where m_i is the ion mass, and n_a is the ambient solar wind density. $\bar{n}_T = \bar{n}_c + \bar{n}_p$ is the total density of the loop and subscript c refers to cavity material and p to prominence material. The gravity force might pull the CME down to the surface or push the CME out to the corona, depending on the relative difference of the flux rope density (n_T) and that of the solar wind (n_a) with respect to ambient density. If the density of the flux rope is greater than the density of the solar wind, the gravity force will pull the CME down to the solar surface. But if the density of the ambient solar wind is greater than the density of flux rope, F_g will pull the flux rope out to the corona, and is equivalent to the buoyancy force. Since the temperature of prominence is less than the temperature of the cavity ($T_p \ll T_c$). The thermal pressure is calculated by $\bar{p} = 2\bar{n}_c k \bar{T}_c$. Within the flux rope the equation of state is given by

$$\frac{d}{dt} \left(\frac{\bar{p}}{\bar{\rho}^\gamma} \right) = 0 \quad (5.4)$$

The average mass density within the flux rope is given by $\bar{\rho} = \bar{n}_c m_i$, and γ is the polytropic index $1 \leq \gamma \leq \frac{5}{3}$. One of the issues I study is how the effect of varying the polytropic index (γ). Chen (1996) used a constant value of 1.2. The equation for internal pressure becomes

$$\bar{p} = C_\gamma \bar{\rho}^\gamma \quad (5.5)$$

Where the constant C_γ is found with the initial equilibrium values and is equal to

$$C_\gamma = \frac{2k\bar{T}_c}{\bar{n}_c^{\gamma-1} m_i} \quad (5.6)$$

where m_i is the ion mass, and k the Boltzmann constant. The total gravitational acceleration is given by

$$g(Z) = \frac{g_s}{(1 + \frac{Z}{R_\oplus})^2} \quad (5.7)$$

Where $g_s = 2.74 \times 10^4 \text{ cm/s}^2$ and $R_\oplus = 6.96 \times 10^5 \text{ km}$ the solar radius. Z is apex height above photosphere. Another force is the drag force F_d which is given by

$$F_d = c_d n_a m_i a (V_a - V) |V_a - V| \quad (5.8)$$

where c_d is the drag coefficient. V_a is the ambient solar wind speed. $V \equiv \frac{dz}{dt}$ is the apex speed. The drag force can also pull or push the CME, because it depends on the velocity difference. If the velocity of the solar wind is greater than the velocity of the flux rope, the F_d will accelerate the flux rope outward. However, if the velocity of the ambient solar wind is less than the velocity of the flux rope, the flux rope will be decelerated by the drag force. The determination of the drag force and its variation with distance is one of the main issues in this dissertation.

The expansion of the flux rope is described by the forces acting on the minor radius, a , which is

$$F_a = M \frac{dw}{dt} = \frac{I_t}{c^2 a} \left(\frac{B_t^2}{B_{pa}^2} - 1 + \beta_p \right) \quad (5.9)$$

Where w is the rate of expansion or minor radial expand speed $\frac{da}{dt}$. $I_t \equiv 2\pi \int J_t(r) r dr$ is the toroidal current component. M is the mass of the flux-rope, $M = \pi a^2 \bar{n}_T m_i$. B_t , B_{pa} , and B_p are discussed before. β_p equals to $8\pi(\bar{P} - P_a)/B_{pa}^2$. F_a can be rewritten as equation 5.10.

$$F_a = \frac{I_t}{c^2 a B_p^2} (B_t^2 - B_p^2 + 8\pi(\bar{P} - Pa)) \quad (5.10)$$

Therefore, the net minor radial force depends on the toroidal magnetic field, poloidal magnetic field, pressure of flux rope and ambient pressure. Toroidal magnetic field and pressure of the flux rope tend to expand the minor radius. However, the poloidal magnetic field and the ambient pressure limit the expansion of the minor radius.

In the original Chen (1996) flux rope model, F_R , F_d and F_a is zero when it starts from equilibrium. However, the modified model starts from a few solar radii above the solar surface. Therefore, the new poloidal magnetic field is shown in equation 5.11. The equation 5.11 is same as Chen (1996) when F_R , F_d and F_a are zero.

$$B_p = \frac{A_1 \pm [A_2 - A_3]^{0.5}}{A_4} \quad (5.11)$$

A_1 , A_2 , A_3 , and A_4 represent as

$$A_1 = (2B_s(\frac{R}{a})) \quad (5.12)$$

$$A_2 = (2B_s(\frac{R}{a}))^2 - 4(\ln(\frac{8R}{a}) - \frac{3}{2} + \frac{\xi_i}{2})8\pi(\bar{P} - Pa) \quad (5.13)$$

$$A_3 = (\frac{2}{a^2}(2(F_R - F_d - F_g)R + aF_a)) \quad (5.14)$$

$$A_4 = 2(\ln(\frac{8R}{a}) - \frac{3}{2} + \frac{\xi_i}{2}) \quad (5.15)$$

B_t can be calculated from

$$B_t^2 = (1 + F_a \frac{c^2 a}{I_t^2}) B_p^2 - 8\pi(\bar{P} - p_a) \quad (5.16)$$

The toroidal current is related to the poloidal flux by

$$I_t = \frac{\Phi_p}{cL} \quad (5.17)$$

The inductance function L is described in terms of major radius R , minor radius at footpoint, and minor radius at apex.

$$L(R, a_a, a_f) \equiv \frac{1}{2} [ln \frac{8R}{a_f} + ln \frac{8R}{a_a}] - 2 - \frac{\xi_i}{2} \quad (5.18)$$

Chen (1996) also presents ambient density function, which depends on height (Z). The density function is represented by the following equation 5.19;

$$n_a(Z) = 4(3R_S^{-12} + R_S^4) \times 10^8 + 3.5 \times 10^5 R_S^{-2} \quad (5.19)$$

Where $R_S \equiv Z + R_{\oplus}$ is the heliocentric distance. Unit of n_a and $R_{\oplus}$ are in cm^3 and cm respectively.

In Chen (1996), the flux rope model uses the magnetic field profiles as a function of secant, which goes to zero in a few solar radius. However, this model starts from a few solar radii above the Sun. Therefore, I simply use Parker's spiral magnetic field profile in interplanetary space, which presents in equation 5.20.

$$B_s = B_{s0} \frac{Z_0^n}{Z^n} \quad (5.20)$$

Z_0 is the initial height and Z is the apex height of the flux rope as show in figure 5.1. n represents the power index, which equals to one. In this study, I need to modify the external magnetic field equation that takes into account the velocity difference between the solar wind velocity and CME velocity. Unlike the low corona, the ambient magnetic field moves together with the solar wind in interplanetary space. The following equation 5.21 represents the solar-wind-modified in my model.

$$B_{sw} = B_s \frac{(V_a - (V + w))}{(V + w)} \quad (5.21)$$

B_s refers to the external magnetic field at a certain height. In the EFR model, w represents the expansion velocity of the flux rope. V is CME velocity. V_a is solar wind speed. This equation indicates that the ambient magnetic field is able to push out or pull down CMEs depending on the relative velocity between ambient solar wind and CME.

Another prescribed equation from the **EFR** model is the solar wind profile. Chen (1996) suggested that the solar wind profile is a hyperbolic tangent profile, which approaches V_{SW} near $Z \simeq 40R_S$. The solar wind profiles with distance that we use Coles *et al.* (1991, figure 4, 5).

$$V_{SW} = \begin{cases} 0 & Z < Z_0 \\ V_{SW0} * (A - \frac{B}{C}) & Z > Z_0 \end{cases} \quad (5.22)$$

A, B and C are in the tangent hyperbolic function, and τ_1 and τ_2 are the free parameters in solar wind profile. Z_0 is initial height. The form of these equations were found empirically by Chen (1996).

$$A = \tanh \frac{\frac{Z-Z_0}{R_S} - \tau_1}{\tau_2} \quad (5.23)$$

$$B = \tanh \frac{-\tau_1}{\tau_2} \quad (5.24)$$

$$C = 1.0 - \tanh \frac{-\tau_1}{\tau_2} \quad (5.25)$$

In this section, I have introduced the **EFR** model. In this model, major and minor radius forces are both included as equation 5.2 and equation 5.10. The internal and external magnetic fields are both explicitly represented. This is the main reason why I choose the **EFR** model, in order to explain the detailed observations of the kinematics and morphology evolution of CMEs in the interplanetary space as presented in Chapter 4.

5.3 Flux Rope Parameters

The previous section explained the major and minor radius equation from the eruptive flux rope model by Chen (1996). Since there are many parameters involved in the model, this section further discuss the parameters needed for the flux rope model to explain the physics of the evolution of CMEs in interplanetary space. I classify these parameters into three types: parameters constrained by observations, parameters prescribed from reasonable assumptions, and unknown free parameters. Table 5.1 shows the parameters constrained by observation, which are ambient solar wind (V_{SW0}) at 1 AU or large distances, initial acceleration of propagation motion (a_0) and initial acceleration of expansion motion (a_{w0}). Ambient solar wind usually goes from 100 to 600 km/s, which can be determined from in-situ observations. The initial acceleration of propagation (a_0) and expansion (a_{w0}) are derived by the fitting study as shown in Chapter 4.

Table 5.2 presents the prescribed parameters which are ambient solar wind density (N_a) profile with distance, ambient temperature (T_a) and ambient magnetic field (B_{ssw} profile with distance. The solar wind density, ambient temperature, and ambient magnetic field can be prescribed with empirical equations, which I provide in Table 5.2. The ambient solar wind density equation was a modified version by Bird & Edenhofer (1990) to fit the

observations from the Helios spacecraft. The ambient temperature equation is an empirical fitting formula to match with observations. The modeling of the flux rope model in this dissertation starts from a few solar radii above the solar surface, where the flux rope and solar wind speed have picked up. However, the flux rope model by Chen (1996) starts from the solar surface, which means the model does not need to deal with initial solar wind velocity because solar wind velocity at the solar surface is zero. Moreover, Chen’s flux rope starts from equilibrium, which means the initial flux rope velocity equal to zero. In our model calculation, we have to provide a non-zero initial solar wind speed, and a non-zero flux rope speed. We will use the same prescribed profiles for different CME events in our study.

Table 5.3 shows the free parameters in the flux rope model, which vary from event to event. These free parameters can be adjusted, by trial and error, to fit observations provided from chapter 4. Drag coefficient is a component of the drag force, which needs to be modified to fit the propagation velocity over a large distance. I found that the drag coefficient C_d ranges from 2.5 to 3.0, depending on the CME velocity. γ is the polytropic index, which can be found by fitting the expansion equation with observation, resulting in a polytropic index between 1.35 – 1.4. However, many studies use different values for the polytropic index. For instance, Chen (1996) uses 1.2 for the polytropic index. The MAS model picks 1.5 (Totten *et al.*, 1995). Other free parameters include footpoint separation, initial height of the flux rope and mass of the flux rope. In next section, I will make a parameter study, to find how sensitive the model results depend on these free parameters.

Table 5.1: Parameters Constrained by Observation

Parameters Constrained by Observation		
Parameters	Name	Detail
V_{SW0}	Ambient solar wind at 1 AU	0 - 600 km/s
w_0	Initial expansion velocity	From observation
V_0	Initial propagation velocity	From observation
a_0	Initial acceleration of bulk motion	From observation
a_{w0}	Initial acceleration of expansion motion	From observation

Table 5.2: Parameters Prescribed

Parameters Prescribed		
Parameters	Name	Detail
N_a	Ambient density profile	$N_a(Z) = 4 * (3R_s^{-12} + R_s^{-4}) * 10^8 + 3.5 * 10^5 * R_s^2$
T_a	Ambient temperature profile	$T_a(Z) = T_0 * R_s^{-\alpha}$
B_{ssw}	Ambient magnetic field profile	$B_s = B_{S0} \frac{Z_0^n}{Z^n}$

Table 5.3: Free Parameters

Free Parameters		
Parameters	Name	Detail
C_d	Drag coefficient	Between 0 - 10
γ	Polytropic index	Between 1.3 - 1.6667
M	Mass of the flux rope	Between $10^{14} - 10^{16}$ grams
S_0	Footpoint separation	trivial
Z_0	Initial height of the flux rope	trivial

5.4 Parameter Study

5.4.1 Dragging Force and Dragging Coefficient

Drag force in the flux rope model tends to dominate the motion of CME propagation in interplanetary space (Chen, 1996; Cagill, 2004; Tappin, 2006; Borgazzi *et al.*, 2009; Vrsnak *et al.*, 2010). Therefore, the free parameter, drag coefficient, is an important parameter that needs to be determined from the model. Special attention will be paid toward the drag force and the drag coefficient in this dissertation.

The top panel of figure 5.2 shows the CME propagation velocity as a function of leading edge distance for different drag coefficients. All other parameters needed for the model calculation, including polytropic index, mass, solar wind velocity, and ambient magnetic field, are fixed. This plot demonstrates that the evolution of the propagation velocity is sensitive to the drag coefficient. The larger the drag coefficient, the more rapidly the propagation velocity decreases. It indicates that solar wind drag force play an important role in propagation velocity.

The bottom panel of figure 5.2 shows the expansion velocity versus distance. The figure shows that the drag coefficient also affects the expansion motion. However, my understanding is that it is an indirect effect of drag coefficient. The true cause of the apparent relation is that the expansion velocity is directly related with the propagation velocity. There is a correlation between expansion velocity and propagation velocity, as shown by the observations in Chapter 4. Theoretically, when a CME propagates fast, its minor radius does not have enough time to expand to a larger size when the CME reaches a certain height. In other words, the minor radius is smaller when a CME propagates faster. A smaller minor radius results in a larger inductance, or a smaller current when the magnetic flux is conserved. As a result of the smaller current, the overall Lorentz force acting on the minor radius is smaller, resulting in larger expansion velocity.

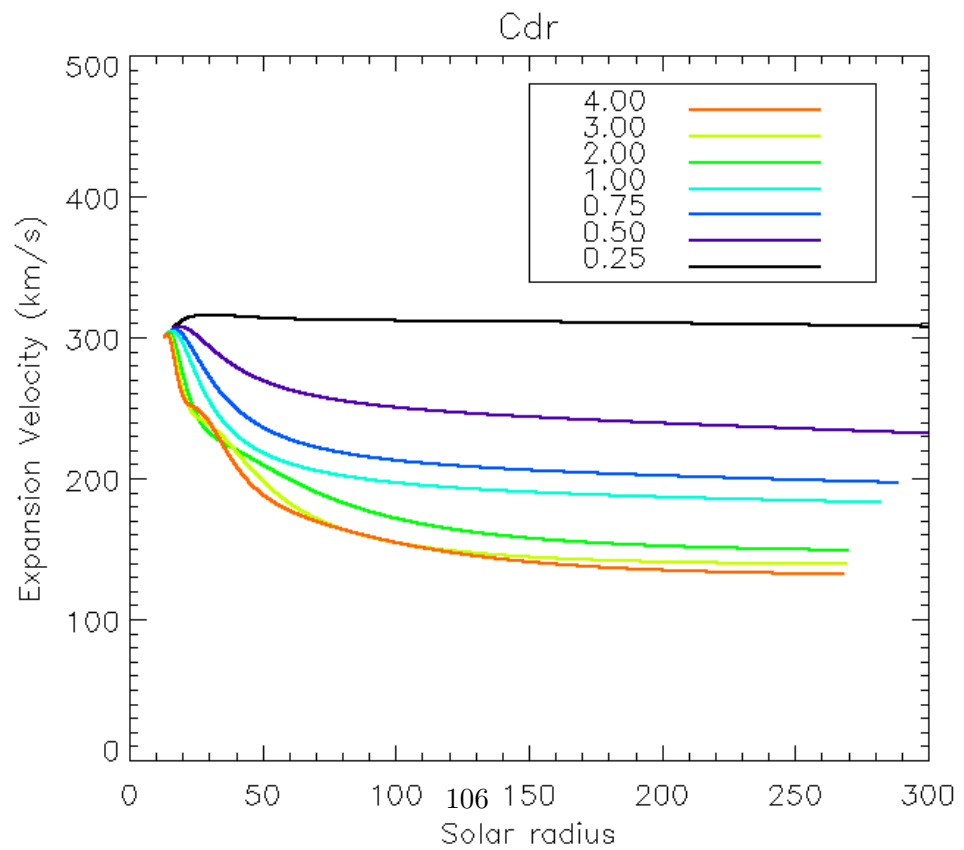
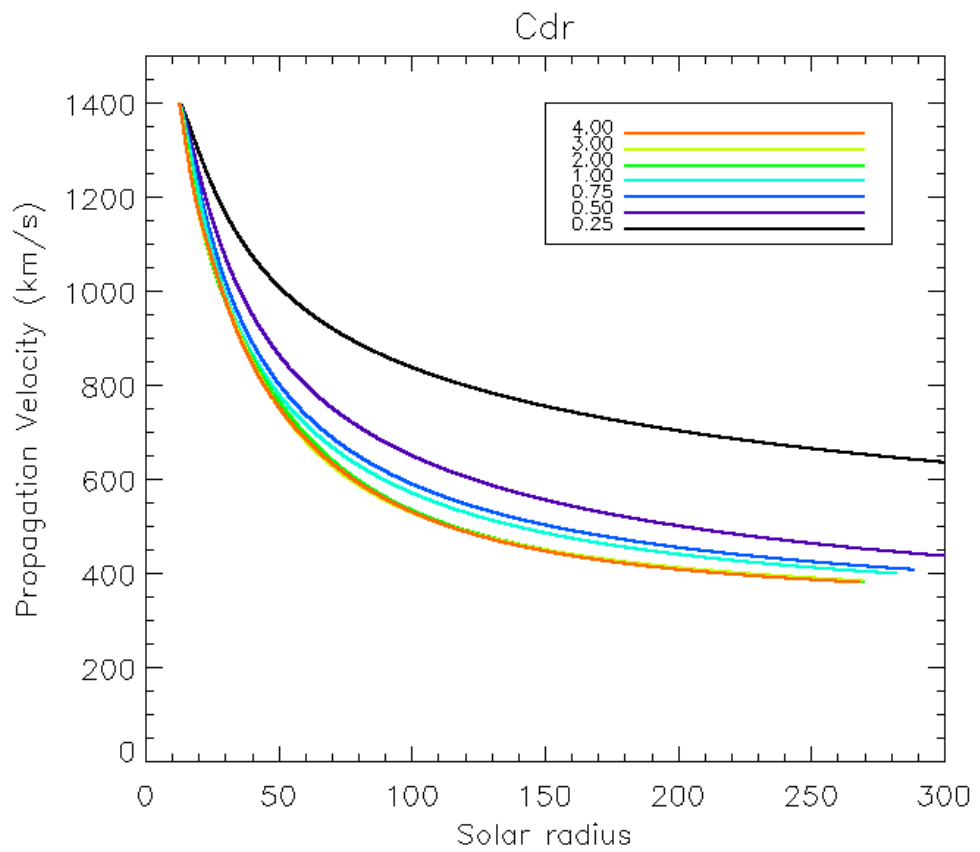


Figure 5.2: Parameter Study of Drag Coefficient

5.4.2 Polytropic Index

The polytropic index plays an important role in CME evolution because the polytropic index regulates the heating process of the plasma as the flux rope expands, thus determines the internal pressure force. I have explained in the beginning of this chapter that four forces are involved CME expansion. These forces are toroidal magnetic field force, poloidal magnetic field force, internal plasma pressure force, and external plasma pressure force. The toroidal magnetic force and the internal plasma pressure force push CMEs outward. On the other hand, the poloidal magnetic force and external plasma pressure prevent CME from expansion into the interplanetary space.

The top panel on figure 5.3 shows how the propagation velocity versus distance varies with polytropic index in these calculation with all other parameters fixed. The Figure indicates that polytropic index affects the propagation velocity after 50 solar radii. Before 50 solar radii, the polytropic index has less effect on the propagation velocity. This is probably caused by the fact that the internal pressure force is relatively not important, when compared with Lorentz force acting on the major radius, at the distance close to the Sun. However, the bottom panel of figure 5.3 shows that the polytropic index affects expansion velocity over all distances. This is expected, because the expansion is sensitive to the internal pressure. A high polytropic index will provide low expansion velocity because less heat is transferred into the plasma. When the index is $5/3$, it would be an adiabatic process. When the index is small, the heat transfer is significant, thus the internal pressure is relatively stronger, resulting in fast expansion. When the index is 1, it is the case of isothermal expansion. The results indicate that the polytropic index is important in expansion motion.

5.4.3 Ambient Solar Wind Velocity

Another parameter to study is the ambient solar wind velocity. The top panel of figure 5.4 represents the propagation velocity, which is affected by ambient solar wind. The ambient solar wind varies from 100 to 600 km/s. If the solar wind velocity is high, the final propagation velocity is also high because the CME speed eventually becomes the same as

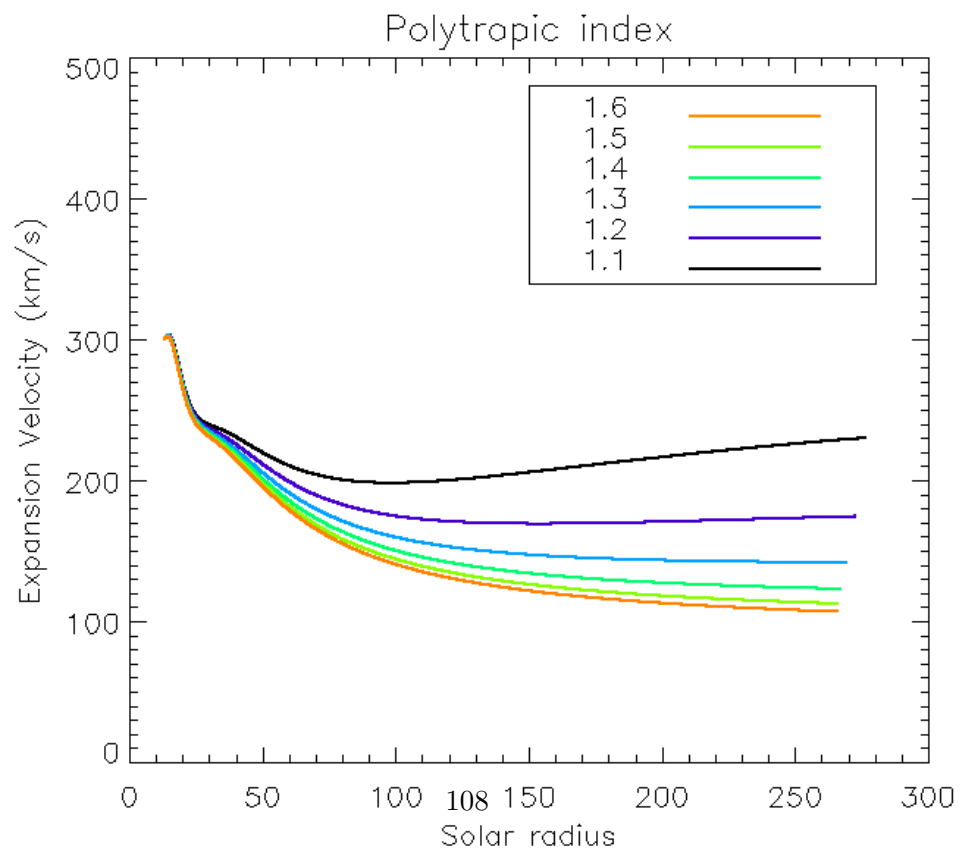
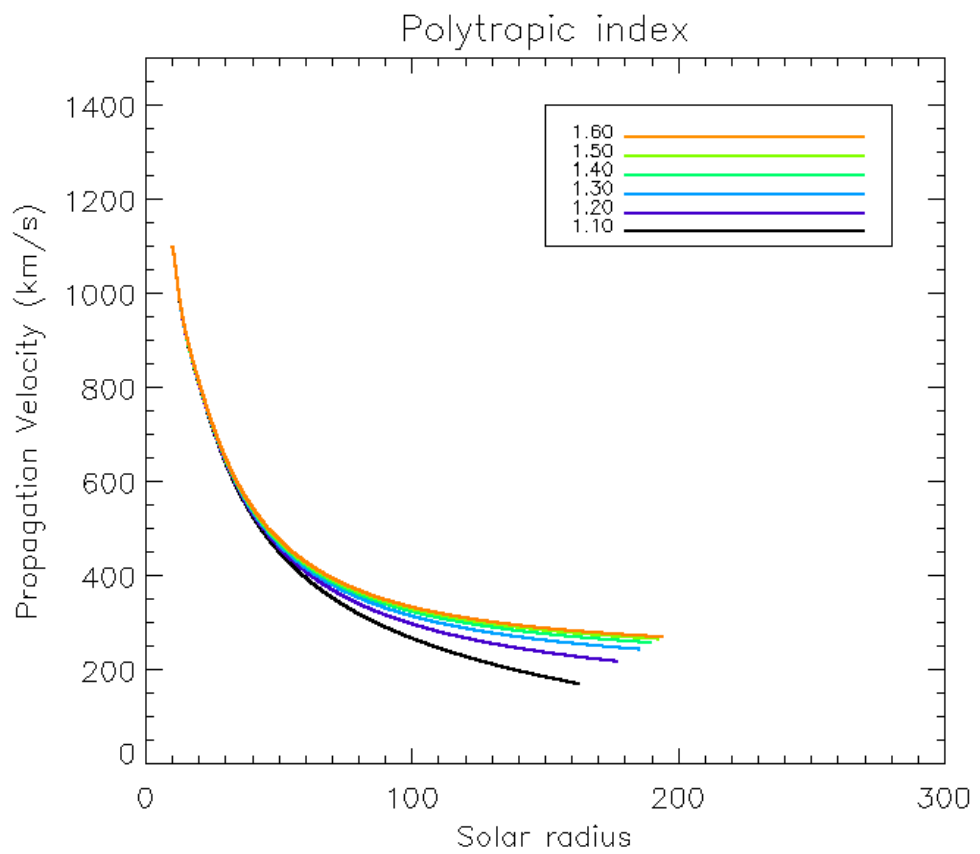


Figure 5.3: Parameter Study of Polytropic Index

the ambient solar wind.

Moreover, the bottom panel of figure 5.4 shows the effect of the ambient solar wind velocity on expansion velocity. AS explained earlier, this is probably the effect of the correlation between propagation velocity and expansion velocity.

5.4.4 Ambient Magnetic field B_{s0}

Ambient magnetic field is another aspect of the parameter study, which has an effect on both propagation and expansion velocity. The top panel of figure 5.5 indicates that high ambient magnetic field causes low propagation velocity because the ambient magnetic field tries to prevent the CME from propagating in interplanetary space. Similarly, high ambient magnetic field provides low expansion velocity. This result is shown in the bottom panel of figure 5.5. This result shows that the ambient magnetic field tries to prevent CME evolution in both propagation and expansion motion.

5.4.5 Footpoint Separation S_0

The last piece of the parameter study is footpoint separation. The top panel of figure 5.6 is the plot of propagation velocity versus leading edge distance with varying footpoint separation. The plot shows that the footpoint separation does not impact on the propagation velocity because the model starts from a few solar radii above the solar surface. The bottom panel of figure 5.6 shows that varying footpoint separation does not have an effect on expansion velocity. This result helps validate our model calculation in which the model starts from the middle of the corona instead from an equilibrium condition in the low corona.

5.5 Flux Rope Fitting with Observational data from SECCHI / STEREO

The first assumption in our model is that the **EFR** starts a few solar radii above the surface of the Sun. It means the **EFR** model is going to ignore the initiation process,

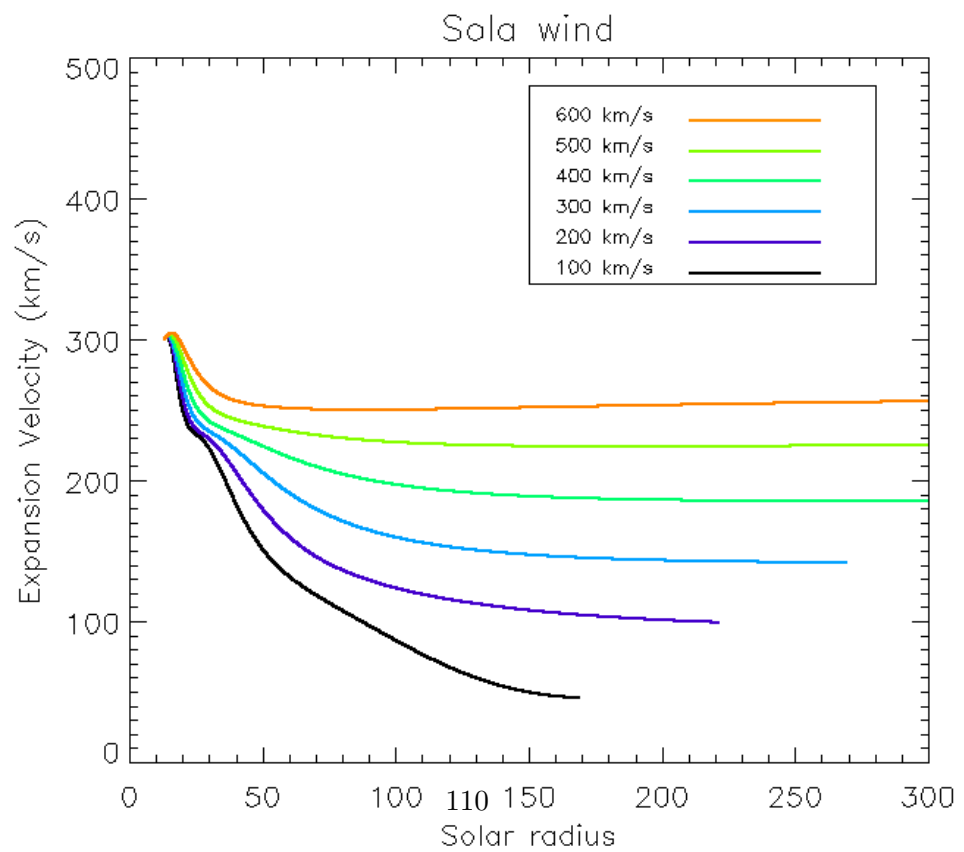
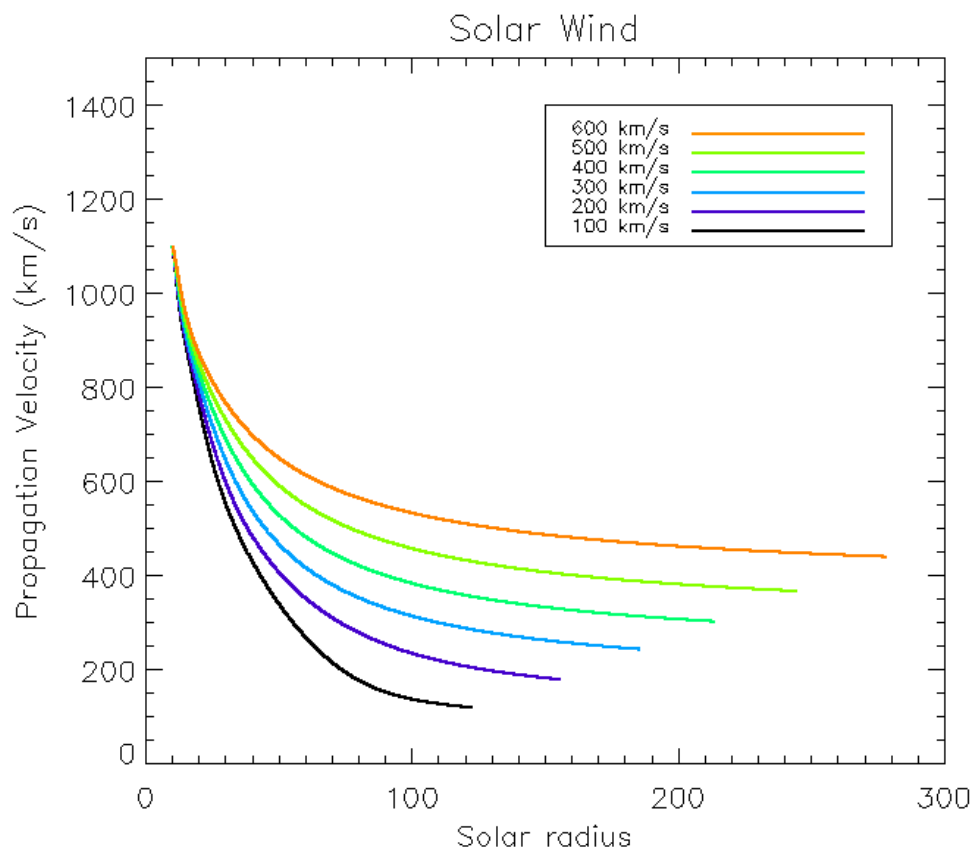


Figure 5.4: Parameter Study of Ambient Solar Wind Velocity

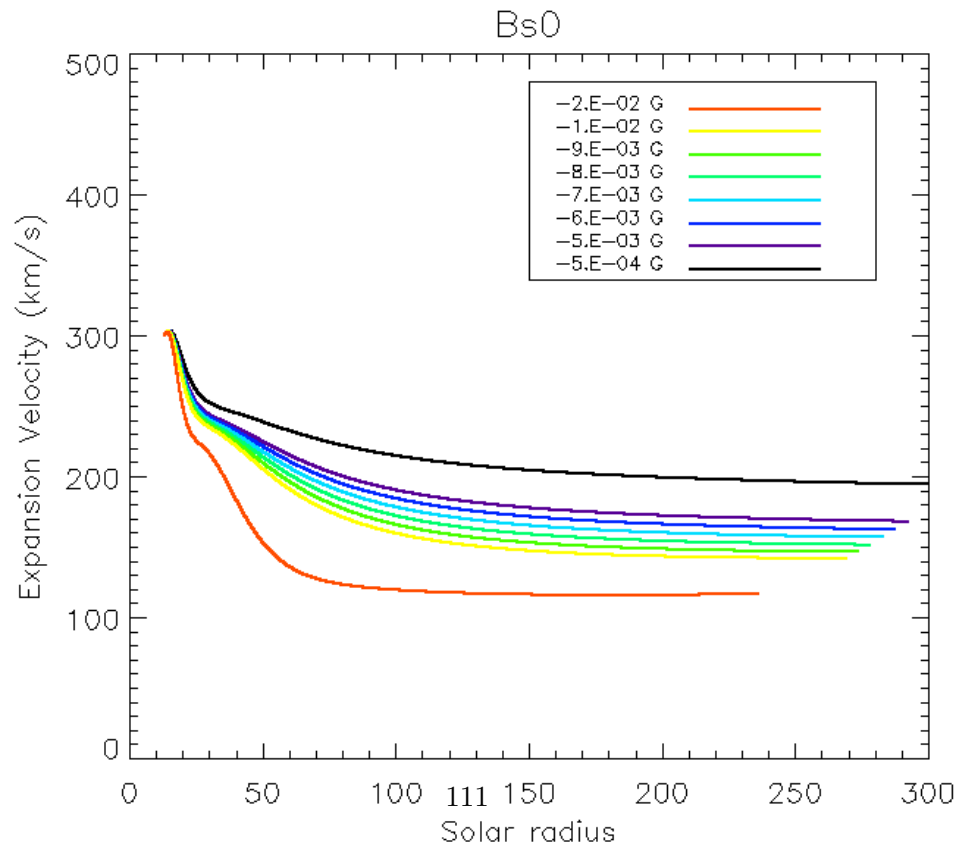
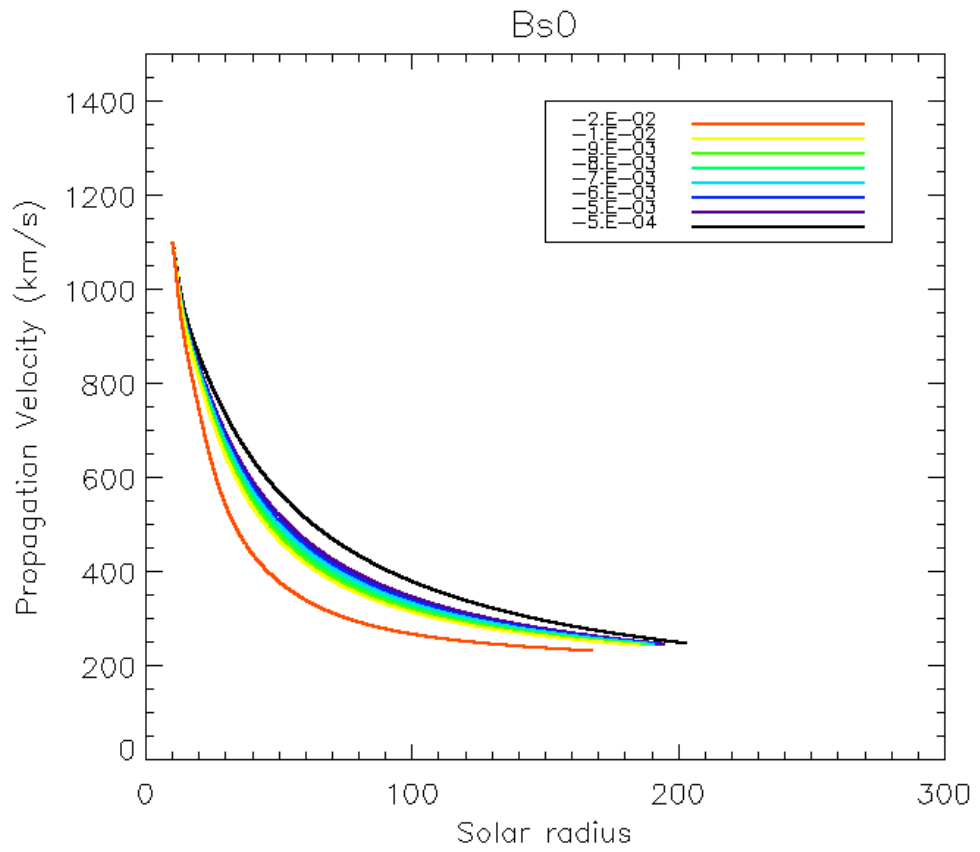


Figure 5.5: Parameter Study of Ambient Solar Wind Velocity

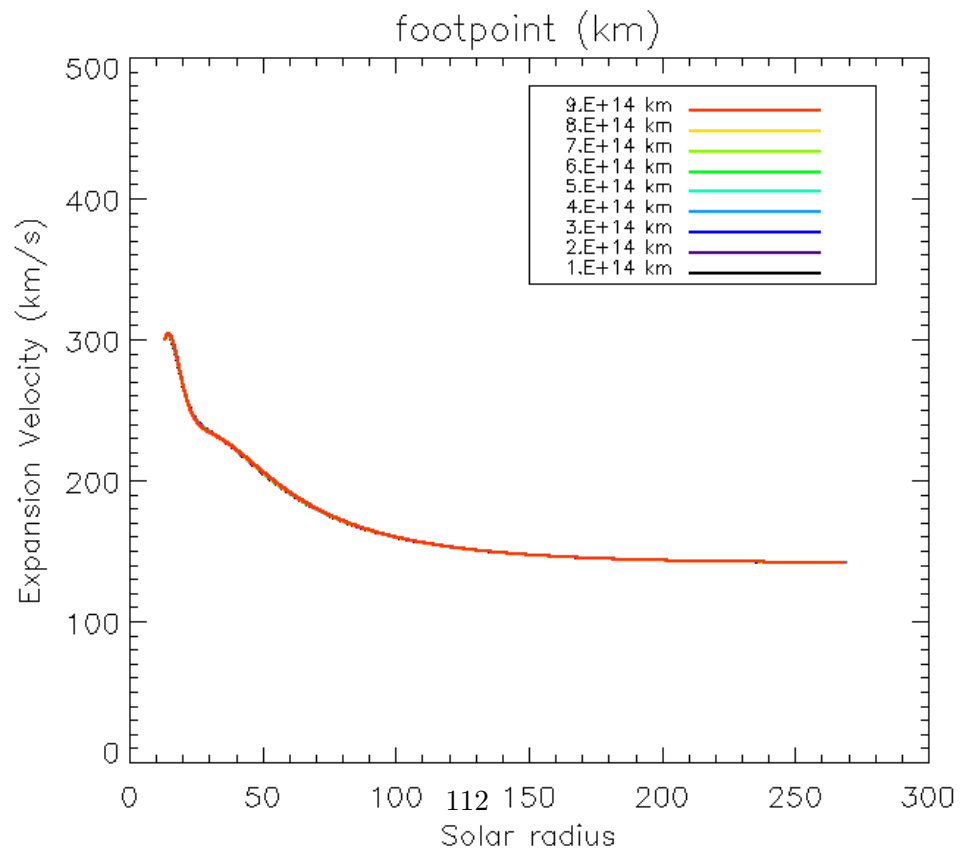
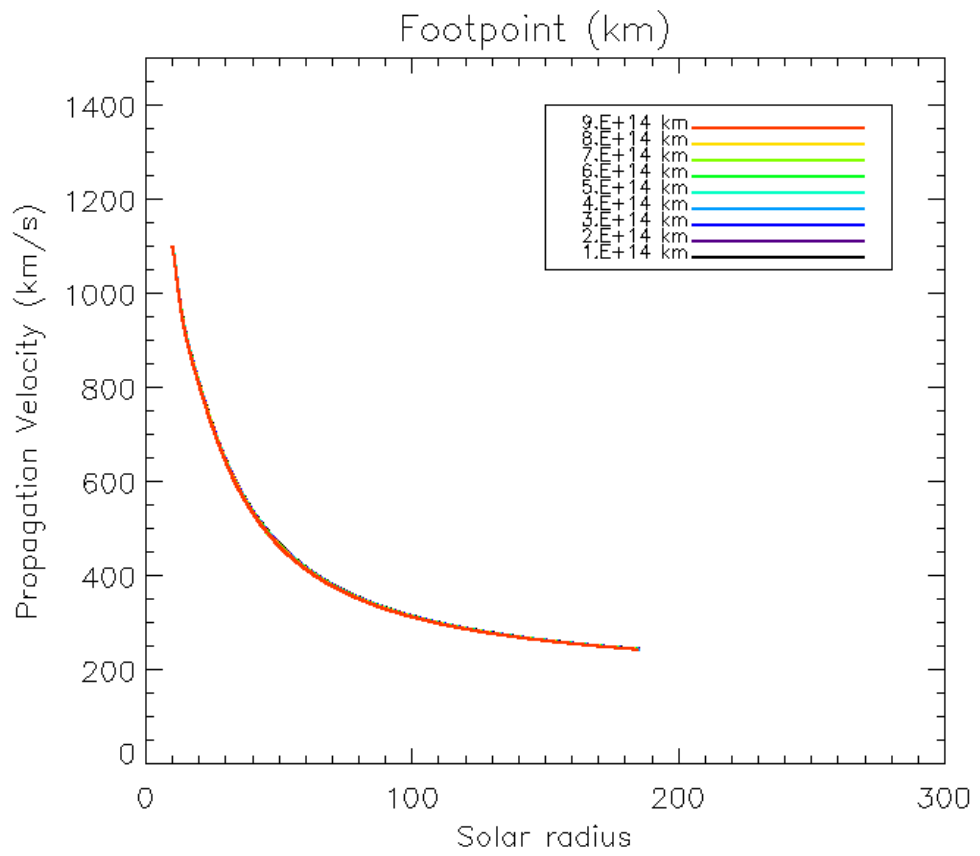


Figure 5.6: Parameter Study of Ambient Solar Wind Velocity

which is not well understood by any means. All four events studied in chapter 4 will be modeled. From the previous discussion, if an ICME hit the in situ spacecrafts, various magnetic and plasma parameters (including magnetic field strength, plasma beta, plasma proton temperature, and proton density) can be measured or inferred from the observations. Usually, the magnetic field strength within an ICME at 1 AU is greater than 10 nT. The proton temperature at 1 AU is around 10^5 Kelvin and the proton density is less than or equal to 20 particles/ cm^3 . Plasma beta in magnetic clouds is less than 0.5. All of these can be used as further constraints in the eruptive flux rope fitting. The following subsection will show the comparison of the flux rope model to the data measurement from STEREO observations.

5.5.1 Flux Rope Model of March 25, 2008 Event

Figure 5.7 consists of four plots. The top left plot is of the height-time profile of the theoretical model. The solid black line in Height-time plot presents the leading edge of the model CME as it travels through interplanetary space. The blue line in this plot represents the apex height, which is the leading edge distance minus minor radius (size of the flux rope). The evolution of the minor radius is shown on the top right panel of Figure 5.7. The bottom panels of the Figure 5.7 show the model evolution of the plasma proton temperature and magnetic field strength respectively. From Figure 5.7, the proton temperature and the magnetic field strength of the flux rope are around 10^5 Kelvin and 10 nT, which are close to the value at 1 AU from in-situ spacecraft.

Figure 5.8 shows the evolution of the model flux rope of the following four parameter: aspect ratio, proton density, propagation velocity and expansion velocity. Proton density at 1 AU is less than 20 particles / cm^3 , which is shown in many studies of ICMEs. The mass of flux rope is conserved, and the flux rope still keeps expanding. Therefore, lower proton density is caused by the expansion of flux rope. In the propagation velocity plot, the measured propagation velocity from STEREO observation is also shown as asterisk (*) symbols. Similarly, the measured expansion velocity is also overlayed on the expansion

velocity from the model by asterisk (*). The propagation and the expansion velocity from the flux rope model fit well with the 3D observational data. The CME velocity profile from the **EFR** decelerates fast within 40 solar radius and has a small change of speed after 50 solar radius. The rate of change in minor radius is around one third of the rate of change in major radius, which is similar to observational data (Poomvises *et al.*, 2010).

Forces acting on the major radius and minor radius of the flux rope are presented in figure 5.9. The top panel shows the force acting on the major radius or force acting on CME propagation. The other panel shows the plot of the forces acting on the minor radius of the flux rope, the forces on the expansion motion. The solid line in the top and bottom panel represents positive forces, which push the flux rope out to interplanetary space. On the other hand, the dashed line in figure 5.9 shows the negative forces that pull down the flux rope or prevent flux rope from expanding.

The forces acting on the propagation motion of the CMEs show that the drag force dominates other forces. In addition, the gravity force is negligible because the gravity force is smaller than drag force by approximately 4 orders of magnitude. Hoop force or Lorentz force or JXB force decreases faster than the drag force in higher corona. This is because the magnetic field at further distances from the Sun is weaker than the magnetic field closer to the surface. In addition, the magnetic drag force decreases slower than the hoop force and the magnetic drag is greater than hoop force when the CME propagates further from the sun. The model initiation velocity of this CME is closely matched with observations. The polytropic index (γ) is around 1.3. Therefore, the adiabatic condition break down in this case of the CME. Moreover, the drag coefficient is 2.5. The drag coefficient is greater than 1, which is consistent with Chen & Kunkel (2008), who used the drag coefficient of around 1.0 but mentioned that it is too small for data fitting.

The expansion forces consist of four forces, toroidal magnetic field force, poloidal magnetic field force, pressure of flux rope force and ambient pressure force. The solid line represents positive forces and the dashed line once again represents negative forces. The

toroidal magnetic field and internal plasma pressure forces try to expand the flux rope; however, poloidal magnetic field and external plasma pressure prevent CME expansion. Figure 5.8 shows when CME propagates further from the Sun, the toroidal magnetic field (positive) and the external plasma pressure (negative) are similar to each other. The poloidal magnetic field and internal plasma pressure almost equal when it propagates further into interplanetary space.

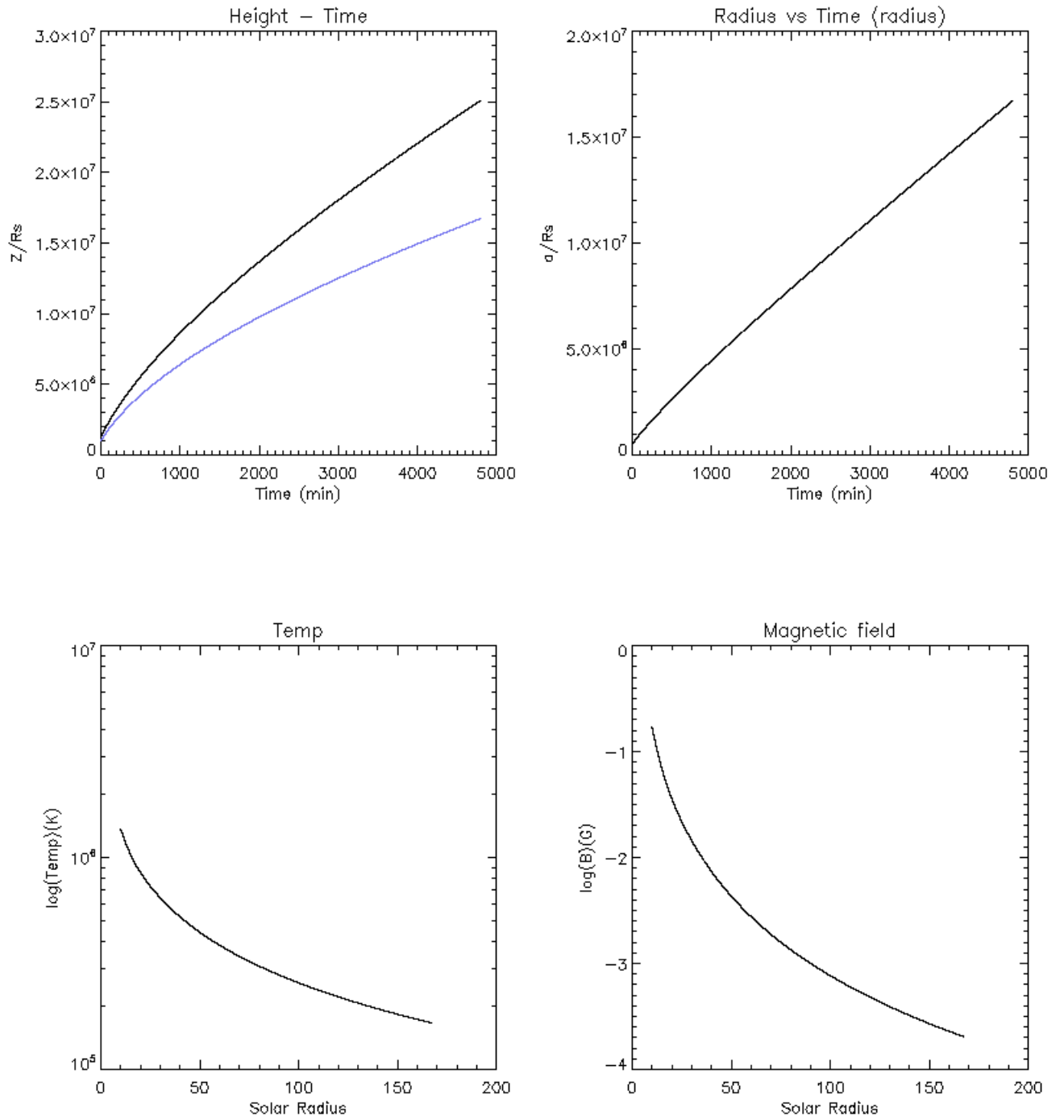


Figure 5.7: Flux rope model of March 25, 2008 CME event. The top left panel is of the height time evolution. The solid black line presents the leading edge of the model flux rope traveling in interplanetary space. The blue represents the apex height. The minor radius of the flux rope is shown in the top right panel. The lower-right panel shows the plasma proton temperature and magnetic field strength of the flux rope.

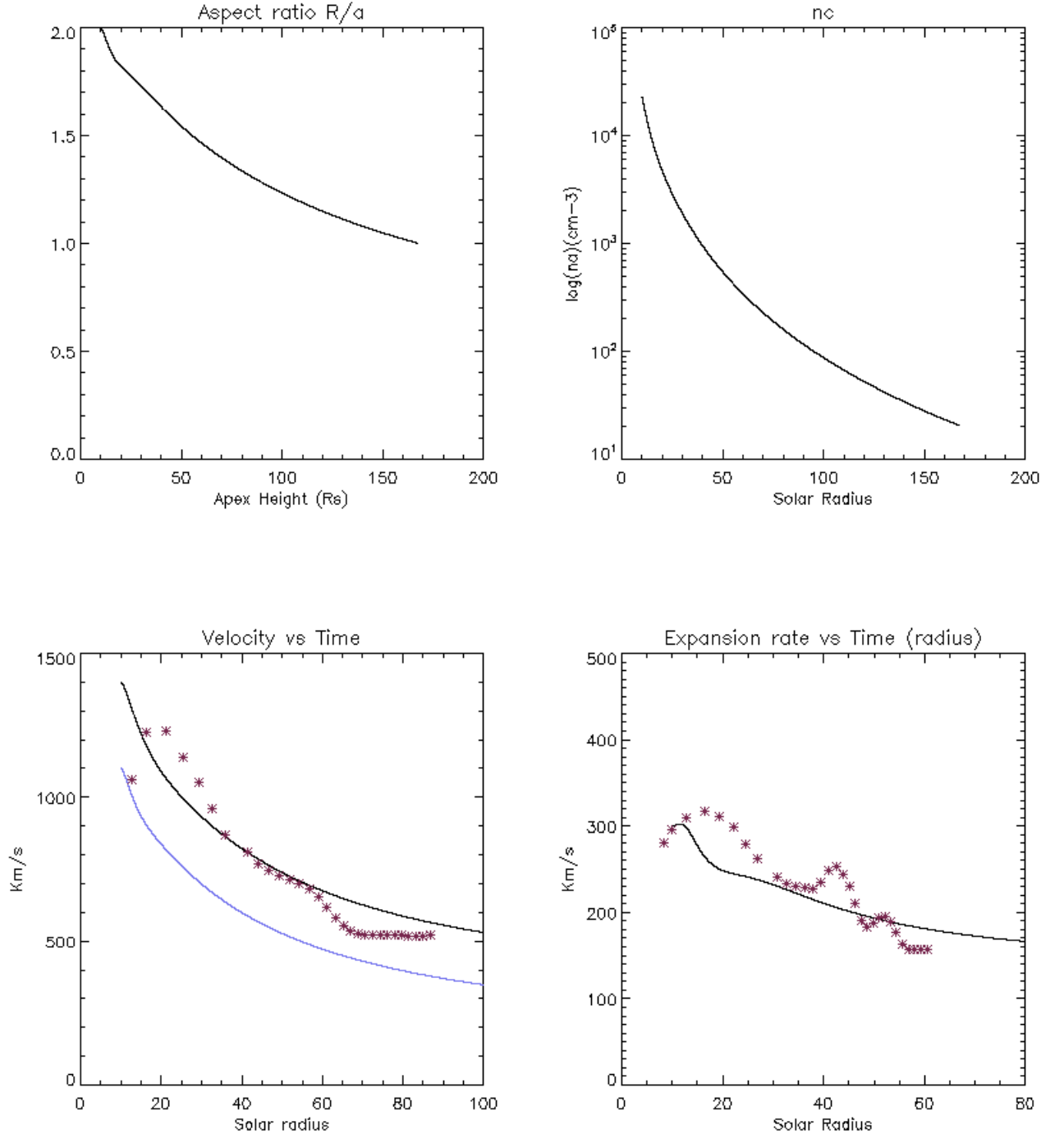


Figure 5.8: Flux rope model of March 25, 2008 CME event. The four panels are for the model evolution of aspect ratio, density, propagation velocity and expansion velocity, respectively. In the propagation velocity plot, the measured propagation velocity from STEREO shown as * symbols. Similarly, the measured expansion velocity is also shown on the expansion velocity plot as *.

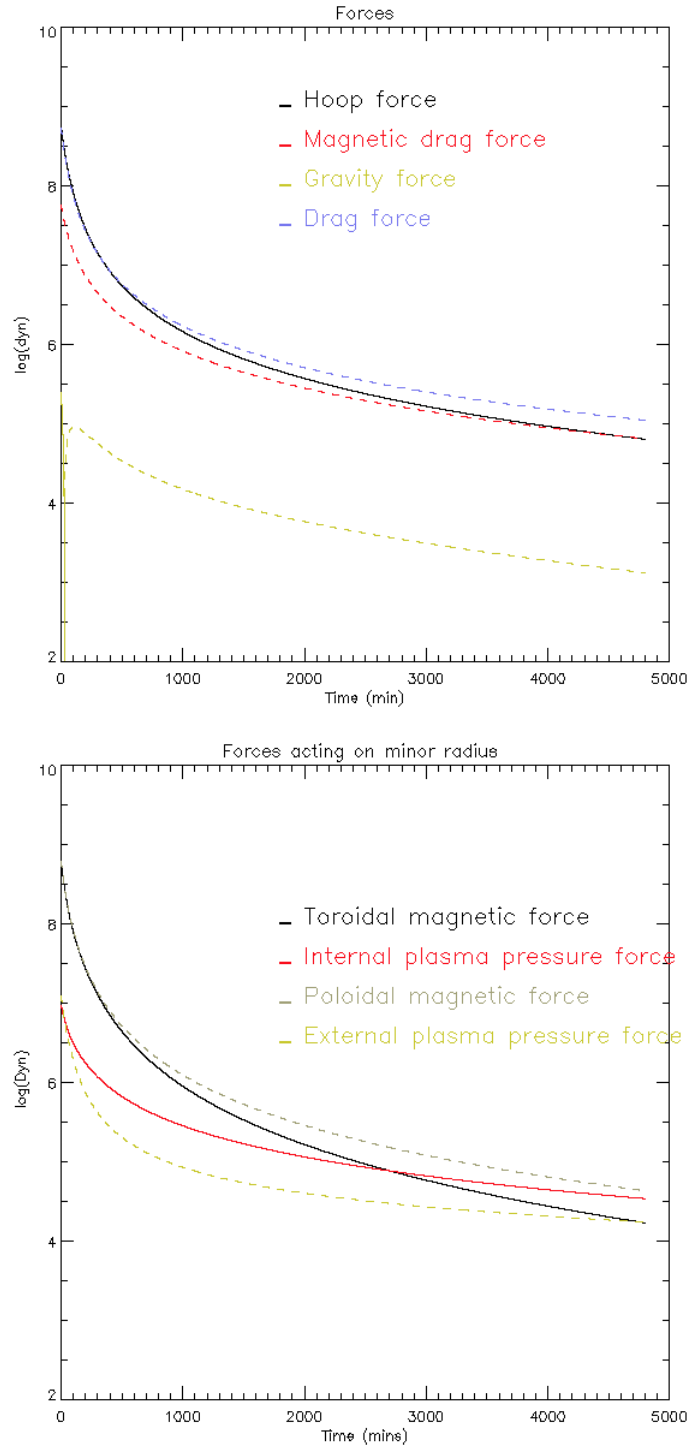


Figure 5.9: Forces acting on major and minor radius of flux rope

5.5.2 Flux Rope Model of April 26, 2008 CME Event

Proton temperature, magnetic field strength, density and aspect ratio are able to be measured or inferred from the observation. In this event, all the parameters from the flux rope model are close to the constraints at 1 AU. The magnetic field strength closes to 10 nT and the plasma proton temperature is around 10^5 Kelvin. Moreover, the plasma density is less than 10 particles / cm^3 , which follows the observational from in situ spacecrafts. Aspect ratio is about 1.5. From statistical study in ICME (Zhang *et al.*, 2007a), we report that the size of magnetic clouds is around 0.25 AU. Therefore, the aspect ratio from the modified model closes to the size of magnetic clouds observed.

Figure 5.12 shows the forces acting on the propagation motion. The gravity force is too small, when compared with other forces. Therefore, the gravity force will be ignored when this CME travels in further distances from the sun. The drag force decreases more slowly than the other forces. Moreover, the magnetic drag force is higher than the hoop force because the magnetic field decreases faster than the difference between propagation velocity and ambient solar wind speed. The drag force dominates when the CME goes beyond 1 AU for this event. The measured data from the STEREO spacecrafts matches in both propagation and expansion velocity (see figure 5.11 bottom panel); however, the expansion velocity shows a spike at 45 solar radii but the jump might come from an uncertainty in measurement.

In the expansion motion, the toroidal magnetic force and internal plasma pressure also push the CME out but the negative forces, poloidal magnetic force and external pressure, pull the CME down. However, the toroidal magnetic force (positive force) and poloidal magnetic force (negative force) are similar and the external (negative force) and internal pressure (positive) also close to each other. The flux rope expands slowly because the net forces acting on minor radius is small.

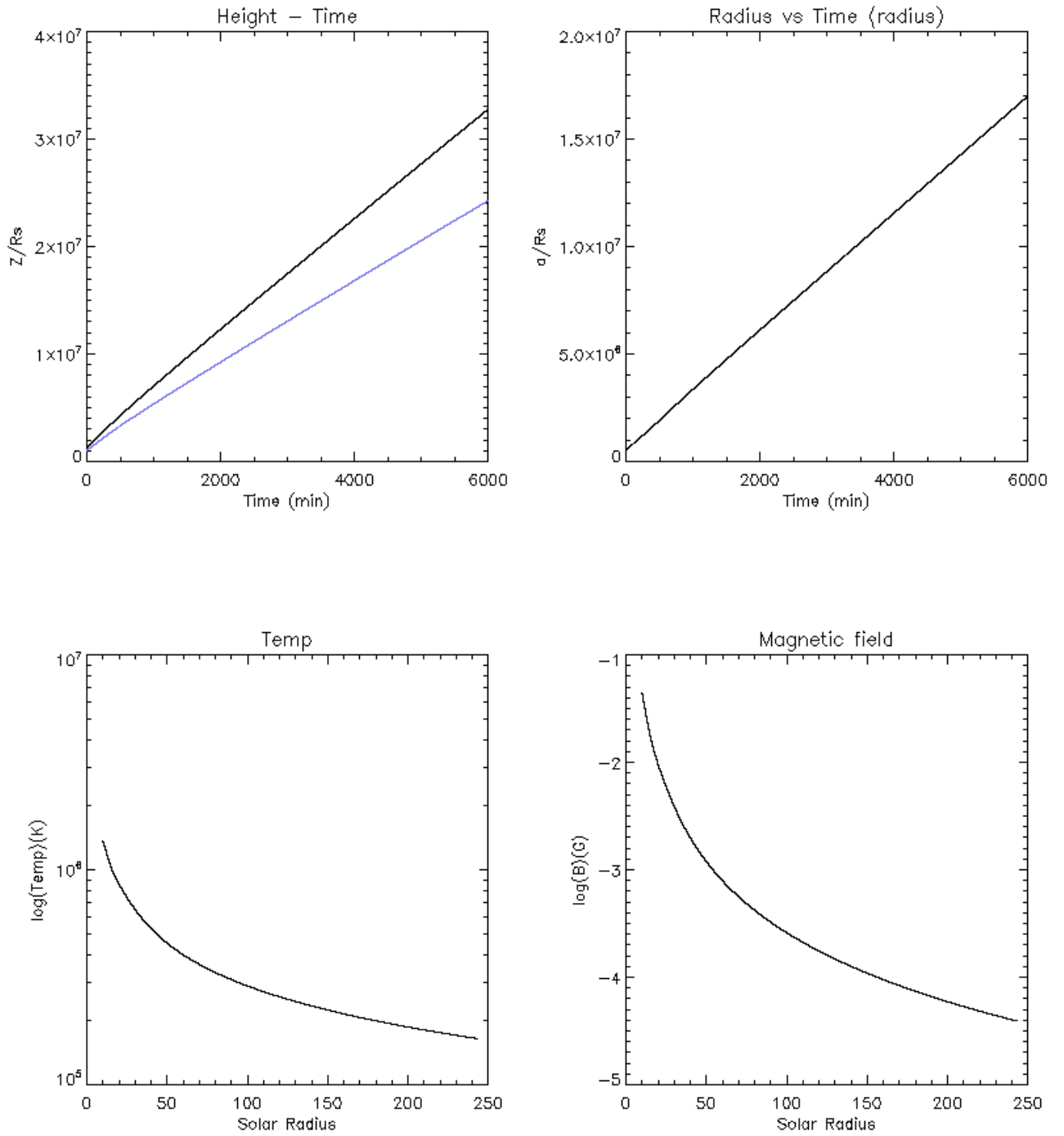


Figure 5.10: Flux rope model of April 26, 2008 CME event. The top left panel is of the height time evolution. The solid black line represents the leading edge of the model flux rope traveling in interplanetary space. The blue presents the apex height. The minor radius of the flux rope is shown in the top right panel. The lower-right panel shows the plasma proton temperature and magnetic field strength of the flux rope.

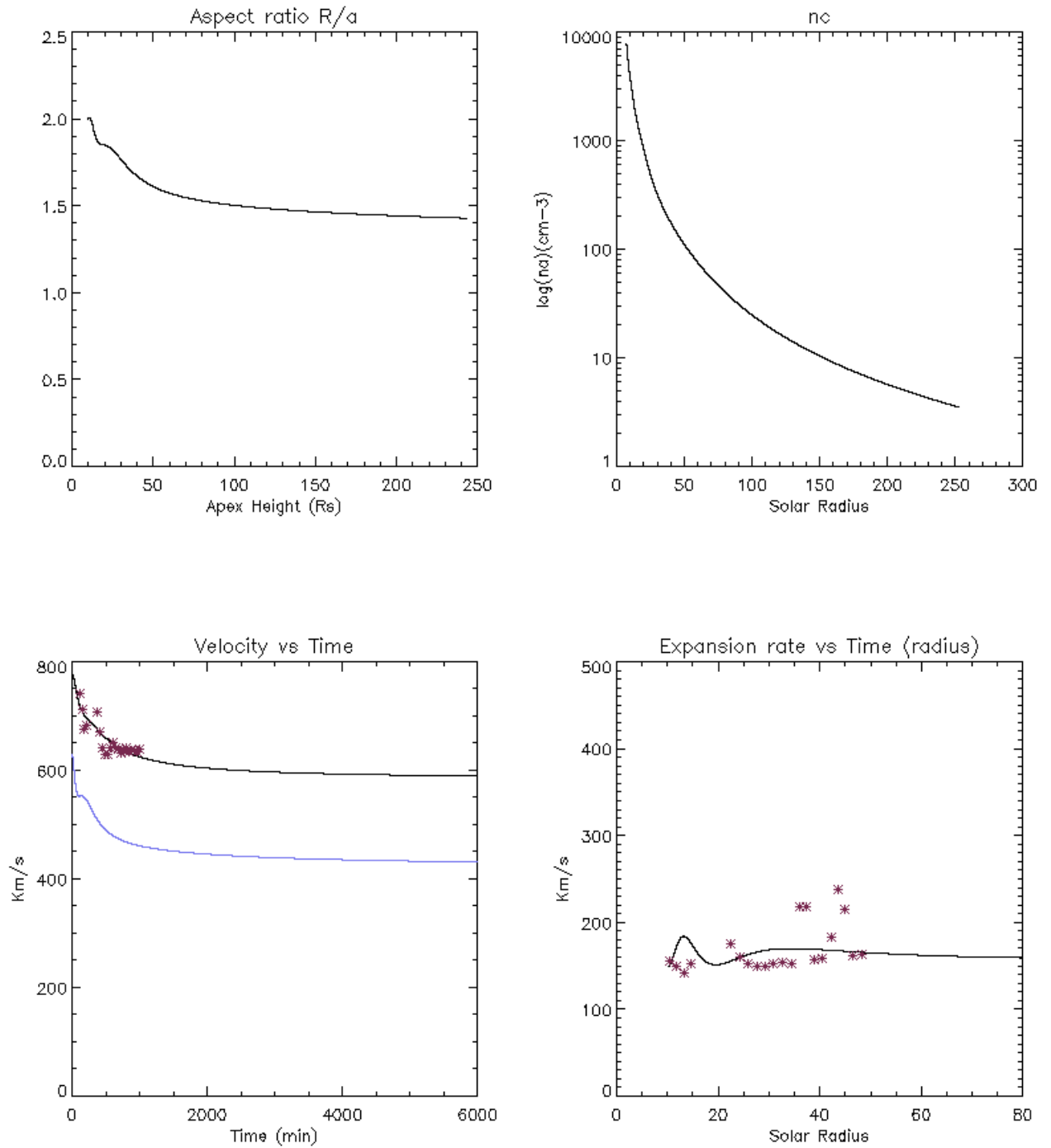


Figure 5.11: Flux rope model of April 26, 2008 CME event. The four panels are for the model evolution of aspect ratio, density, propagation velocity and expansion velocity, respectively. In the propagation velocity plot, the measured propagation velocity from STEREO is shown as * symbols. Similarly, the measured expansion velocity is also shown on the expansion velocity plot as *.

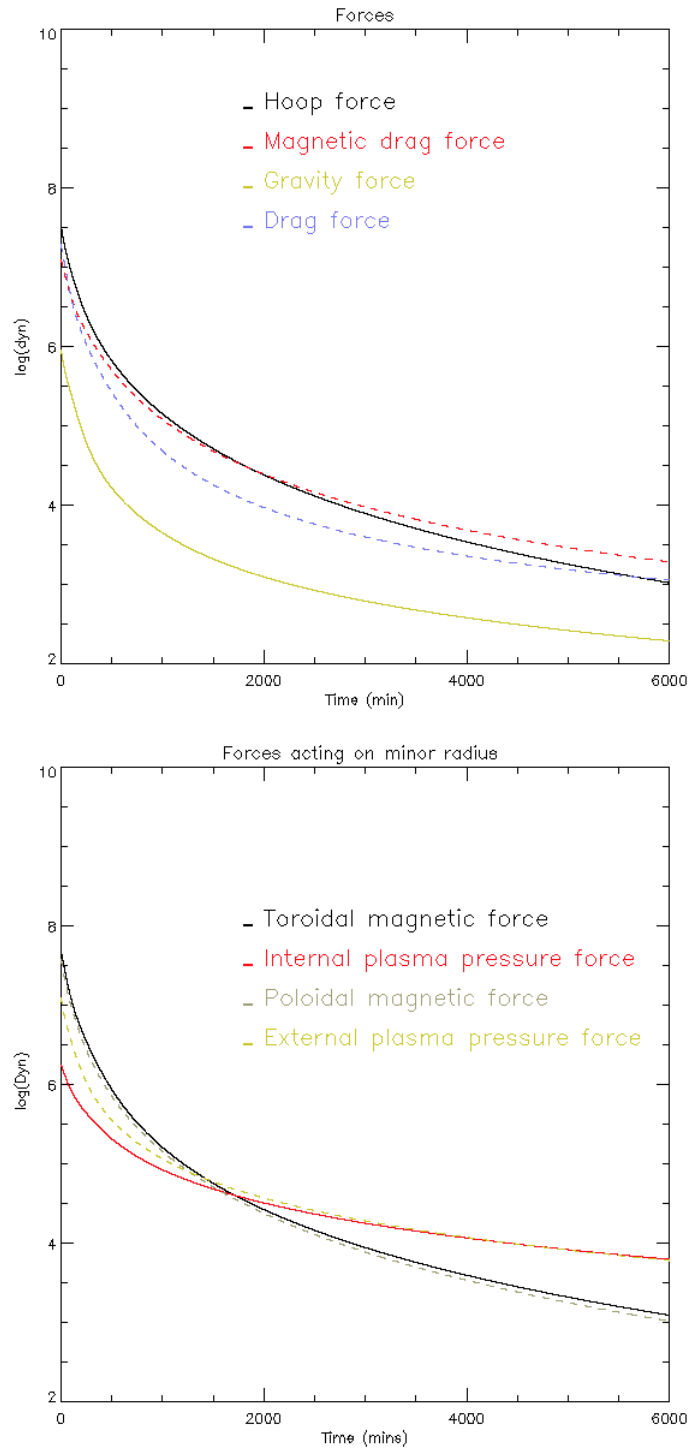


Figure 5.12: Forces acting on major and minor radius of flux rope

5.5.3 Flux Rope Model of May 17, 2008 CME event

Bottom panel of Figure 5.13 and top panel of figure 5.14 represent the temperature, magnetic field strength, aspect ratio and density from the **EFR** model. The Magnetic field strength is about 10 nT, and temperature is around 10^5 Kelvin. Additionally, all the values are close to constraints from the in situ spacecrafts at 1 AU.

The fittings in this event close in both propagation and expansion evolution. However, the expansion velocity shows a few bumps, which might occur from measurement uncertainty. Nevertheless, the tendency of expansion velocity is matched well with the observational data after 22 solar radii.

Hoop force, and gravity forces are positive forces but the gravity is really small when compared with the others. Drag force and magnetic drag are negative forces, which slow down this CME. The three forces acting on the major radius, the Lorentz force, magnetic drag force and drag force are all close to one another. Hence, the CME decelerates because the only force push CME out is the hoop force. Although, the hoop force is a bit larger than drag force and magnetic drag force at the beginning of the propagation, drag force dominates other forces at the further distances.

Expansion motion, the toroidal magnetic force and internal pressure force try to expand the CME; but the negative forces, the poloidal magnetic field and external pressure force, prevent CME expansion. When the flux rope propagate and expand in interplanetary space the external plasma pressure dominates other forces in the expansion motion. Therefore, this CME decelerates faster because the negative forces in both expansion and propagation motions are greater than the positive forces.

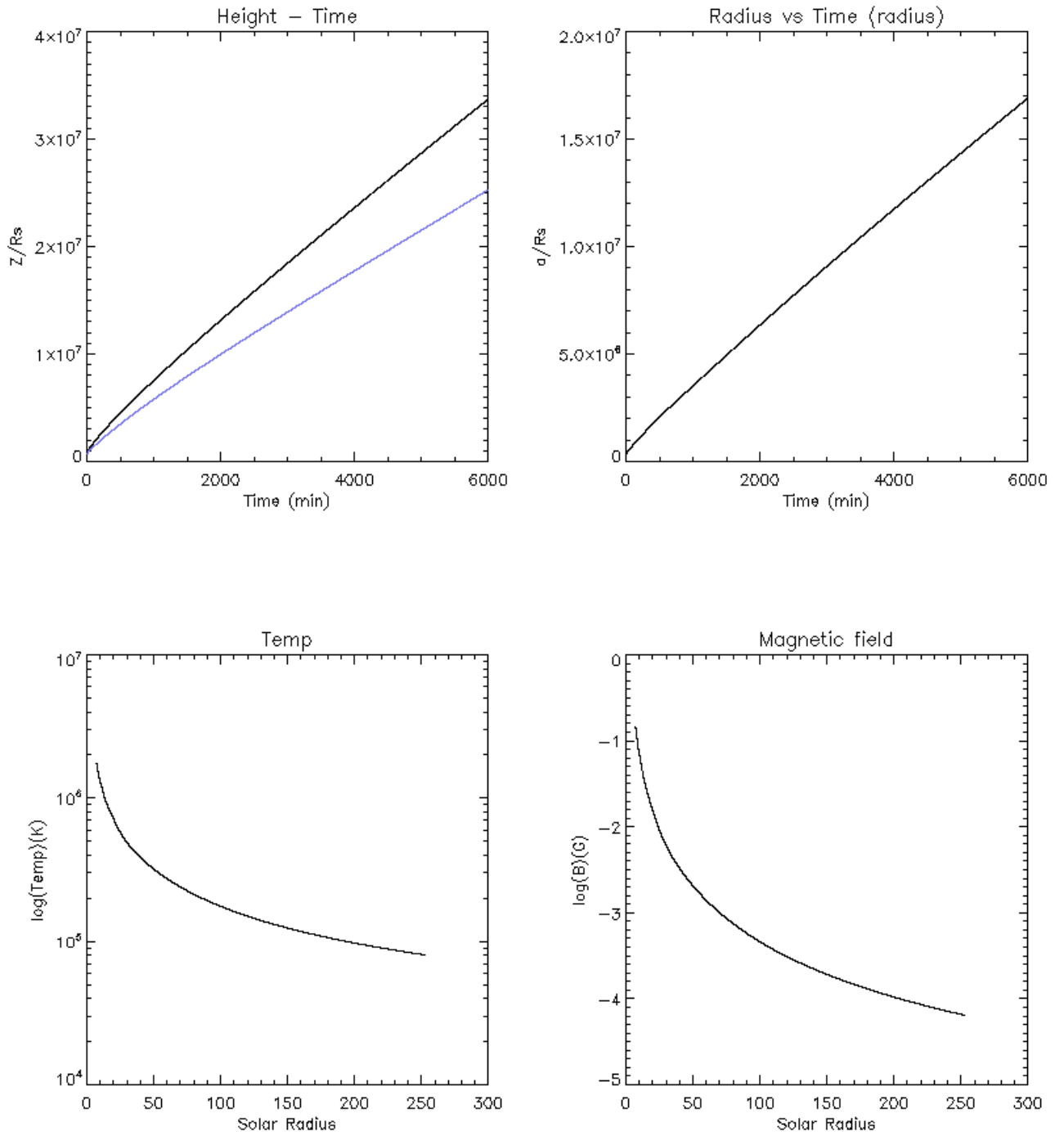


Figure 5.13: Flux rope model of May 17, 2008 CME event. The top left panel is of the height time evolution. The solid black line represents the leading edge of the model flux rope traveling in interplanetary space. The blue presents the apex height. The minor radius of the flux rope is shown in the top right panel. The lower-right panel shows the plasma proton temperature and magnetic field strength of the flux rope.

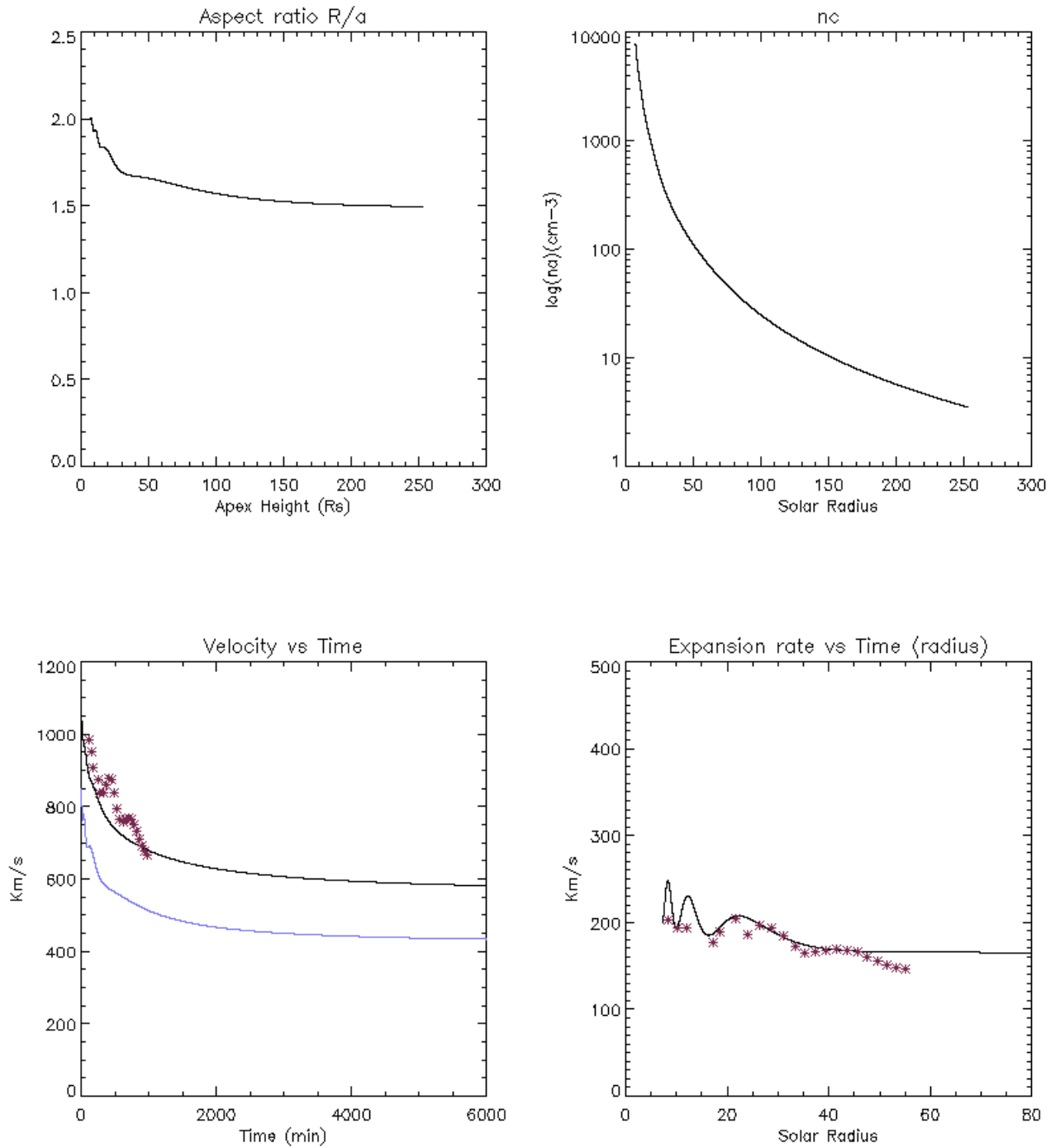


Figure 5.14: Flux rope model of May 17, 2008 CME event. The four panels are for the model evolution of aspect ratio, density, propagation velocity and expansion velocity, respectively. In the propagation velocity plot, the measured propagation velocity from STEREO is shown as * symbols. Similarly, the measured expansion velocity is also shown on the expansion velocity plot as *.

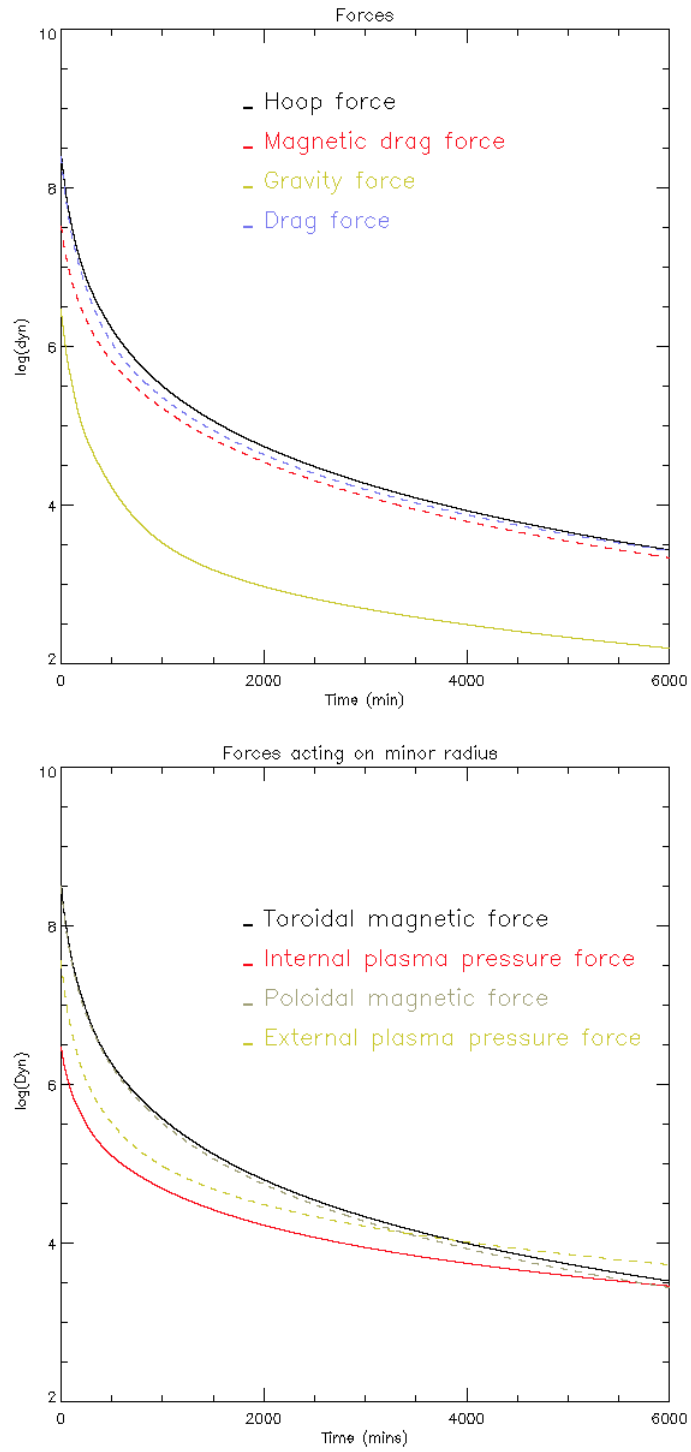


Figure 5.15: Forces acting on major and minor radius of flux rope

5.5.4 Flux Rope Model of December 12, 2008 CME Event

This event is the only gradual CME that is well detected by the STEREO spacecrafts. Figure 5.16 and Figure 5.17 show the parameter constraints at 1 AU. The magnetic field strength is close to the magnitude of magnetic field during storm. The temperature is around 1×10^5 Kelvin and the proton temperature of this event is higher than the other events, which might come from the magnetic field lines still connected to the sun. The particle density is higher than other events also, which may be caused by slow expansion. The expansion and propagation motion match well with observation.

The acting force on major radius (Figure 5.18) shows that drag force dominates other forces. Moreover, the magnetic drag force is positive, meaning the force pulls out the CME but the gravity force is negative. The gravity force cannot compare to the other forces when the flux rope is at 1 AU. The flux rope proton density and the ambient density are similar. Therefore, the gravity force in equation 5.3 is going to be negligible when compared with the other three forces.

The internal plasma pressure and toroidal magnetic field forces are positive and while the remaining forces are negative. The total of the positive forces is greater than the total of negative forces, which makes the flux rope expand more in interplanetary space.

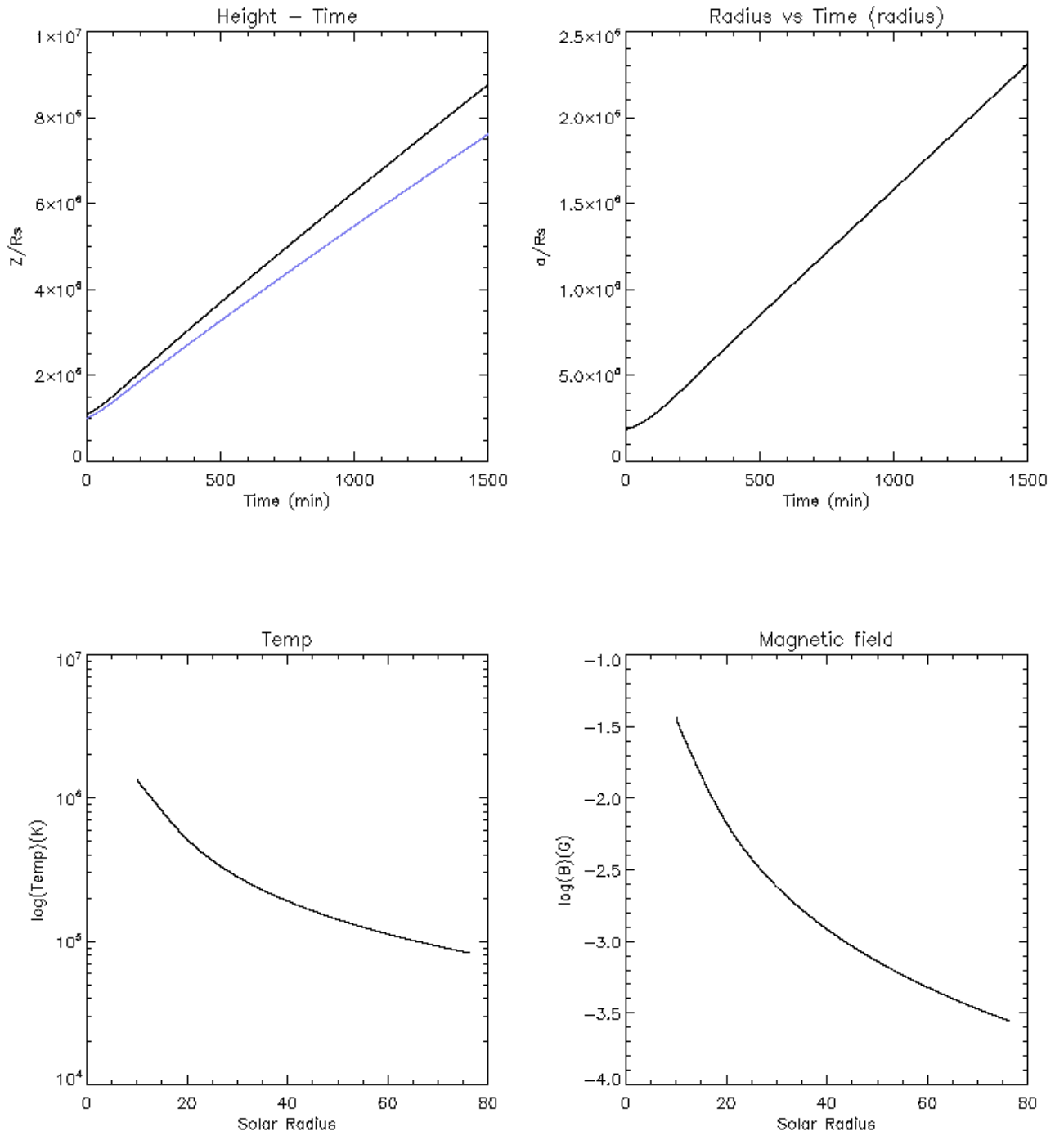


Figure 5.16: Flux rope model of December 12, 2008 CME event. The top left panel is of the height time evolution. The solid black line represents the leading edge of the model flux rope traveling in interplanetary space. The blue presents the apex height. The minor radius of the flux rope is shown in the top right panel. The lower-right panel shows the plasma proton temperature and magnetic field strength of the flux rope.

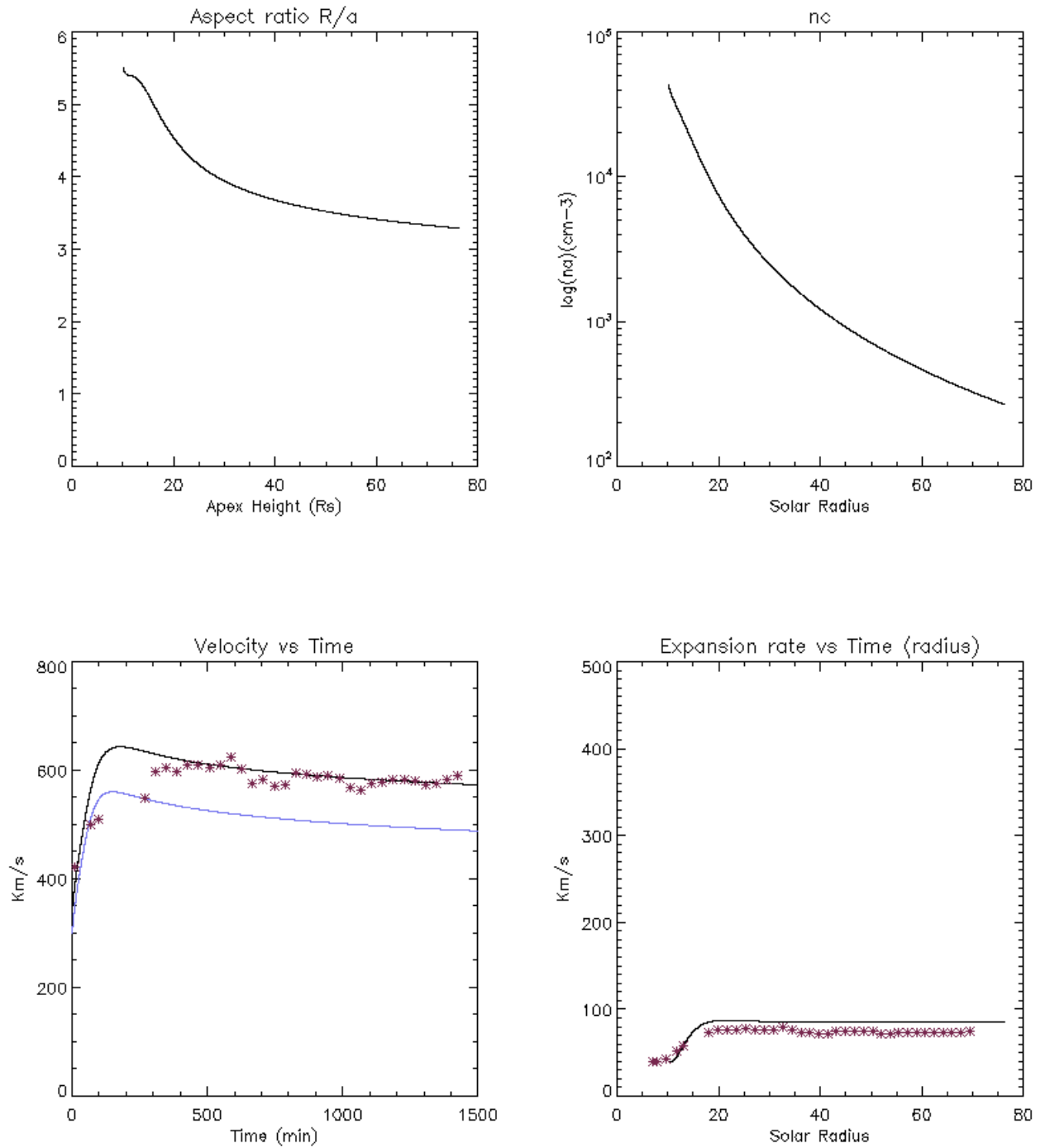


Figure 5.17: Flux rope model of December 12, 2008 CME event. The four panels are for the model evolution of aspect ratio, density, propagation velocity and expansion velocity, respectively. In the propagation velocity plot, the measured propagation velocity from STEREO is shown as * symbols. Similarly, the measured expansion velocity is also shown on the expansion velocity plot as *.

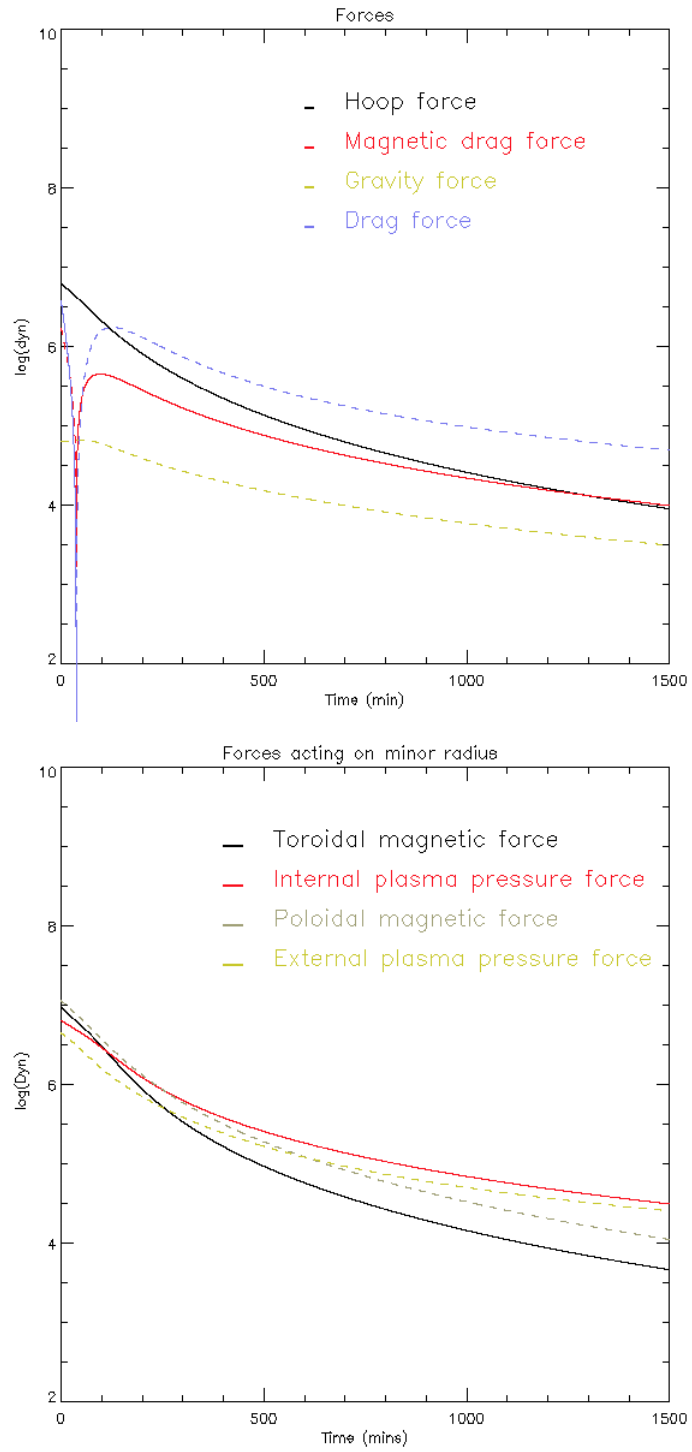


Figure 5.18: Forces acting on major and minor radius of flux rope

5.6 Conclusion and Discussion

Understanding the kinematic and morphological evolution of CMEs from solar surface to 1 AU is important for space weather prediction. I have investigated various forces acting on CMEs and how they evolve with distance. The drag force dominates other forces in interplanetary space and can decelerate or accelerate the CME or flux rope-like structure. However, in the initiation phase, close to the surface of the sun, the Lorentz force may dominate. Table 5.4 presents the parameters of the flux rope model; the initial height Z_0 , footpoint separation S_0 , mass of CME, polytropic index, drag coefficient, initial expansion and propagation velocity and initial external magnetic field. The drag coefficient in table 5.4 is between 2.5 to 3.0. As seen in a previous study (Chen, 1996), the drag coefficient varies between 1 and 12. Therefore, we are able to narrow down the range significantly.

For expansion motion, this study also narrows down the polytropic index, which is shown in the fourth row of the table 5.4. The range of the polytropic index is between 1.3 and 1.55. This confirms the assumption the adiabatic conditions of ICMEs at 1 AU should not be used throughout CME evolution.

In the parameter space study, I am able to show that the footpoint separation does not effect either the propagation or expansion motions. However, the study also provides the results that the drag coefficient, ambient solar wind velocity and ambient magnetic field have an effect on the propagation and expansion motions of CME evolution. In addition, the polytropic index has a greater impact on expansion motion than propagation motion.

However, the model has several caveats. For instance, the cause of the pancake effect, the flattening of the CME cross-section, is not addressed. In addition, the model assumes that mass is conserved. When CMEs propagate into space, mass may pile up.

Table 5.4: Parameters in EFR model

Parameters in EFR model					
Parameters / unit	Name	20080325	20080426	20080517	20081212
S_0 (cm)	Footpoint separation	2.2×10^9	2.2×10^9	1.9×10^9	3.0×10^9
Z_0 (cm)	Height of the flux rope	7×10^{11}	7×10^{11}	5×10^{11}	7×10^{11}
M gram	Mass of the flux rope	8×10^{15}	2×10^{15}	1×10^{15}	2×10^{15}
γ	Polytropic index	1.3	1.3	1.38	1.55
C_d	Drag coefficient	2.5	2.5	2.5	3.0
w_0 (km/s)	Initial expansion velocity	3×10^7	1.5×10^7	2×10^7	3×10^7
V_0 (km/s)	Initial propagation velocity	1.1×10^8	5.7×10^7	5.5×10^7	4.8×10^7
B_{S0} (G)	Initial external magnetic field	-5.5×10^{-3}	-4.8×10^{-3}	-5.3×10^{-3}	2.0×10^{-3}

Chapter 6: Summary and Future plan

In summary, I have studied the kinematic and morphological evolution and dynamics of CMEs in interplanetary space. The data was obtained from the Solar TERrestrial RElations Observatory (STEREO) spacecrafts. In this dissertation, the Raytrace model is utilized as a powerful tool to measure CMEs in interplanetary space. I also used the theoretical model to explain the observations that have been supported by the good match of the fitted results to the observational data. The evolution of CMEs can be explained by the different forces that act on them: Lorentz force, thermal pressure force, gravity force, drag force, and magnetic drag force. In addition, the drag coefficient has effects on both propagation and expansion motion of CMEs, which shows in the parameter space study section. Moreover, we found that the drag coefficient in table 5.4 is between 2.5 to 3.0. In previous studies (Chen, 1996), the drag coefficient varied from 1 to 12. Therefore, we have been able to narrow down the range of drag coefficient. In addition, the magnetic drag force, calculated with the **EFR**, matches the observational data in 3D. In the expansion, we found that the range of the polytropic index is 1.3 to 1.55. Additionally, the polytropic index does not have much effect on CMEs propagation within 50 solar radii. All these results are important for us to create models for space weather prediction in the future.

In an early study, the sequence of 88 geomagnetic storms from 1996 to 2005 (defined by minimum Dst $\sim$ - 100 nT) from the Sun to the Earth were investigated. We classify the Solar-IP sources into three broad types: (1) S-type, in which the storm is associated with a single ICME and a single CME at the Sun; (2) M-type, in which the storm is associated with a complex solar wind flow produced by multiple interacting ICMEs arising from multiple halo CMEs launched from the Sun in a short period; (3) C-type, in which the storm is associated with a CIR formed at the leading edge of a high-speed stream originating from

a solar coronal hole (CH). For the 88 major storms, the S-type, M-type, and C-type events number 53 (60 %), 24 (27 %), and 11 (13 %), respectively. For the 85 events for which the surface source regions could be investigated, 54 (63 %) of the storms originated in solar active regions, 11 (13 %) in quiet Sun regions associated with quiescent filaments or filament channels, and 11 (13 %) were associated with coronal holes. Remarkably, nine (11 %) CME-driven events showed no sign of eruptive features on the surface or in the low corona (e.g., no flare, no coronal dimming, and no loop arcade, etc.), even though all the available solar observations in a suitable time period were carefully examined.

Another observational aspect of my dissertation is to study sizes and relative geoeffectiveness of interplanetary coronal mass ejections. This study shows that there is a wide distribution in the radial sizes of both ICMEs (0.08 to 0.63 AU) and sheaths (0.03 to 0.31 AU), and the transients combining the two components (0.12 to 0.73 AU), associated with S-type intense geomagnetic storms. The average ICME size we observe is 0.37 AU, which is significantly larger than, but not inconsistent with, the ~ 0.25 AU size reported by other researchers (Forsyth *et al.*, 2006; Lepping *et al.*, 2006). The difference may be a selection effect due to the fact that all the 46 events used in this study produced major geomagnetic storms, and therefore may possess different properties than the general ICME population; possibly including a larger physical size that may help to sustain geoeffective solar wind conditions. While ICMEs are the dominant transient features that produce major geomagnetic storm, sheaths are also important, contributing about 29 % of the total energy input into the magnetosphere during these storms.

The last observational part of my work in this dissertation is an application of the Raytrace model to measure 3D distance of propagating CMEs. We then find that their leading edge (LE) velocity converges from an initial range between 400 km/s and 1500 km/s at 5 to 10 R_S to a narrow range between 500 km/s and 750 km/s at 50 R_S . The expansion velocity is also found to converge into a narrow range between 75 km/s and 175 km/s. Both LE and expansion velocities are nearly constant after 50 R_S . We further find that the acceleration of CMEs in the inner heliosphere from ~ 10 to 90 R_S can be described

by an exponential function, with an initial value as large as $\sim 80 \text{ m/s}^2$ but exponentially decreasing to almost zero (more precisely, less than $\pm 5 \text{ m/s}^2$ considering the uncertainty of measurements). Moreover, we also introduce the new empirical formula, which is able to describe either decelerating or accelerating events.

This dissertation has produced new and important results regarding our understanding, both observationally and theoretically, of the kinematic and morphological of CMEs in interplanetary space. Nevertheless, many questions still remain that must be studied in the future. For instance, the Raytrace model needs to be modified for use in the lower corona. The assumption in geometry of the observational measure the flux rope-like structure and the legs of flux rope originate at the center of the Sun. If the model is changed to utilize a more dynamic starting point for the flux rope, this model will be usable in the lower corona, improving the understanding in CME initiation. Further, cause of the pancake effect, the flattening of the CME cross-section, is not addressed. In addition, the model assumes that mass is conserved. When CMEs propagate into space, mass may pile up. Nevertheless, it is currently a good time to study the kinematic and morphological evolution of CMEs because the Sun is starting to move toward the solar maximum. Many CMEs will be soon detected by STEREO/SECCHI. Even though the angle between the two spacecrafts is too wide, the SOHO spacecraft is still working so it provides another angle view of the Sun.

Appendix A: Flux Rope Equations

Major radius force of flux rope:

$$F_R = \frac{I_t}{C^2 R} \left[\ln\left(\frac{8R}{a}\right) + \frac{1}{2}\beta_p - \frac{1}{2}\frac{B_t^2}{B_{pa}^2} + 2\frac{R}{a}\frac{B_s}{B_{pa}} - 1 + \frac{\xi_i}{2} \right] + F_g + F_d \quad (\text{A.1})$$

Gravity force equal

$$F_g = \pi a^2 m_i g(Z) (n_a - \bar{n}_T) \quad (\text{A.2})$$

Drag force equal

$$F_d = c_d n_a m_i a |V_a - V| |V_a - V| \quad (\text{A.3})$$

Minor radius force of flux rope:

$$F_a = M \frac{dw}{dt} = \frac{I_t}{c^2 a} \left(\frac{B_t^2}{B_{pa}^2} - 1 + \beta_p \right) \quad (\text{A.4})$$

plasma beta

$$\beta_p = 8\pi(\bar{P} - P_a)/B_{pa}^2 \quad (\text{A.5})$$

Appendix B: Methodology for Solving Flux Rope Equations

Runge-Kutta algorithm is used to solve the force equations, which are rewritten as a set of first order ODE's

$$\frac{dZ}{dt} = V \quad (\text{B.1})$$

$$M \frac{dV}{dt} = \frac{I_t^2}{C^2 R} \left[\ln \frac{8R}{a} + \frac{1}{2} \beta_p - \frac{1}{2} \frac{B_t^2}{B_{pa}^2} + 2 \frac{R}{a} \frac{B_s}{B_{pa}} - 1 + \frac{\xi_i}{2} \right] \quad (\text{B.2})$$

$$+ [\pi a^2 m_i g(Z)(n_a - \bar{n}_T)] + [c_d n_a m_i a (V_a - V) |V_a - V|]$$

$$\frac{da}{dt} = w \quad (\text{B.3})$$

$$M \frac{dw}{dt} = \frac{I_t^2}{c^2 R} \left(\frac{B_t^2}{B_{pa}^2} - 1 + \beta_p \right) \quad (\text{B.4})$$

where M is the mass of the flux-rope, $M = \pi a^2 \bar{n}^T m_i$. To initialize an eruption, the system must be driven out of equilibrium. Increasing the poloidal flux or equivalently increasing the toroidal current can achieve this. However, I will not focus on the initial driven force that causes the flux rope loss of equilibrium. Instead I will focus on how a flux rope expands and propagates in interplanetary space. Therefore, I start this model from a specific height, which is around 6-10 R_S .

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Curriculum Vitae

Watanachak Poomvises was born in 1977 in Bangkok, Thailand. He graduated from Assumption University in Bangkok, Thailand with a Bachelor's degree in Electronics Engineering in 1999. He also received a master degree in Civil and Environmental Engineering from The George Washington University, Washington D.C. in 2002. He was employed for 7 years as a research assistant under the instruction of Dr. Jie Zhang. His research involves CME-ICME identification, size of sheath and ICME regions, and CME evolution in interplanetary space.

During 7 years on his research worked, he was primary author and co-authors in four papers

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- Co-author: Zhang, J., Poomvises, W., and Richardson, I., (2008) "Sizes and relative geoeffectiveness of interplanetary coronal mass ejections and the preceding shock sheaths during intense storms in 1996-2005", *Geophysical Research Letters*, Vol 35, DOI: 10.1029/2007GL032045
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- Co-author: Zhang, J., Poomvises.W., et al (2007)," Solar and interplanetary sources of major geomagnetic storms ($Dst \leq -100nT$) during 1996-2005", *Journal of Geophysical Research*, Vol 112, DOI:10.1029/2007JA012321

In addition, he also attended many major conferences:

- Solar, Heliospheric, and INTERplanetary Environment or SHINE in 2005, 2007, 2009, and 2010
- Solar Physics Divisions (SPD) in 2006, 2007, 2009
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