
Characterizing Magnetic Clouds Associated with Solar Coronal Mass Ejections through in situ Observations

A Thesis

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Doctor of Philosophy

By

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Certificate

Certified that the work incorporated in the thesis entitled '*Characterizing Magnetic Clouds Associated with Solar Coronal Mass Ejections through in situ Observations*', submitted by *Debesh Bhattacharjee* was carried out by the candidate, under my supervision. The work presented here or any part of it has not been included in any other thesis submitted previously for the award of any degree or diploma from any other university or institution.

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Prof. Prasad Subramanian

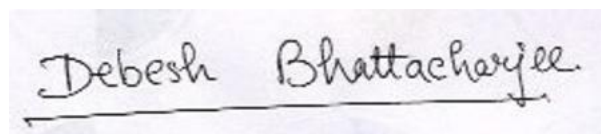
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A photograph of a handwritten signature in black ink on a light-colored background. The signature reads "Debesh Bhattacharjee" and is underlined with a single horizontal line.

Debesh Bhattacharjee

Roll No - **20152036**

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To
Maa, Baba, Chandra & Nature

Acknowledgements

Standing at the end of my doctoral journey, I recall a few moments down memory lane. It is like standing on the river bank during sunset and immersing oneself in the chuckling sound of water while swimming through the fragrance of rain-soaked earth. In the same way that the waves in a river flow, memories are like ripples in time. I have been fascinated by the beauty of the night sky since childhood. At night, I used to climb up to the roof of our house and sit there for hours gazing at the stars and planets. From that time onwards, I decided to become an astronomer. Then, gradually my interest in physics and mathematics started to develop. That created a platform for me to study some basic astrophysics. During all these years, my parents provided me with enough support and inspiration to carry on my passion. Since then, they have been with me and my passion. After I completed my BSc in Physics, I joined IISER as an Integrated PhD student. Finally, I joined Prof. Prasad Subramanian's research group and began studying the Sun. The sheer beauty and dynamicity of solar Coronal Mass Ejections (CMEs) attracted me so much that I decided to do my PhD on them.

In my opinion, a PhD is more than just a degree. Throughout life, it is a journey to remember. It shapes our way of looking at the world. Every doctoral student's PhD journey differs from one another. Indeed there are many ups and downs and that is part of this journey. In the end, I am satisfied and happy with my PhD experience. My sincere gratitude goes out to everyone who was integral to this process.

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Abstract

Coronal mass ejections (CMEs) are occasional expulsions of plasma and magnetic fields from the solar corona. It is well-known that Earth-directed CMEs are the primary drivers of geomagnetic storms that lead to space weather disturbances in the near-Earth space environment like the magnetosphere and ionosphere. We rely on a wide range of technologies in response to such disturbances in space weather. Astronauts are also affected by the radiation from solar energetic particles. A thorough understanding of CME dynamics and realistic estimates of Sun-Earth CME propagation times are therefore very crucial for space weather forecasting. In situ measurements of plasma parameters by near-Earth satellites provide detailed information on CME interiors along the line of intercept of the spacecraft. We analyze and interpret such data for a large number of well-observed Earth-directed CMEs in my thesis.

CMEs are well-known to expand as they propagate through the heliosphere. However, their cross-sections are usually modeled as static plasma columns under the framework of ideal magnetohydrodynamics (MHD). We test the validity of these assumptions for CME plasma. We find that the Joule heating rate is too low to meet the required heating budget inside CMEs. We also study the amplitude of turbulent fluctuations in the proton density and total magnetic field for a large sample of near-Earth CMEs. We find that the velocity fluctuations inside and at the boundaries of CMEs are subsonic in nature. Our results show that the anomalous resistivity coming from the electrons scattering due to magnetic field turbulence is significantly higher than the Spitzer resistivity in the CME plasma. In CMEs, such enhanced resistivity may supplement Joule heating. The pressure and specific energy of CME plasma are assumed to play a key role in governing the dynamics of CMEs during their propagation through the solar wind. We estimate the total specific energy (comprising kinetic, thermal, and magnetic field contributions) inside near-Earth CMEs and compare it with the ambient solar wind background. We also examine if the excess thermal+magnetic specific energy in CMEs might make them resemble rigid objects in the context of CME aerodynamic drag.

Publications

1. **“On modeling ICME cross-sections as static MHD columns”** – **Debesh Bhattacharjee**, Prasad Subramanian, Volker Bothmer, Teresa Nieves-Chinchilla, Angelos Vourlidas, **2022**, **Solar Physics**, 297, 45
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Chapter 1

Introduction

A Brief Overview

In this chapter, we explore the overall properties of the Solar corona, coronal transients, solar coronal mass ejections (CMEs) and related space weather impacts on the Earth. This chapter begins with an introduction to the various properties of the Sun, its basic structure, and its atmosphere. Here we discuss some historical and observational details of CMEs, describing the instruments which are used to observe the Sun and solar transients. We also discuss the Earth's space weather and its impacts in detail, and how CMEs play a significant role in the overall Sun-Earth connection. Finally, we outline the organization of the rest of the thesis.

1.1 Solar Corona

The solar atmosphere is broadly divided into three parts – from inside to outside, these are the photosphere, chromosphere, and corona. The photosphere is also called the solar surface in the visible spectra. This layer is tens of thousands of kilometers thick. The Chromosphere is the second layer of the solar atmosphere and has a height of roughly 3,000 to 5,000 kilometers. It is called the chromosphere because of its characteristic color which is produced due to electromagnetic emission from H_α spectral line. The region between the chromosphere and the corona is called the transition region.

The outermost layer of the Sun is known as the corona. This is a tenuous layer that lies above the chromosphere and extends up to millions of kilometers in the outerspace. The word ‘corona’ means ‘crown’ in Latin and it was coined by Spanish astronomer José Joaquín de Ferrer in 1809. Based on the results of his

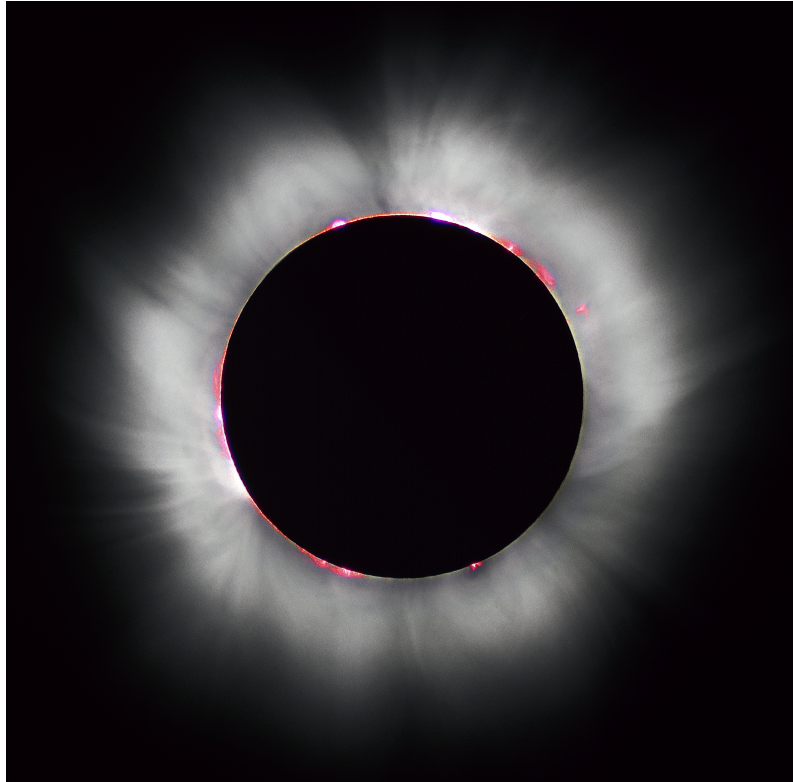


Figure 1.1: The image of a total solar eclipse (France, 1999). One can see the solar corona as the ethereal aura encircling the ‘dark-faced’ Sun. This photograph was taken by Luc Viatour (<https://Lucnix.be>).

own observations of the 1806 solar eclipse at Kinderhook (New York), de Ferrer also proposed that the corona was part of the Sun and not of the Moon. Since the corona is very faint, it can be observed with the naked eye only during an eclipse, when the bright photosphere is occulted. The lower part of the corona has a particle density of 10^{15} to 10^{16} m^{-3} . The average coronal temperature is ≈ 1 to 2 million K, which is much higher than that of the photosphere. The hottest coronal regions are recorded to have temperatures up to 20 million K. No complete theory exists till date to explain such huge coronal temperature. The solar corona is an extended atmosphere of the Sun and its volume is much larger than the Sun enclosed by the photosphere.

In addition to the sunlight and heat, the Sun also releases a continuous flow of plasma and it is known as solar wind.

This never-ending flow of coronal plasma is of considerable significance for our Earth and all the other objects in the solar system

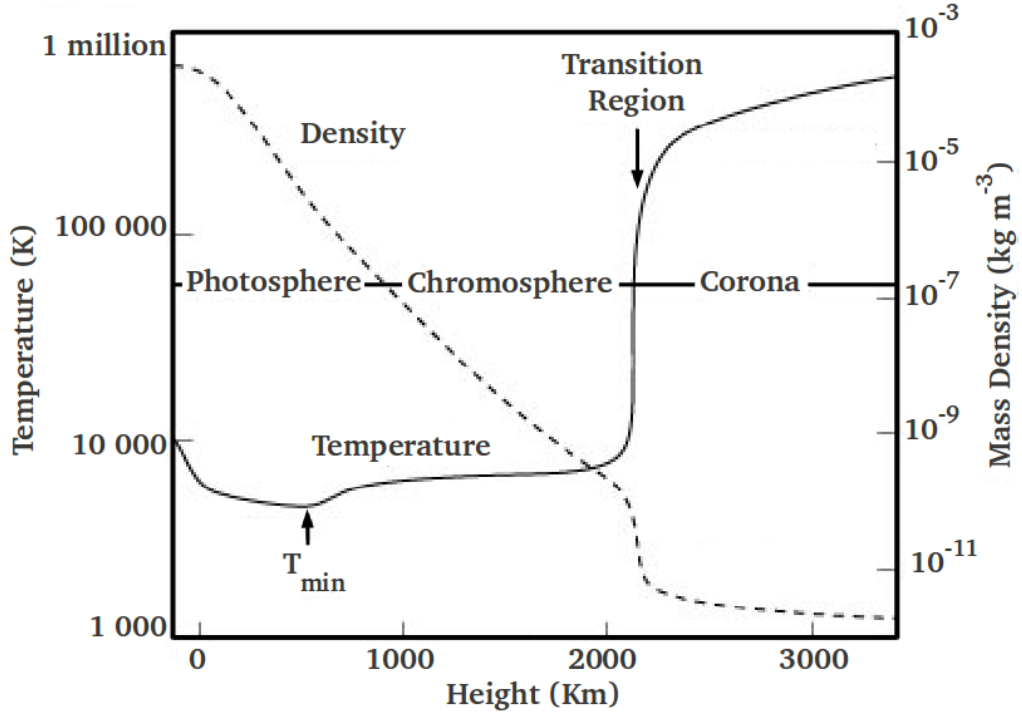


Figure 1.2: A 1D model of plasma mass density (in the units of kg m^{-3}) and temperature (K) profile of the solar atmosphere. This is taken from [Lang \(2001\)](#).

1.2 Coronal Transients

During past few decades, the study of coronal transients (solar flares, coronal mass ejections (CMEs), corotating interaction regions (CIRs), interplanetary shocks, eruptive prominences, etc) has become one of the most important genres of solar astrophysics. These transients play a crucial role in the solar-terrestrial physics and also in astrophysics. In the former field, coronal transients and the associated interplanetary disturbances caused by them are responsible for solar and galactic cosmic ray modulations, as well as various types of planetary magnetospheric and ionospheric disturbances. Thus solar coronal transients play an important testing ground for the theories of different energetic astrophysical phenomena. The coronal transients which arise from the solar flares have their energy release within the range of $10^{29} - 10^{33}$ ergs.

1.3 Coronal Mass Ejections

1.3.1 Introduction

A solar Coronal Mass Ejection (CME) is “...an observable change in coronal structure that 1) occurs on a time scale of a few minutes and several hours and 2) involves

the appearance and outward motion of a new, discrete, bright, white-light feature in the coronagraph field of view” (Hundhausen et al., 1984; Schwenn, 1996). CMEs are massive chunks of plasma accompanied with magnetic fields which erupt from the solar corona into the heliosphere. The average kinetic energy of a typical CME is $\approx 10^{32}$ ergs and this makes it one of the most energetic solar eruptive events in the entire solar system (Hudson et al., 2006). The interplanetary counterparts of CMEs are called interplanetary coronal mass ejections or ICMEs. CMEs have a wide range of speeds, from as low as ≈ 50 kilometers per second to more than 3500 km/s. The average mass ejected by a typical CME is approximately 10^{15} g to 10^{16} g. The occurrence rate of CMEs varies with the solar cycle; usually, it is higher during the solar maximum. Generally, it could be 4-5 CMEs per day during solar maximum, while ≈ 1 in the solar minimum (Yashiro et al., 2004). If the CME speed happens to cross the plasma characteristic speed in that medium, it can produce a shock in front of it. The average transit time for an Earth-directed ICME to reach the Earth is about 3.5 days. Earth-directed ICMEs are the primary drivers of the geomagnetic storms, leading to severe space weather disturbances like disrupting telecommunication systems, navigation mechanisms, satellite damages, strong space radiation effects to astronauts, etc. Therefore, realistic estimates of ICME transit times, their speeds and associated energies is very crucial in order to mitigate their effects on Earth’s space weather. This marks the importance of studying CMEs under the umbrella of solar astrophysics.

1.3.2 CME Observation

CME observation is broadly classified into three categories – remote sensing, in situ and interplanetary scintillation.

Remote Sensing

Generally, remote observations of CMEs are done by using coronagraphs when the solar radiation is scattered by free electrons present in the CME plasma via Thompson scattering. A coronagraph is an instrument which occults the Sun’s bright photosphere so that we can clearly observe the corona and coronal transients. In a sense, it acts like an artificial total solar eclipse. The first optical observation of CME was made on 14th December 1971 using a coronagraph on board *Orbiting Solar Observatory 7* (OSO-7). This was first described in a research paper by R. Tousey (Tousey, 1973) in 1973. However, the indirect effects of CMEs on Earth have been observed by people for many thousand years. Such indirect effects include the aurora which is reported in various documents both in Eastern and Western cultures (Howard, 2006). Evidence for CMEs can also be found in some early records of total

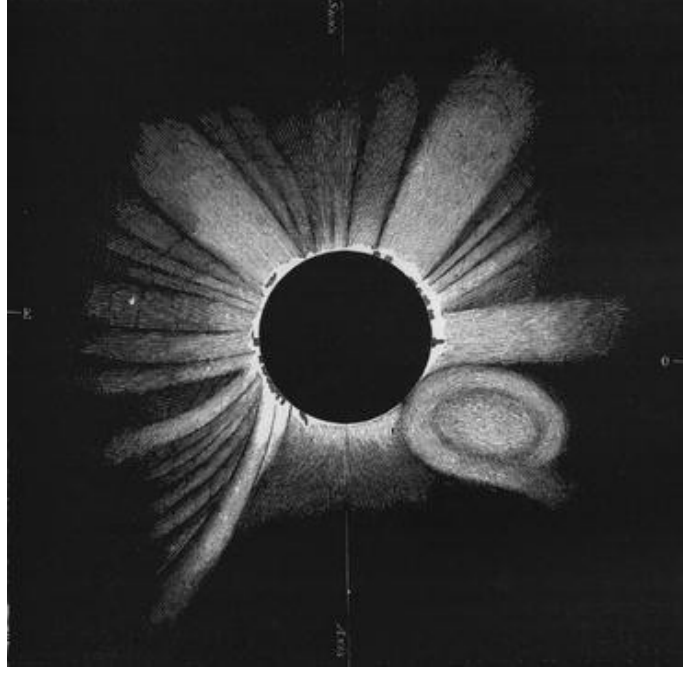


Figure 1.3: The drawing of a CME by G. Tempel during a total solar eclipse in 1860 over Spain ([Eddy, 1974](#)).

solar eclipse observations (Figure 1.3). During the 1970s, *OSO-7* observed 20 CMEs before re-entering into the Earth’s atmosphere. The next milestone of CME observations came through the *NASA Skylab* telescope (1973-1974). The contributions from both the *OSO-7* and *Skylab* helped to establish the importance of CMEs. The *Apollo Telescope Mount* (ATM) coronagraph on board *Skylab* mission observed 77 CMEs between 1973 and 1974 ([MacQueen et al., 1974](#)). One of the most significant observations during the 1980s was the detection of the first Earth-directed CME (observed in November 1979) by [Howard et al. \(1982\)](#). The white light coronagraph, *Solwind* on board *P78-1* spacecraft observed this CME. The *Solwind* coronagraph ([Michels et al., 1980](#)) and the *Coronagraph/Polarimeter* (CP) on board the *Solar Maximum Mission* (SMM, 1980) satellite [MacQueen et al. \(1980\)](#) contributed significantly to the CME observations during 1980s. [Howard et al. \(1985\)](#) analyzed 997 CMEs observed by the *Solwind* coronagraph between 1979 and 1981. These observations gave us a better estimate of the mass, density, and volume of these objects under a statistical view.

The interest to explore CMEs was thus rapidly building up and by the late 90s solar physics community was looking for new ways to get more information about these massive plasma blobs. The *Large Angle Spectrometric COronagraph* (LASCO) aboard the *Solar and Heliospheric Observatory* (SOHO) which was launched in 1995 considerably expanded our knowledge of CMEs. SOHO was a NASA-ESA project designed to study the Sun inside out – starting from its interior to its extreme

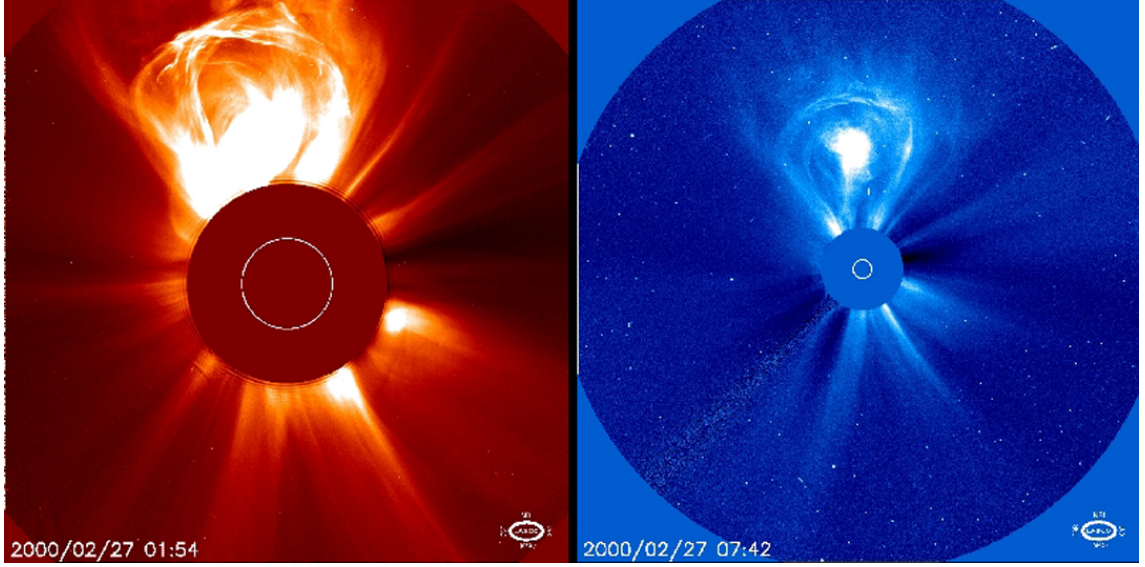


Figure 1.4: A CME white light image taken on 27th February, 2000 by LASCO C2 (left panel) and C3 (right panel) coronagraphs. *Image credit: SOHO NASA and ESA.*

atmosphere, and the associated CMEs. By observing the Sun over two decades, it has provided an immense amount of data which made numerous new discoveries in the field of solar astrophysics or *Heliophysics*. SOHO was started as a quiet sun mission to study the coronal structures and solar wind. However, the observations by LASCO and *Extreme Ultraviolet Imaging Telescope* (EIT), the study of CMEs became a major goal to the mission. LASCO has 3 coronagraphs that scans through the solar corona from $1.1 R_{\odot}$ to $30 R_{\odot}$, it is the first coronagraph to detect ‘Halo CMEs’ with high resolution. Till 2003, LASCO has detected 7000 CMEs (Yashiro et al., 2004). A CME white light image taken by LASCO C2 and C3 coronagraphs is shown in Figure 1.4. Next came in 2003, the *Solar Mass Ejection Imager* (SMEI) coronagraph on board the *Coriolis* spacecraft which observed the outer corona in white light (Eyles et al., 2003). It observed 139 CMEs in its first 1.5 years (Webb et al., 2006). In 2008, with the launch of the twin satellites, *Solar Terrestrial Relations Observatory* (STEREO), the CME remote sensing observation entered into another new era. This mission consists of two spacecraft – STEREO Ahead or STEREO A and STEREO Behind or STEREO B. It has two coronagraphs (COR 1 and COR 2) and two heliospheric imagers (HI 1 and HI 2) which track the CME evolution over a large field of view (1.4 to $318 R_{\odot}$). Other than these, there are the *Reuven Ramaty High Energy Solar Spectroscopic Imager* (RHESSI, 2002) and *Hinode* spacecraft (2006) which study the hard and soft X-Ray responses of CMEs. Other solar missions like *Solar Dynamics Observatory* (SDO, 2010) and recent *Parker Solar Probe* (PSP, 2018) and *Solar Orbiter* (SolO, 2019) heralded a new age in CME observations.

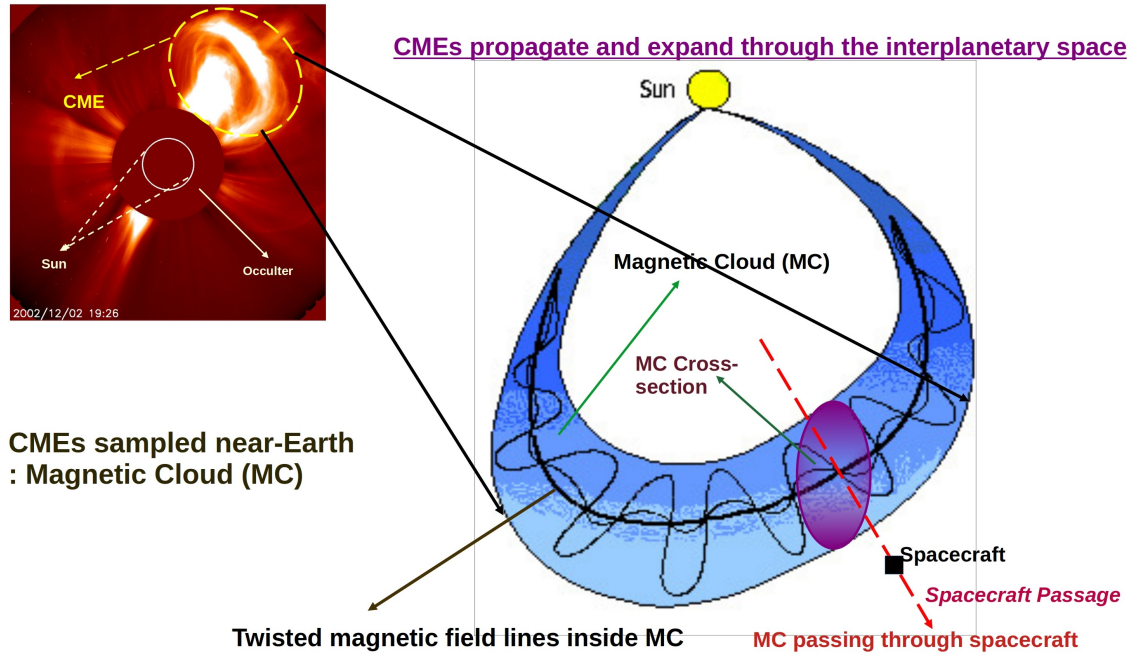


Figure 1.5: A cartoon describing the in situ observation of CME through a spacecraft.

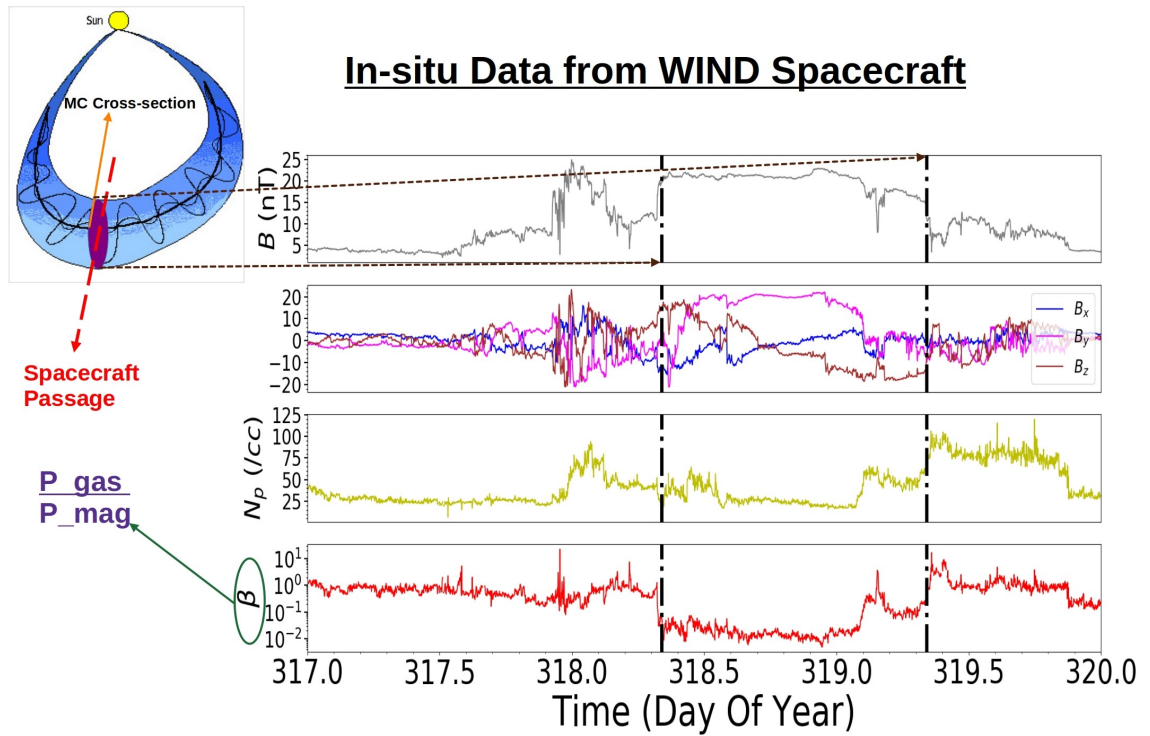


Figure 1.6: A cartoon example of CME in situ data observed by the WIND spacecraft at 1 AU.

In situ Observations

Although we get a good overall picture of CMEs via remote sensing observations, they cannot provide the direct sampling of the CME interiors. In situ spacecraft measurements do just this. When a CME passes through a spacecraft, it records the important magnetic and plasma parameters like total magnetic field (B), magnetic field components (B_x , B_y , B_z), their rotations, velocity components (v_x , v_y , v_z), temperature (T), particle number density (n), polar and azimuthal angles of CME rotation, plasma beta (β), etc. as a function of time along the passage of the spacecraft. Therefore such observations give us data along the interior (sometimes along the cross-section) of the CMEs. In situ observations also provide crucial information about the location and width of the CME-driven shocks. During its propagation phase, when the CME travels through the solar wind, it accumulates plasma in front of it. This region of draped plasma is known as ‘CME-sheath’. Sheaths can also drive geomagnetic storms and affect Earth’s space weather (Borovsky and Denton, 2006; Lugaz et al., 2016). Through in situ observation, one can observe the cloud-like structures configured by magnetic fields and associated with ICMEs. These are known as magnetic clouds or MCs and are considered to be a part of the magnetic flux rope (Nieves-Chinchilla and Viñas, 2008; Nieves-Chinchilla et al., 2018b). MCs are usually defined by – strong magnetic field, rotations in magnetic field components, low proton density, low plasma beta, etc. (Klein and Burlaga, 1982). A cartoon of CME in situ measurement is displayed in Figure 1.5. The *Ulysses* spacecraft, a joint mission by NASA and ESA, was launched in 1990. It sampled a significant number of ICMEs and their evolution through the solar wind via in situ technique (Du et al., 2010; Maunder et al., 2022). 1 AU or 1 astronomical unit is the distance between the Sun and the Earth and it is equal to $215R_\odot$, where $R_\odot$ implies the solar radius. On the other hand, the *Helios mission* (Helios, 1974 and 1976) which includes two spacecrafts – Helios 1 and 2 sampled numerous ICMEs from 0.29 AU to 1 AU. This mission, therefore, gave an opportunity to look inside the ICMEs during their propagation through the solar wind and also the subsequent ICME-solar wind connection (Bothmer and Schwenn, 1998). Another important milestone is the NASA *WIND* mission which was launched in 1994 and is located at 1 AU. In situ data also helps in understanding the plasma turbulence inside ICMEs and sheath regions, creating a bridge between the microphysics and macroscopic magnetohydrodynamics (MHD) (Bhattacharjee et al., 2023a; Kilpua et al., 2021). One example of *WIND* data as a function of time is shown in Figure 1.6. The *Advanced Composition Explorer* (ACE, 1997) is also a very crucial mission in understanding the ICME plasma characteristics. The recent in situ observations from *Parker Solar Probe* (PSP) mission have opened up new windows in

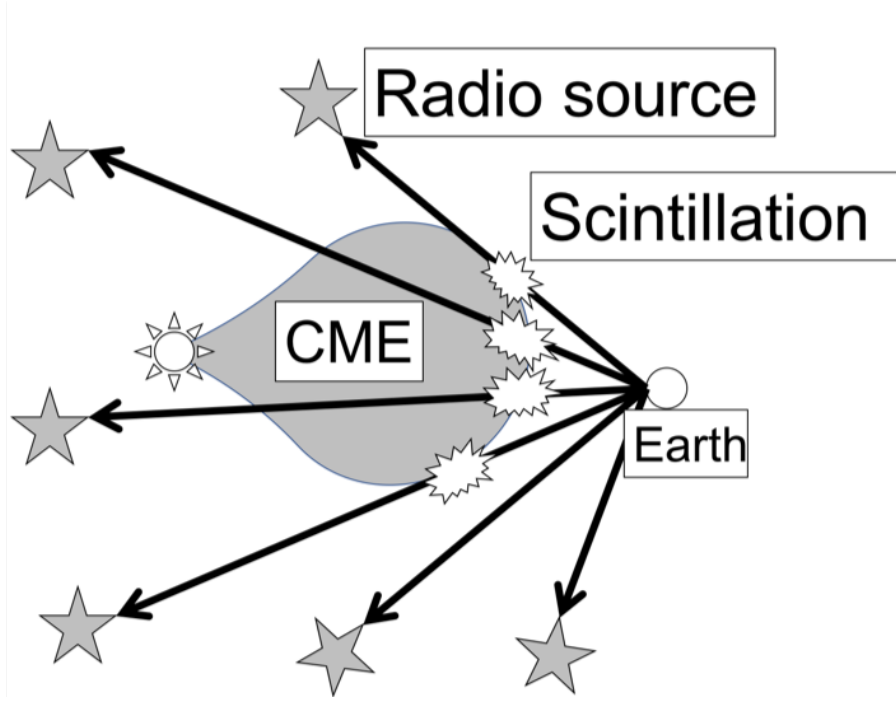


Figure 1.7: Schematic image of the IPS observation that detect the propagating CME in the interplanetary space. *Image Credit: Institute for Space-Earth Environmental Research, Nagoya University.*

the world of CME evolution (Moestl et al., 2020; Weiss et al., 2020a; Winslow et al., 2021). The in situ data from PSP also gave us a closer look into the CME-CME interaction (Nieves-Chinchilla et al., 2022). In situ data from multiple spacecraft (PSP, SoHO, WIND, BepiColombo) provides an amazing opportunity to look into the fundamentals of CME evolution and structure (Möstl et al., 2022; Weiss et al., 2021).

Interplanetary Scintillation

The Interplanetary scintillation (IPS) method is generally used to detect ICMEs, in an indirect way. This method of observation has been used for a long time (Hewish et al., 1964; Houminer and Hewish, 1974; Manoharan, 2006, 2010). The IPS technique is based on the variation in the radio signal from distant sources due to density perturbations in the interplanetary medium. The distortions in those radio sources indicate the density fluctuations in the passage of ICMEs during their propagations through the solar wind. A schematic diagram of the IPS mechanism is displayed in Figure 1.7.

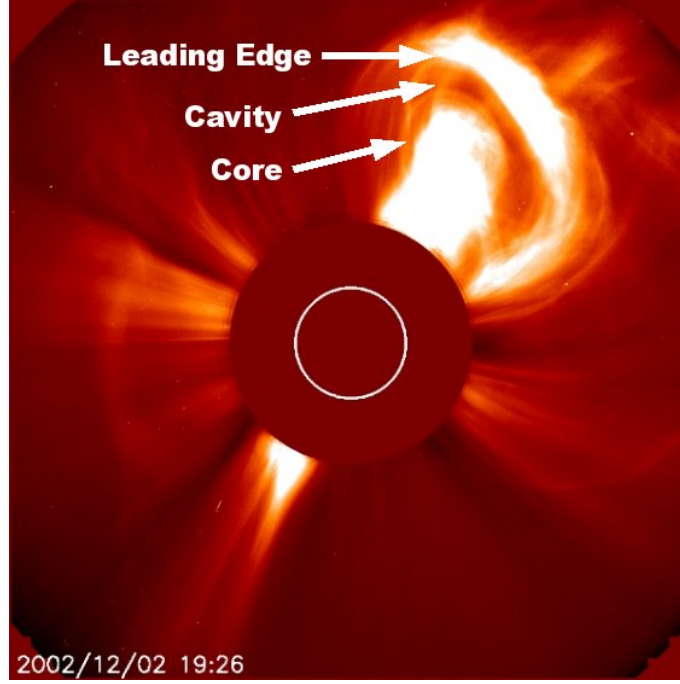


Figure 1.8: A three-part structure CME showing the loop-like leading edge, dark cavity, and bright core as seen by SOHO-LASCO C2 on December 2, 2002 (Colaninno, 2012).

1.3.3 CME Morphology

A quick survey of white light coronagraph images of CMEs will reveal a variety of shapes and morphologies. One of the reasons being the projection of the image on the plane of the sky. The classical CME morphology consists of a ‘three-part-structure’ – a bright core, a dark cavity, and an outer leading edge (Hundhausen, 1999; Low, 1996). An example is given in Figure 1.8. The core is usually thought to be associated with the prominence material in the corona, while the low-density cavity is assumed to be a part of CME flux rope configuration. The leading edge is assumed to be made of compressed plasma material ahead of the flux rope. However, some recent studies show that both the prominence and flux rope is connected to the CME core (Song et al., 2022). The evidence of CME flux rope structure associated with an event (April 13, 1997) is described in detail by Chen et al. (1997). This CME was observed by LASCO C2 and C3 telescopes. During propagation through the heliosphere, these parts merge together and form the magnetic cloud configuration. Simulations show that the dark cavity becomes the primary contributor to the magnetic cloud or flux rope in ICMEs, while the leading edge along with the solar wind plasma form the sheath region (Riley et al., 2008).

Because of the viewing perspective based on the plane of the sky, the LASCO/SOHO categorizes CMEs with angular width $\approx 360^\circ$ as ‘Halo’ CMEs and width $> 120^\circ$ as

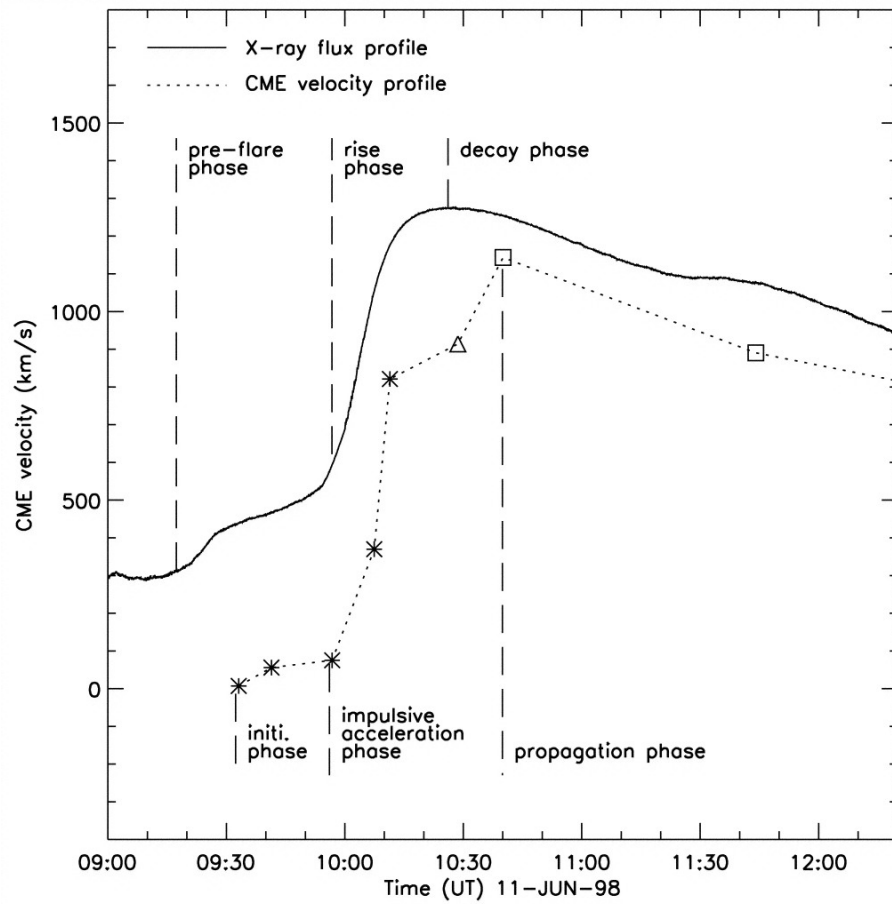


Figure 1.9: The speed-time profile of a CME on June 11, 1998,, along with the soft X-Ray response of the associated flare. The three phases of CME acceleration and evolution of flare intensity are displayed in this figure (Zhang et al., 2001).

‘Partial Halo’ (Yashiro et al., 2004). Halo CMEs can propagate towards or away from the Earth, spanning over all the coronagraph disk. During solar minimum, CMEs usually erupt near solar equator, while the eruptions occur over a wider range of latitudes of the solar disk in solar maximum (St. Cyr et al., 2000).

1.3.4 CME Initiation and Propagation

In this section, we will briefly discuss the initiation mechanisms of CMEs and their propagation.

Initiation

Although CMEs have been observed over 50 years, a lot of questions about their onset, dynamics, energetics, propagation, etc. are still unanswered. Owing to the limitations in the observations, scientists develop new theoretical ways to understand the birth and propagation of CMEs. We note that we do not yet have any clear picture of the CME onset process. Our current understanding is as follows:

the strong magnetic field, which is generated at the tachocline layer, and emerges throughout the convection zone. Then it rises into the tenuous corona. Owing to differential rotation at its footpoints, the coronal magnetic field structure gets progressively more twisted and stressed. After a certain threshold, that magnetic structure cannot sustain its equilibrium and begins to erupt. However, in this picture, it is still an open question whether the pre-CME structure should always possess a flux rope configuration. Or, the so-called magnetic flux rope is actually an extreme case of the ordinary magnetic arcade with a sufficiently strong twist (Chen, 2008). One can consider the beautiful review by Chen (2017) for more details. This review paper talks about the advancement of theory and observations related to CMEs. One of the most important and still unclear issues is how the flux rope system is triggered. We note that the magnetic energy that is stored in the field lines can manifest in different forms – the eruption of CMEs, acceleration charged particles, initiation solar flares, etc. Multi-wavelength observations provide important clues to understanding different stages of these onset mechanisms (Chen, 2011).

CME onset models can broadly be classified into two different categories: with magnetic reconnection or without magnetic reconnection. The reconnection is thought to be responsible in restructuring the magnetic field lines to release the stress owing to flux emergence and Sun’s differential rotations (Aschwanden, 2005). The models that include the reconnections are tether-cutting or flux-cancellation model (Moore et al., 2001; Sturrock, 1989) and magnetic break-out model, etc (Antiochos et al., 1999; Lynch et al., 2008). We note that in the tether-cutting model, the overlying magnetic field does not reconnect; it only expands. The reconnection happens beneath the overlying field. On the other hand, in the breakout model, the flux or field lines that reconnect are a part of the central magnetic flux and the overlying magnetic field configuration. The models that do not invoke reconnection include flux injection (Chen, 1996), kink instability (Török and Kliem, 2003), and torus instability models (Kliem and Török, 2006).

Propagation

According to Sachdeva et al. (2015), the fast CMEs (CMEs with speed more than 1000 km/s) experience the acceleration due to the Lorentz force very close to the Sun and they are subsequently dragged down by the ambient solar wind. On the other hand, the slow CMEs experience the drag domination at much higher heights (between 15 to 50 $R_{\odot}$). Figure 1.9 shows the velocity profile of a CME on June 11, 1998, along with the soft X-Ray response of a flare associated with it. The figure illustrates the three phases of CME kinematics – the slow initiation, the impulsive acceleration and the drag dominated deceleration (Zhang et al., 2001).

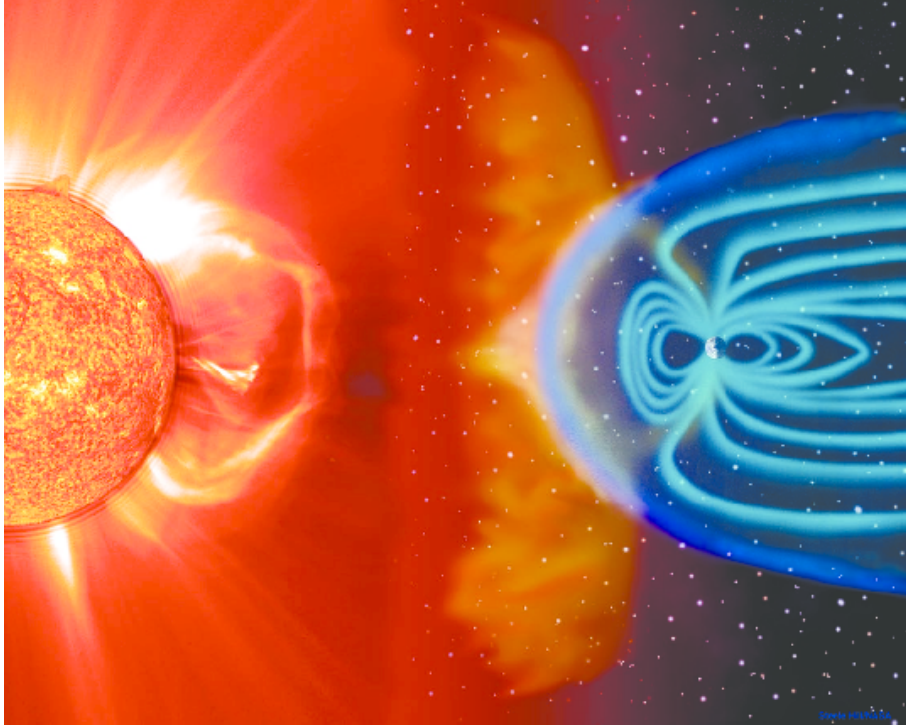


Figure 1.10: A cartoon (not to scale) describing a CME impacting on the Earth’s outer atmosphere *Image credit: NASA space weather awareness.*

The aerodynamic drag is one of the key players in the CME propagation phase (Borgazzi et al., 2009; Cargill, 2004; Sachdeva et al., 2015; Vrřnak and Gopalswamy, 2002a). This is caused due to the momentum exchange between the CME and the ambient solar wind medium during its motion through the heliosphere. The CME-solar wind interaction tries to equilibrate the CME with the ambient solar wind, i.e., the fast CMEs are dragged down by the solar wind, while the slow ones are accelerated. However, we note that the deceleration of fast CMEs is not down to the ambient solar wind speed.

Another important parameter that plays a crucial role is the presence of shock in front of the ICMEs. The shock-based models like Dryer et al. (1984) treat ICMEs with shocks as perturbations on the solar wind background. On the other hand, models like ENLIL (Falkenberg et al., 2010; Taktakishvili et al., 2009) consider ICMEs as plasma blobs moving through the solar wind. In situ data sampling of ICMEs provides us with a very good opportunity to study the propagation phase (Bhattacharjee et al., 2023b; Nieves-Chinchilla et al., 2018b). The in situ observations from the new missions like the *Parker Solar Probe*, *Solar Orbiter*, *Beppi Colombo* which observe the CMEs between the Sun and the Earth add more details to it.



Figure 1.11: A beautiful image of the aurora australis or the Northern lights from Alaska captured during September 2022.

1.3.5 CME and Space Weather

Figure 1.10 shows a not-to-scale representation of a CME impacting the Earth's outer atmosphere. The Sun affects the near-Earth space environment directly and / or indirectly creating the 'Sun-Earth connection'. In 1716 Edmund Halley first suggested that the beautiful Northern lights (Figure 1.11) are due to charged particles from outer space impinging on the Earth's magnetosphere, leading to the first observations of the Sun-Earth connection. Later, by mid-twentieth century various studies using multiple ground-based and space-based observatories proved the essential connection between the Sun and the Earth's space weather.

Before discussing the impacts of CMEs on Earth's space weather, let us first define what we mean by the term 'space weather'. Space weather refers to conditions on the Sun and the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can affect human life and health (definition by U.S. National Space Weather Plan). Various solar activities (including CMEs) can directly create space weather disturbances – leading to the disruption of satellite systems, telecommunications, the Global Positioning System (GPS), damaging electrical power grids, causing severe radiation hazards to astronauts and airplane passengers, affecting the underground electronic pipelines and many more. The cartoon of Figure 1.12 describes some of these space weather effects. The main solar events that cause such



Figure 1.12: A cartoon displaying the space weather effects. *Image credits: South African National Space Agency (SANSA).*

disruptions are Earth-directed ICMEs, solar energetic particles (SEPs), co-rotating interaction regions (CIRs), etc. ICMEs are considered as the primary drivers of geomagnetic storms and therefore, leading to space weather disturbances ([Gopal-swamy, 2009a,b](#); [Howard et al., 2006](#)).

Coronal mass ejections (CMEs) develop into large-scale structures very quickly and therefore expanding to sizes greater than that of the Sun itself. When Earth-directed, these massive eruptions of plasma along with strong magnetic fields can cause intense geomagnetic storms. If the CME speed is larger than the plasma characteristic speed of that medium, they can drive interplanetary shocks in front of them. These shocks then interact with the Earth's bow-shock, transferring energy, magnetic field and high-speed charged particles into the magnetosphere and compressing the dayside magnetopause. These compression effects then travel towards the tailward side of the magnetosphere at the solar wind speed (few hundred kms per second), causing strong auroral activity observable almost instantaneously all around the auroral oval ([Bothmer and Daglis, 2007](#); [Zhou and Tsurutani, 2001](#)). We note that, CMEs can also accelerate SEPs that have sufficient energies to penetrate the skins of space-borne probes and damage technical systems. The SEP fluxes from strong flares and CMEs can increase radiation levels which can endanger the lives of astronauts and high-latitude aircraft passengers. These radiations can also enhance ionization and excitations in the Earth's middle atmospheric polar caps causing ozone depletion ([Jackman et al., 2005](#); [Rohen et al., 2005](#)).

The most intense geomagnetic storm in recorded history took place in September 1859 (solar cycle 10) and it was caused by a CME associated with a very strong flare. This was recorded independently by British astronomers Richard Carrington and Richard Hodgson. Because of the geomagnetically induced currents (GICs), the telegraph posts in most of North America, Alaska and all over Europe failed with some creating electric sparks which lead to fire. Another very intense storm was the Halloween storm in 2003 (solar cycle 23) which took place due to a series of CMEs and associated flares. Apart from power outages and damaging telecommunication systems, it also damaged some parts of SOHO and ACE satellites.

These damaging effects of solar phenomena necessitate an accurate warning and predictive tool in order to determine the space weather affects, mitigate disruptions in technical and communication systems and also ensure the safety of airlines and astronauts. Therefore, a good understanding of all the solar transients (CMEs, CIRs, solar wind, interplanetary shocks, etc) is of utmost importance to go deeper into the impacts on the Earth's space weather. This makes the study of the dynamics and characteristics of CMEs increasingly important ([Chen, 2011](#)). Advances in observational capacity (both ground and space-based) of heliospheric missions as well as scientific efforts in developing both theoretical and numerical models are bringing us closer to building a dependable framework for forecasting the arrival and effects of these massive plasma blobs on the Earth.

1.4 Thesis Organization

The rest of the thesis is organized as follows:

1. **Chapter 2: On Modeling ICME Cross-Sections as Static MHD Columns**

It is well-known that CMEs expand during their propagation through the solar wind. However, their cross-sections are usually modeled as static plasma columns within the assumptions of magnetohydrodynamics (MHD). In this chapter, we check the validity of these assumptions using the in situ data of a large sample of well-observed MCs. We also compute the Joule heating rates inside CME plasma using the estimates of electrical conductivities. The heating of CME plasma is a departure from the ideal MHD framework.

2. **Chapter 3: Characterizing the specific energy and pressure in near-Earth magnetic clouds**

The pressure and energy associated with the magnetic field and plasma inside CMEs are thought to play a crucial role in CME expansion and their overall

dynamics in the propagation phase. In this chapter, we compare the specific energy (which comprises thermal, magnetic, and kinetic counterparts) of CME plasma with that inside the ambient solar wind background for a large sample of well-observed near-Earth ICMEs. Next, we seek to understand if the thermal+magnetic specific energy and pressure is responsible for the propagation and expansion of these near-Earth ICMEs. Finally, we ask whether, the excess thermal+magnetic specific energy inside the CME plasma might make them appear like rigid objects in the context of aerodynamic drag.

3. **Chapter 4: Turbulence and Anomalous Resistivity inside Near-Earth Magnetic Clouds**

This chapter aims at understanding different turbulent modulation indices (density, magnetic field, acoustic Mach number, etc.) and quantify the anomalous (non-Spitzer) resistivity inside CME plasma. Such resistivity is associated with the electrons which are stochastically scattered due to the fluctuations in the magnetic field. As in the previous study of Chapter 3, we use a large sample of well-observed near-Earth ICMEs. We compare the turbulent modulation indices and anomalous resistivity between the plasma inside the ICMEs and in the ambient solar wind. The enhanced Joule heating arising from this anomalous resistivity might be a supplement to the heating mechanism inside ICME plasma.

4. **Chapter 5: Future Work**

In this chapter, we propose the problem statements and methodology of our future research. We will primarily focus on three problems – CME heating, aerodynamic drag and CME-magnetosphere coupling. Realistic estimates of turbulent transport coefficients such as viscosity, thermal, and electrical conductivity are key aspects in addressing these problems, leading to a bridge between the microphysics and macrophysics. The third problem directly concerns estimates of geoeffectiveness caused by the Earth-directed CMEs.

Chapter 2

On Modeling ICME

Cross-Sections as Static MHD Columns

A Brief Overview

Solar coronal mass ejections are well-known to expand as they propagate through the heliosphere. Despite this, their cross-sections are usually modeled as static plasma columns within the magnetohydrodynamics (MHD) framework. We test the validity of this approach using in situ plasma data from 151 magnetic clouds (MCs) observed by the WIND spacecraft and 45 observed by the Helios spacecraft. We find that the most probable cross-section expansion speeds for the WIND events are only ≈ 0.06 times the Alfvén speed inside the MCs, while the most probable cross-section expansion speeds for the Helios events is ≈ 0.03 . MC cross-sections can thus be considered to be nearly static over an Alfvén crossing timescale. Using estimates of electrical conductivity arising from Coulomb collisions, we find that the Lundquist number inside MCs is high ($\approx 10^{13}$), suggesting that the MHD description is well justified. The Joule heating rates using our conductivity estimates are several orders of magnitude lower than the requirement for plasma heating inside MCs near the Earth. While the (low) heating rates we compute are consistent with the MHD description, the discrepancy with the heating requirement points to possible departures from MHD and the need for a better understanding of plasma heating in MCs.

2.1 Introduction

Before delving into the technical details of the research work presented in this chapter, we first summarize the essentials of the MHD framework and their use in modeling the ICMEs.

2.1.1 A Brief Note on MHD

Magnetohydrodynamics (MHD) is the study of the dynamics of electrically conducting fluids such as plasma, electrolytes, liquid metals, etc (Sheikholeslami and Ganji, 2016; Sturrock, 1994). The term, ‘magnetohydrodynamics’ is derived from ‘*magneto*’ meaning related to magnetic fields, ‘*hydro*’ which means liquid and ‘*dynamics*’ meaning movement. The research field of MHD was initiated by Hannes Alfvén for which he was awarded the Nobel Prize in Physics in the year 1970. The fluids which follow the MHD prescription are known as ‘magnetofluids’. Throughout this thesis, the terms, ‘plasma’, ‘magnetized fluid’, and ‘magnetofluid’ are interchangeably used. The MHD formalism is described by combining the Navier-Stokes equation of fluid dynamics and the Maxwell’s equations for electromagnetism. We use cgs units throughout this thesis.

The Navier-Stokes Equation

Before considering magnetic fields, we introduce the equations of hydrodynamics which treat the conservations of mass, momentum, and energy. The equation for mass conservation with respect to the lab frame (also known as Eulerian frame of reference) is:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (2.1)$$

where, ρ and $\mathbf{v}$ are the mass density and the velocity of a fluid parcel respectively. The first and the second term on the left-hand side (LHS) of Equation 2.1 describe the temporal change of mass density and the divergence of the mass flux respectively. The ∂ of any parameter represents the partial derivative of that parameter measured in the lab frame. If for a fluid, the mass density has no spatial and temporal variations, then Equation 2.1 is reduced to $\nabla \cdot \mathbf{v} = 0$. Such fluid is known as ‘incompressible fluid’. The momentum conservation or force balance equation is given as,

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\frac{1}{\rho} \nabla p + \frac{\mathbf{F}}{\rho} \quad (2.2)$$

where, p is the fluid pressure which can be derived from $p = nk_B T$, where n , k_B and T are the number density, Boltzmann’s constant and absolute temperature respectively. The first term in the right-hand-side (RHS) of the Equation 2.2, therefore,

represents the force per unit mass density due to the pressure gradient, while the second term in the LHS depicts the fluid advection. $\mathbf{F}$ is the body force that acts at all the points within the body of the fluid parcel. An example of such body force is the gravity. Equation 2.2 is also known as the Euler equation. On the inclusion of the viscous term on the RHS of Equation 2.2, we get the following equation

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\frac{1}{\rho} \nabla p + \frac{\mathbf{F}}{\rho} + \frac{\mu}{\rho} \nabla^2 \mathbf{v}. \quad (2.3)$$

This equation (Equation 2.3) is generally known as the ‘Navier-Stokes equation’. The term $\frac{\mu}{\rho} \nabla^2 \mathbf{v}$ is responsible for the viscous effects with μ as the viscosity. Sometimes, the term μ/ρ is represented by ν and called ‘the kinematic viscosity’. The viscous effects assume importance when the velocity gradients are sufficiently high and/or the fluid has a larger viscosity. We note that this version of the Navier-Stokes equation (Equation 2.3) is only valid if the spatial variation of μ is neglected, the heat production due to viscous damping of motions is also neglected and any term involving $\nabla \cdot \mathbf{v}$ is set to zero (Choudhuri et al., 1998). Despite these limitations, Equation 2.3 is extensively used as the Navier-Stokes equation in fluid dynamics. This is one of the fundamental equations governing the motion of a fluid parcel. If we take the curl of Equation 2.3, then we get for incompressible barotropic fluids (i.e., fluids with $p = f(\rho)$),

$$\frac{\partial \omega}{\partial t} = \nabla \times (\mathbf{v} \times \omega) + \nu \nabla^2 \omega. \quad (2.4)$$

$\omega = \nabla \times \mathbf{v}$ is called the vorticity of the fluid. Equation 2.4 can be re-written as,

$$\frac{\partial \omega'}{\partial t'} = \nabla' \times (\mathbf{v}' \times \omega') + \frac{1}{R_e} \nabla'^2 \omega' \quad (2.5)$$

where the primed notations represent the usual quantities in a scaled unit. $R_e = LV/\nu$ is a dimensionless number known as the Reynolds number. L and V are the length scale of interest and typical fluid velocity.

The MHD Equations

In the MHD framework, the mass conservation equation (Equation 2.1) remains unaffected. In the non-relativistic regime i.e., when the fluid speed is much smaller than the speed of light in the vacuum (c), the effect of magnetic field ($\mathbf{B}$) is taken into account by the addition of the Lorentz force term to the Navier-Stokes equation (Equation 2.3) in the following way (Choudhuri et al., 1998; Sturrock, 1994),

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\frac{1}{\rho} \nabla p + \frac{\mathbf{F}}{\rho} + \frac{\mu}{\rho} \nabla^2 \mathbf{v} + \frac{1}{\rho c} \mathbf{j} \times \mathbf{B}. \quad (2.6)$$

where, $\mathbf{j}$ ($= \frac{c}{4\pi} \nabla \times \mathbf{B}$) is the current density. The Lorentz force ($\frac{1}{c}(\mathbf{j} \times \mathbf{B})$) can be expanded as,

$$\frac{1}{c}(\mathbf{j} \times \mathbf{B}) = \frac{1}{4\pi}(\nabla \times \mathbf{B}) \times \mathbf{B} = -\frac{1}{8\pi}\nabla B^2 + \frac{1}{4\pi}(\mathbf{B} \cdot \nabla)\mathbf{B} \quad (2.7)$$

where, the first term on the RHS represents the gradient of the magnetic pressure while the second term shows the gradient of magnetic tension in a magnetofluid. These two terms rise due to the anisotropy caused by the presence of the magnetic field. These two terms work in combination to make the magnetic field lines act like ‘elastic bands within the fluid’ which resists being stretched: either pushed together or pulled transverse to their length. Another equation that assumes a great importance in the MHD framework is the induction equation. The induction equation is written as,

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} \quad (2.8)$$

where, η is called the magnetic diffusivity and is defined as $\eta = \frac{c^2}{4\pi\sigma}$. c and σ are the speed of light in the vacuum and electrical conductivity of the magnetofluid respectively. This equation (Equation 2.8) describes the character of the magnetic fields inside a moving magnetofluid with a specified conductivity (σ). The first term in the RHS of Equation 2.8 describes the induction due to the motion of the fluid while the second term explains the magnetic diffusion by allowing the magnetic field lines to ‘leak out’ or ‘diffuse’ from their original positions. The hypothetical limit of infinite conductivity (or zero magnetic diffusion) is known as the *ideal MHD limit*. In this limit, Equation 2.8 becomes

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}). \quad (2.9)$$

The magnetic flux (ψ) through a contour (C) which is co-moving with the plasma is:

$$\psi = \int_S \mathbf{B} \cdot d\mathbf{S} \quad (2.10)$$

where, S is the surface that spans C . The total time rate of change of ψ can be written as (Choudhuri et al., 1998):

$$\frac{d\psi}{dt} = - \int_S \nabla \times (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot d\mathbf{S} \quad (2.11)$$

where, $\mathbf{E}$ is the electric field. The total time derivative implies that we are in frame moving with a magnetized fluid parcel. In ideal MHD, $\mathbf{E} + \mathbf{v} \times \mathbf{B} = 0$ (Choudhuri et al., 1998), suggesting, $d\psi/dt = 0$. This implies that ψ remains constant in time for any arbitrary contour. This, in turn, indicates that magnetic field-lines must move with the magnetized fluid. In other words, the field-lines are frozen into the

magnetized fluid. This was first discovered by Alfvén and therefore called *Alfvén's theorem of flux freezing*.

2.1.2 Magnetohydrostatic Equilibrium

The magnetohydrostatic equilibrium refers to the hydrostatic equilibrium ($\mathbf{v} = 0$) in the framework of MHD (see, e.g., § 14.3 in Choudhuri et al., 1998; § 4.3 in Boyd and Sanderson, 2003a). The gravitational attraction due to the Sun becomes negligible beyond a few solar radii above the photosphere, and the body force $\mathbf{F}$ can therefore be ignored (see § 2 in Cargill, 2004). If we now neglect the viscous term, then in the magnetohydrostatic equilibrium, the MHD force balance equation (Equation 2.6) reduces to (Nieves-Chinchilla et al., 2016)

$$\frac{1}{4\pi\rho}(\nabla \times \mathbf{B}) \times \mathbf{B} = \frac{1}{\rho}\nabla p. \quad (2.12)$$

Equation 2.12 shows the balance between the Lorentz force and the force due to the pressure gradient in the plasma. ICME cross-sectional structures are generally modeled as static-plasma columns based on such magnetohydrostatic equilibrium. This includes early studies like Lundquist (1951), Burlaga (1988) to work that is based on the Grad-Shafranov equation (Hu and Sonnerup, 2002; Isavnin et al., 2011; Möstl et al., 2009) and similar formalisms (Cid et al., 2002; Nieves-Chinchilla et al., 2016, 2018a). These approaches are similar to those used in describing the static equilibrium configuration of laboratory plasma columns (Boyd and Sanderson, 2003a). It is a well-known fact that ICMEs expand as they travel through the heliosphere, suggesting that they are dynamic and expanding structures; (see, e.g., Bothmer and Schwenn, 1998; Gulisano et al., 2010; Vandas et al., 2009). However, ICME cross-sections are generally modeled as static plasma columns. It is therefore worth examining how the apparent success of such static models can be reconciled with the observation of the expansion of the ICME cross-sections. This chapter addresses the following:

1. Although ICME cross-sections are observed to expand, how do the expansion speeds compare with typical signal propagation speeds (like the Alfvén speed) inside the ICME plasma? If the expansion speeds are slow, the concept of a static column would be justified.
2. The MHD description used to model ICME cross-sections assumes that the bulk plasma velocities are taken to be equal to zero. We check if the electrical conductivity of the medium is large (it is technically infinite in ideal MHD), which means that the magnetic diffusivity is very small. This is the basis of the well-known *frozen-in* condition for magnetic fields in magnetohydrodynamics.

The Lundquist number, which is the ratio between the magnetic diffusion timescale and the Alfvén crossing timescale, is a standard measure to quantify the goodness of the *frozen-field* assumption. The larger the Lundquist number, the better the validity of the MHD description.

3. An infinitely conducting plasma would be non-dissipative, which disagrees with the expectations of plasma heating inside ICMEs. Having computed the electrical conductivity for item 2, we use an approximate estimate of the current density to estimate the Joule heating rate and to compare it with inferred MC plasma heating rates.

The data we use in this chapter and the associated event selection criteria are explained in § 2.2. From here on, we will restrict our attention only to the magnetic clouds (MCs) within the overall ICME structure. MCs are the magnetically well-structured parts of ICMEs and their boundaries and expansion speeds are typically better defined. We compare the observed MC expansion speeds with the Alfvén speed in § 2.3. We evaluate the collisional conductivity and use it to evaluate the Lundquist numbers for MCs are calculated in § 2.4. The conductivity is used to compute Joule heating rates in § 2.5. Our overall conclusions on the applicability of the MHD paradigm to MCs and the caveats are presented in § 2.6.

2.2 Data

2.2.1 A Brief Note on the Spacecraft

The WIND (<https://wind.nasa.gov/>) is a spin-stabilized spacecraft launched on November 1, 1994, and placed at the Lissajous orbit around the Lagrange 1 or L1 point. The WIND and another spacecraft named Polar were a part of the Global Geospace Science (GSS) program which is a part of the International Solar-Terrestrial Physics (ISTP) program. The ISTP also included some additional missions like Geotail, SoHO and Cluster. The primary science objectives of the WIND mission are to provide a complete picture of plasma, energetic particle, and magnetic fields for the magnetospheric and ionospheric studies, investigate the basic plasma processes occurring in the near-Earth solar wind and provide a baseline at 1 AU for the inner and outer heliospheric missions. Helios 1 and Helios 2 are a pair of spacecraft that were launched in December 1975 and January 1976 respectively into the heliocentric orbit in order to study different solar processes. Both the probes executed their orbits in the inner heliosphere, from 0.29 to 1 AU with roughly a six-month orbital period, thus providing us with a unique opportunity to study a significant portion of the solar wind. Magnetic field data were recorded at high res-

olution, with plasma data recorded at approximately 40.5-second resolution. These datasets give the highest resolution plasma (proton and helium) moments with the corresponding average magnetic field for each plasma measurement. The Helios mission primarily studied the velocity and distribution of the solar wind plasma, measured the field strength and direction of magnetic fields, measured the scattering of sunlight by interplanetary dust particles, and investigated the composition, charge, mass, velocity, and distribution of the dust particles. In this study, we use the 1-minute cadence Magnetic Field Investigation (MFI) and Solar Wind Experiment (SWE) time series data from the WIND observation while 40.5-second magnetic field and plasma time series data from the Helios observations. These data use two different Cartesian coordinate systems: the geo-centered solar ecliptic (GSE) for the WIND (<https://wind.nasa.gov/>) and spacecraft-centered solar ecliptic (SSE) for the Helios (Di Matteo et al., 2019).

2.2.2 Data

For this study (Bhattacharjee et al., 2022), we use 151 well-observed Earth-directed ICMEs from the WIND-ICME catalog (wind.nasa.gov/ICMEindex.php) as observed by the WIND spacecraft (Nieves-Chinchilla et al., 2018b, 2019). The magnetic clouds (MCs) associated with these near-Earth ICMEs are categorized into different types depending on how well the observed plasma parameters fit the expectations of a static flux rope configuration. Of all the ICMEs observed between the years 1995 and 2015 listed on the WIND website, we first shortlist those that are categorized as F+ and Fr events. These events best fit the expectations of the flux rope model (Nieves-Chinchilla et al., 2016, 2018b). Fr events indicate MCs with a single magnetic field rotation between 90° and 180° and F+ events indicate MCs with a single magnetic field rotation greater than 180° . We further shortlist events that are neither preceded nor followed by other ICMEs or ejecta two days before and after the event under consideration, so as to exclude interacting CMEs. Our final shortlist thus comprises 151 ICMEs from the WIND catalog. We also use in situ data from the 45 well-observed MCs from Helios observations shortlisted by Bothmer and Schwenn (1998). These 45 events, observed between December 1974 and July 1981, provide us with a unique opportunity to analyze ICMEs at heliocentric distances ranging from 0.3 AU to 1 AU. This composite dataset helps us analyze the behavior of well-observed MCs over a wide range of heliospheric distances. The shortlisted events from the WIND spacecraft are listed in Table A.1.1, while those from the Helios 1 and 2 spacecraft are listed in Table A.1.2 of the Appendix.

2.3 How Good is the Static Assumption for ICMEs?

ICME cross-sections are typically modeled as static plasma columns. However, it is clearly evident from various observations that they expand as they propagate in the heliosphere.

Our findings show how and why the static assumption is justified. In the static equilibrium, the governing equation is Equation 2.12. It is important to note that, one can obtain Equation 2.12 from Equation 2.6 (neglecting the viscous term) via two ways: if the plasma velocity $\mathbf{v} = 0$ and/or if the material derivative of the plasma velocity $D\mathbf{v}/Dt \equiv \partial\mathbf{v}/\partial t + (\mathbf{v} \cdot \nabla)\mathbf{v} = 0$. In the current context, magnetohydrostatic equilibrium refers to the first assumption ($\mathbf{v} = 0$). As mentioned previously, Equation 2.12 depicts the balance between the Lorentz force and the force due to the pressure gradient in the plasma. Magnetic flux ropes are bundles of twisted magnetic field lines with electrical currents flowing through them (Zhong et al., 2021). They play crucial roles in explaining the structure of the MCs and associated ICMEs (Dasso et al., 2007; Gopalswamy et al., 2013). Early models (Burlaga, 1988; Lepping et al., 1990) considered that the flux rope would be force-free (i.e., $\mathbf{j} \times \mathbf{B} = 0$), in which case the RHS of Equation 2.12 would become zero. Some later models; e.g., Möstl et al. (2009); Nieves-Chinchilla et al. (2016); Scolini et al. (2019a) relax this force-free assumption and assume the term ∇p in the RHS of Equation 2.12 to be non-zero.

For each of the events listed in Tables A.1.1 and A.1.2, we compute the expansion speed of the MC cross-section using (Nieves-Chinchilla et al., 2018b)

$$v_{\text{exp}} = \frac{1}{2}(v_s - v_e) \quad (2.13)$$

where v_s and v_e are the speeds at the start and at the end of the MC boundary as obtained using a linear fit of the temporal profile of the plasma speed, v (see Figure 2.1). This expansion speed (v_{exp}) which we estimate is only for the MC part of the overall ICME. This is primarily because only the magnetic cloud boundaries are well determined for the Helios events; so, we retain the same scheme for the WIND events for consistency. However, the expansion speed need not be strictly zero in order for the MHD static equilibrium (Equation 2.12) to be valid. If $|v_{\text{exp}}|$ is significantly small compared to the characteristic speeds, like the Alfvén speed, the static approximation can be considered to be valid. The WIND ICME website (wind.nasa.gov/ICMEindex.php) provides a detailed time profile of the Alfvén speed v_A , using which we compute the following ratio:

$$R_A = \frac{|v_{\text{exp}}|}{\langle v_A \rangle}, \quad (2.14)$$

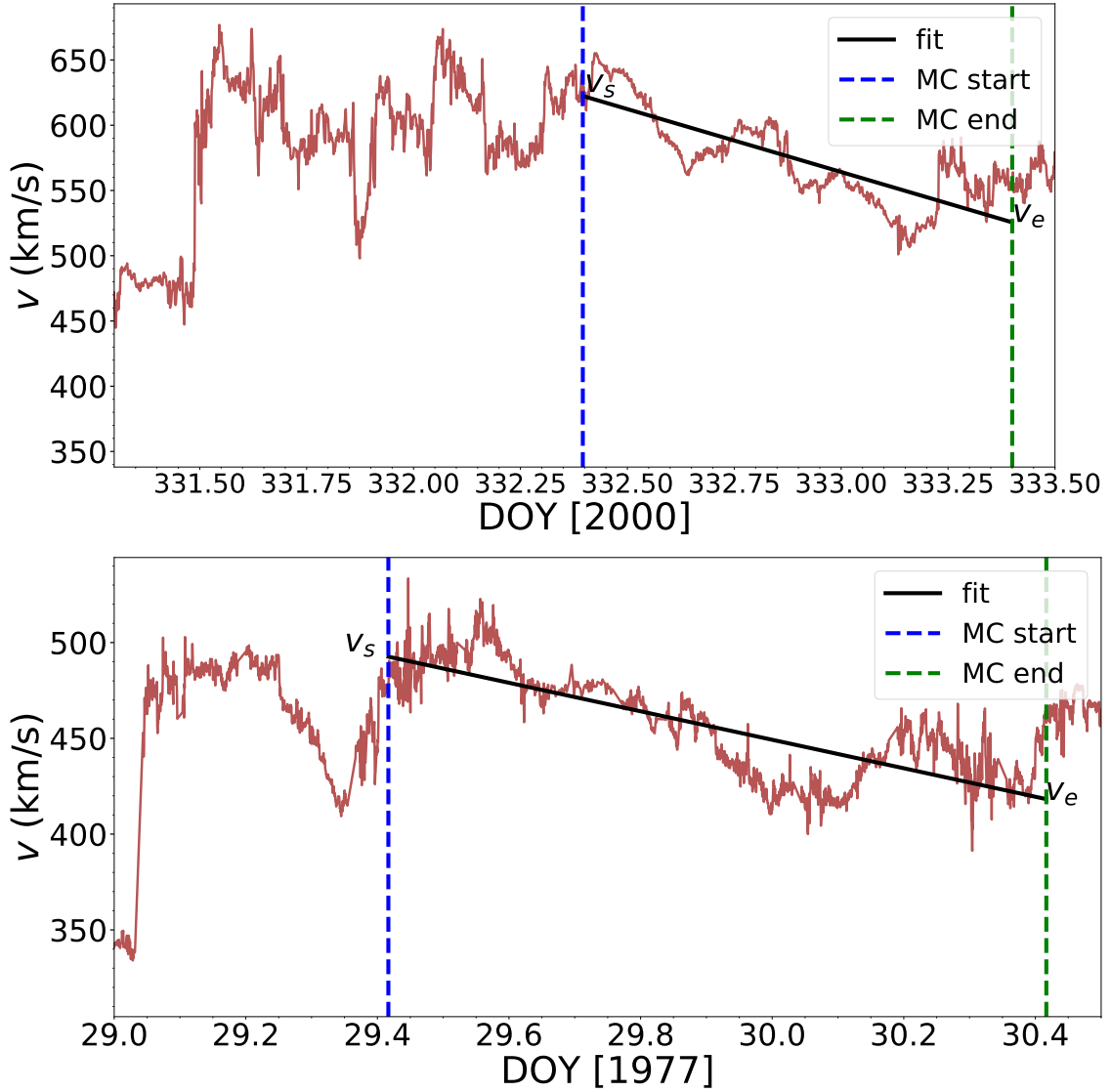


Figure 2.1: Examples of the linear fit of the plasma velocity (v) profile inside the MC. The top and the bottom panels describe event 53 of Table A.1.1 (WIND observations) and event 8 of Table A.1.2 (Helios observations), respectively. The black lines in the plots denote the linear fit. v_s and v_e are the speeds at the MC start (t_s ; blue dotted line) and at the MC end (t_e ; green dotted line), respectively as obtained from the linear fit. We compute the MC expansion speeds (Equation 2.13) using v_s and v_e .

where $\langle v_A \rangle$ is the temporal average of the Alfvén speed inside the MC. The results for R_A (Equation 2.14) for the WIND ICMEs (Table A.1.1) and the Helios ICMEs (Table A.1.2) are shown in Figure 2.2. The mean, median, and most probable value for R_A from the analysis of the WIND events (top panel, Figure 2.2) are 0.29, 0.24, and 0.06, respectively. The mean, median, and most probable value of R_A for the events observed by the Helios mission (bottom panel, Figure 2.2) are 0.28, 0.25, and 0.03, respectively. With reference to point 1 in § 2.1.2, we thus conclude that the expansion speeds of magnetic clouds are significantly smaller than the Alfvén speeds

inside them. In other words, the magnetic cloud boundaries are static (to a fairly good extent) over an Alfvén crossing timescale.

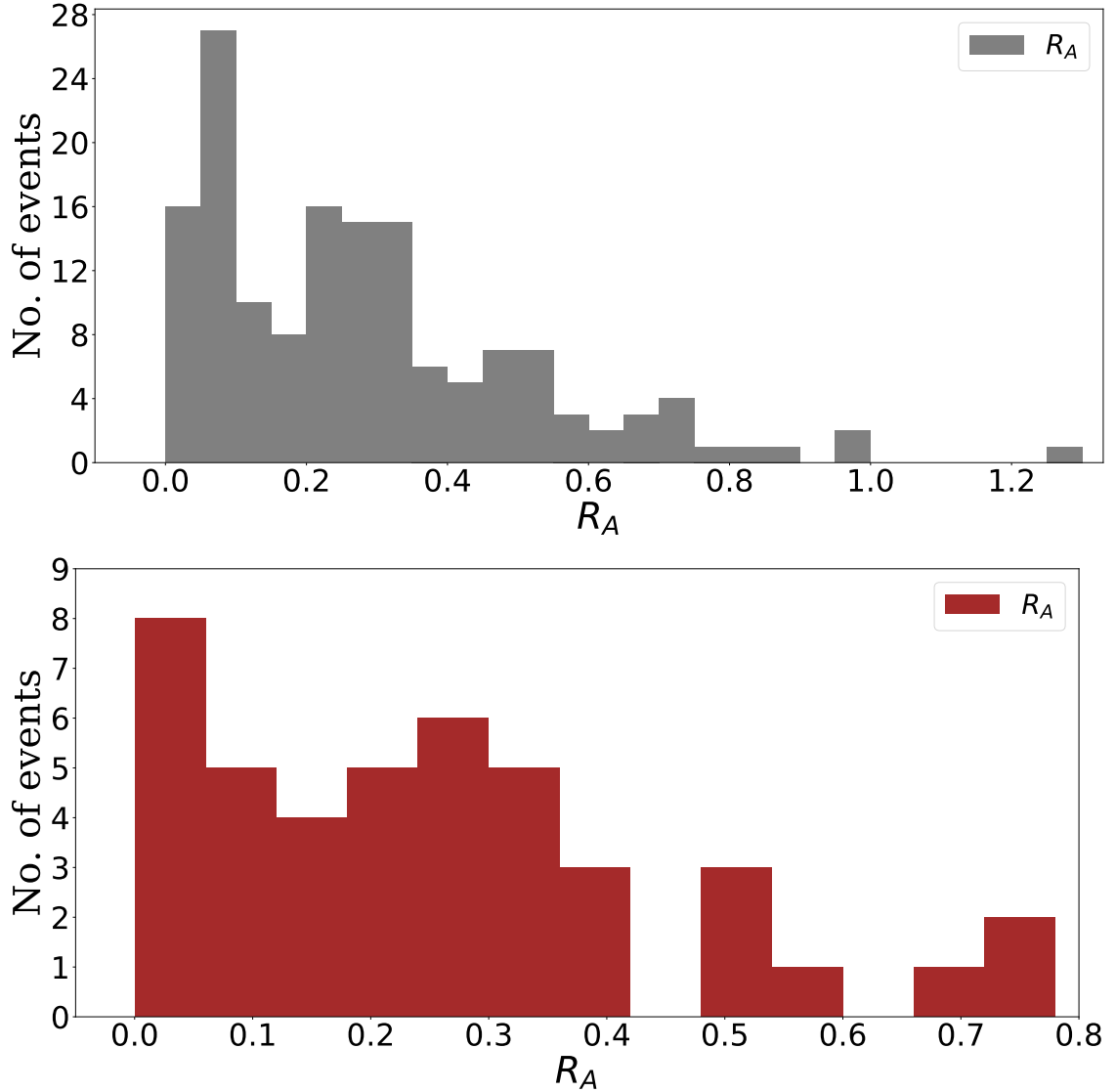


Figure 2.2: Histograms of R_A , the ratio of the MC expansion speed to the Alfvén speed (Equation 2.14) for the events listed in Tables A.1.1 (top panel) and A.1.2 (bottom panel). The mean, median, and most probable values of the histogram in the top panel are 0.29, 0.24, and 0.06, respectively. For the bottom panel, the mean, median, and most probable values are 0.28, 0.25, and 0.03, respectively.

2.4 On MH in the MHD Description

The “*magnetohydro*” aspect of the ideal MHD framework mandates that the medium is an infinitely conducting fluid. In turn, it implies that the magnetic diffusivity, $\eta \rightarrow 0$, which signifies that the magnetic field is frozen into the plasma. The Lundquist number, the ratio between the magnetic diffusion timescale and the Alfvén crossing

timescale, is a measure of the goodness of this assumption. For an infinitely conducting plasma, the Lundquist number $\rightarrow \infty$. In this section, we assess how well the MC plasma conforms to this expectation. In order to estimate the Lundquist number in our situation, we need to know the conductivity of the MC plasma. The collisional timescales can be used to compute the electrical conductivity. In the evaluation of the electrical conductivity, we restrict ourselves only to Coulomb collisions, and do not consider any anomalous effects such as scattering due to wave-particle interactions in the plasma. The timescale for electrons to relax to a Maxwellian distribution following an electron-electron collision is given by (Huba, 2013)

$$t_{ee} \approx 4 \times 10^4 \frac{T_4^{3/2}}{n \ln(\Lambda)}, \quad (2.15)$$

where T_4 is the electron temperature in units of 10^4 K, n is the electron number density (assumed to be equal to the proton number density) in units of cm^{-3} and $\ln(\Lambda)$ is the Coulomb logarithm (considered to be 20 for this study). Considering the fact that, Equation 2.15 gives the electron-electron collisional relaxation timescale in units of seconds, the proton collisional relaxation timescale would be a factor of $\sqrt{m_p/m_e}$ larger and the electron-proton collisional thermalization timescale would be a factor of m_p/m_e larger (Sturrock, 1994). We do not have direct access to electron temperature measurements; the WIND and Helios databases only provide measurements of proton temperature. Some authors (Richardson et al., 1997) suggest that the electron temperature is typically $\gtrsim 2$ times the proton temperature, while some others (see, e.g., Osherovich et al., 1993) believe that this factor is between 7 and 10. Furthermore, the ICME electrons often have a thermal core and non-thermal wings (Nieves-Chinchilla and Viñas, 2008). Taking these factors into account, we assume that the electron temperature is 10 times the proton temperature. Ohm's law for a magnetized plasma is generally written as

$$\mathbf{j} = \sigma_0 \mathbf{E}_{\parallel} + \sigma_P \mathbf{E}_{\perp} + \sigma_H (\hat{\mathbf{b}} \times \mathbf{E}), \quad (2.16)$$

where $\mathbf{j}$ is the current density of the plasma, $\hat{\mathbf{b}}$ is the unit vector in the direction of $\mathbf{B}$, $\mathbf{E}_{\parallel}$ and $\mathbf{E}_{\perp}$ are the components of the electric field ($\mathbf{E}$) in the directions parallel and perpendicular to the $\mathbf{B}$, respectively. The various electrical conductivities are

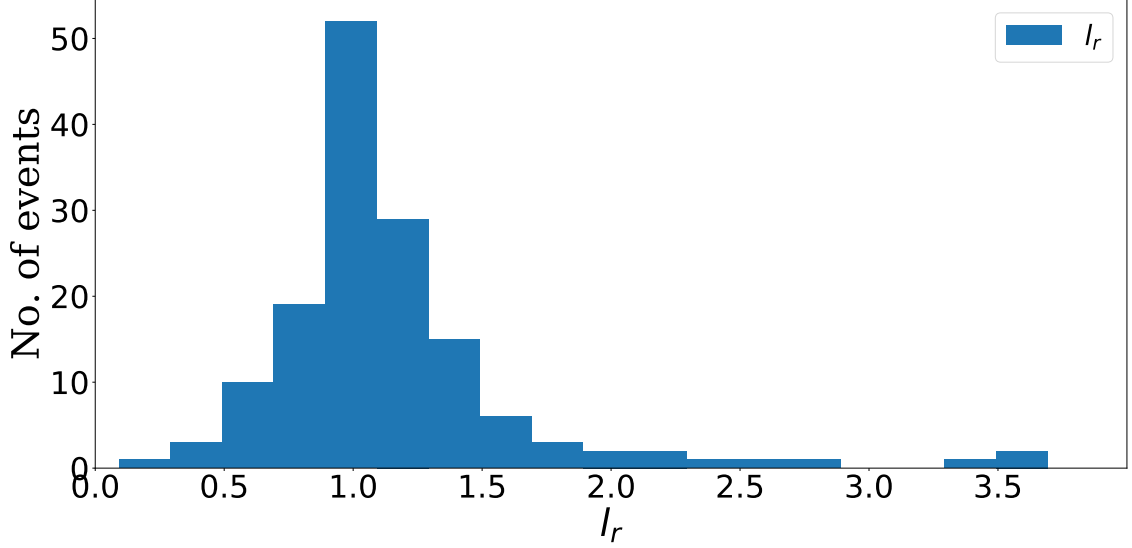


Figure 2.3: Histogram of l_r (Equation 2.23). The mean, median, and most probable value of l_r are 1.22, 1.06, and 1.01, respectively.

(Sturrock, 1994):

$$\sigma_0 = \frac{n e^2 t_{ee}}{m_e} \quad \text{isotropic conductivity,} \quad (2.17)$$

$$\sigma_P = \sigma_0 \frac{t_{ee}^{-2}}{t_{ee}^{-2} + \Omega^2} \quad \text{Pedersen conductivity,} \quad (2.18)$$

$$\sigma_H = \sigma_0 \frac{t_{ee}^{-1} \Omega}{t_{ee}^{-2} + \Omega^2} \quad \text{Hall conductivity,} \quad (2.19)$$

where e is the electron charge in cgs units, m_e is the electron mass in g, t_{ee} (Equation 2.15) is the electron collisional timescale in seconds, and $\Omega \equiv q|B|/m_e c$ (where $|B|$ with the magnitude of the magnetic field) is the electron gyrofrequency in the unit of Hz. The isotropic conductivity $[\sigma_0]$ is the effective conductivity in an unmagnetized plasma. In a magnetized plasma, it can be thought of as the conductivity parallel to the magnetic field. The other two conductivities $[\sigma_P]$ and $[\sigma_H]$ work in the direction perpendicular to the magnetic field. The Lundquist number is usually defined only with respect to the magnetic diffusivity arising from the isotropic conductivity $[\sigma_0]$. Accordingly, the isotropic magnetic diffusivity $[\eta_0]$ and the corresponding diffusion timescale are described as:

$$\eta_0 = \frac{c^2}{4\pi\sigma_0}, \quad t_{\eta 0} = \frac{L_{MC}^2}{\eta_0} \quad (\text{cgs units}), \quad (2.20)$$

where L_{MC} signifies the diameter of the magnetic cloud. For WIND events (Table A.1.1), we use

$$L_{\text{MC}} = 2 \times R_{\text{cc}}, \quad (2.21)$$

where R_{cc} is the magnetic cloud radius fitted using the circular-cylindrical (cc) flux-rope model (Hidalgo et al., 2002; Nieves-Chinchilla et al., 2016) and is available in the WIND ICME catalog (wind.nasa.gov/ICMEindex.php). As we do not have access to a quantity such as R_{cc} for the 45 Helios events (Table A.1.2), we define L_{MC} for these events as

$$L_{\text{MC}} \equiv \int_{t_s}^{t_e} |v(t)| dt. \quad (2.22)$$

The quantity $v(t)$ signifies the velocity of the plasma along the spacecraft trajectory, while t_s and t_e denote the start and end times of the magnetic cloud, respectively (Figure 2.1). In order to check the reliability of L_{MC} as defined in Equation 2.22, we define a ratio

$$l_r = \frac{\int_{t_s}^{t_e} |v(t)| dt}{2 \times R_{\text{cc}}} \quad (2.23)$$

for the 151 WIND events (Figure 2.3). The mean, median, and most probable value of the histogram displayed in Figure 2.3 are 1.22, 1.06, and 1.01, respectively. In other terms, $l_r \approx 1$ and L_{MC} that is determined using Equation 2.22 is close to the value obtained by fitting a static flux rope model (Equation 2.21). This justifies the use of Equation 2.22 in computing L_{MC} for the Helios events (Table A.1.2).

The Lundquist number is defined as

$$S_0 = \left\langle \frac{t_{\eta 0}}{t_A} \right\rangle, \quad (2.24)$$

where, $t_A \equiv L_{\text{MC}}/v_A$ is the Alfvén timescale and $\langle \rangle$ denotes a temporal average inside the MC. We estimate the Lundquist number which is defined in Equation 2.24 on the set of events listed in Table A.1.1 (observed by the WIND spacecraft) and Table A.1.2 (observed by Helios 1 and 2 spacecraft). The mean, median and, most probable value of the Lundquist number (S_0) for the WIND events (top panel, Figure 2.4) are 9.8×10^{13} , 2×10^{13} , and 9×10^{12} , respectively. For the Helios events (bottom panel, Figure 2.4), the mean, median and, most probable value of S_0 are 3.4×10^{14} , 1.4×10^{14} , and 4.3×10^{13} , respectively. As discussed earlier, we have assumed the electron temperature to be 10 times the proton temperature for the computation of the Lundquist number. If instead, the electron temperature is taken to be equal to the proton temperature, the numbers on the x-axis of Figure 2.4 would need to be multiplied by a factor of 0.03. Consequently, the mean, median, and most probable value values would also need to be multiplied by 0.03. The main

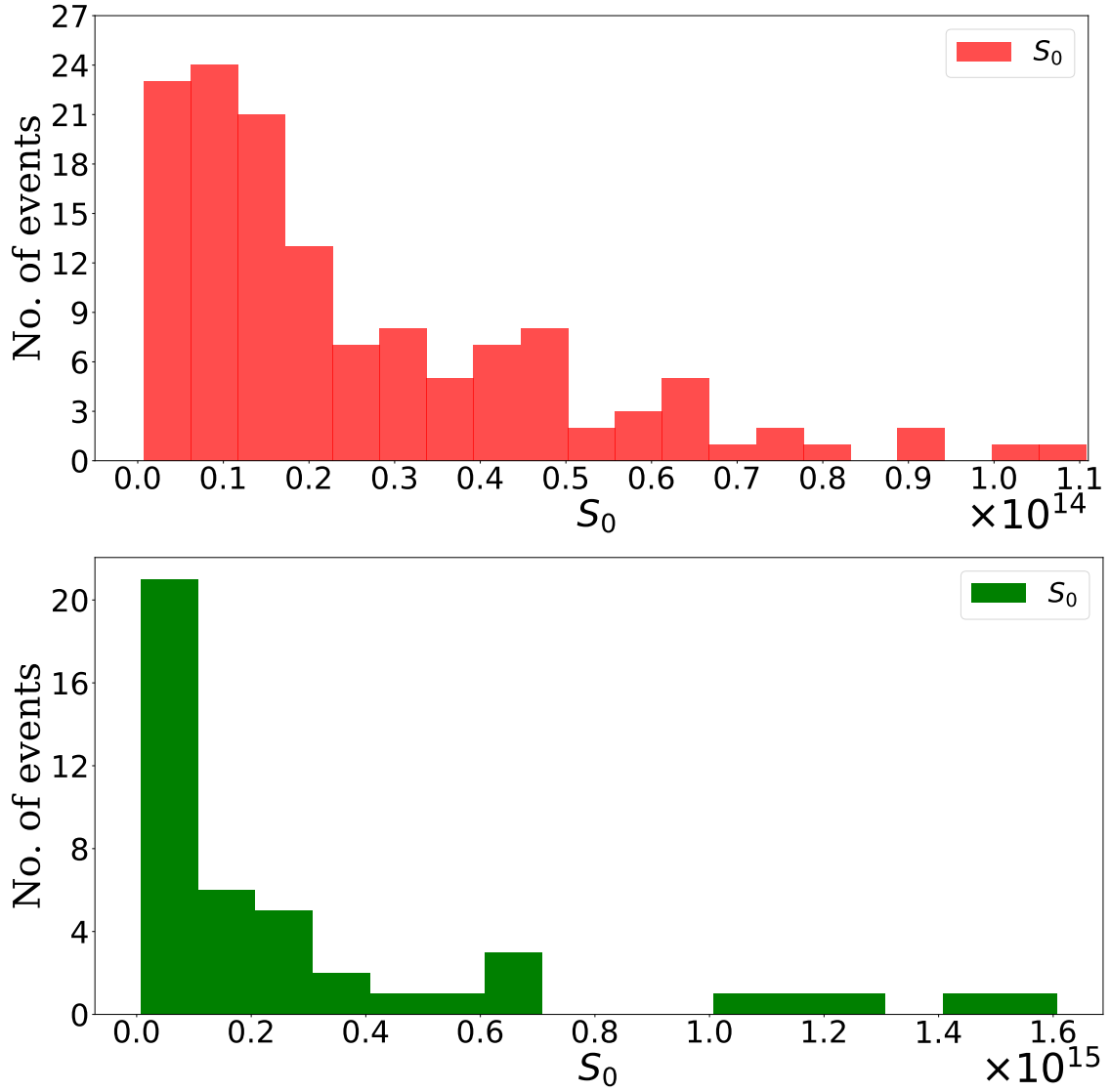


Figure 2.4: Histograms of the Lundquist number S_0 (Equation 2.24) for the events listed in Table A.1.1 (top panel) and Table A.1.2 (bottom panel). The mean, median, and most probable values of the histogram describing the WIND events are 9.8×10^{13} , 2×10^{13} , and 9×10^{12} , respectively. The mean, median, and most probable values for the histogram describing the Helios events are 3.4×10^{14} , 1.4×10^{14} , and 4.3×10^{13} , respectively.

result is that the magnetic diffusivity arising out of the isotropic conductivity is very small, and the corresponding Lundquist number is therefore quite large. By comparison, we note that the Lundquist number for typical laboratory Tokamak plasmas is $\gtrsim 10^7$ (Ali and Zhu, 2019; Günter et al., 2014) and that for plasmas in the magnetic reconnection experiment (MRX) is $\lesssim 10^3$ (Ji et al., 1998). Based on this comparison, it is fair to conclude that MC plasmas adhere better (than laboratory plasmas) to the basic assumptions in the MHD framework. Considering the fact that the electrons in ICMEs can be non-Maxwellian (Nieves-Chinchilla and Viñas, 2008), we note that transport coefficients such as the conductivity could be

somewhat enhanced ([Husidic et al., 2021](#)).

2.5 Joule Heating of MC Plasma

In this section, we will focus on the dissipation rate implied by the collisional conductivity calculated in § 2.4. In order to do this, we need an estimate of the current density $[\mathbf{j}]$. The current density in ideal MHD is defined as

$$\mathbf{j} = \frac{c}{4\pi}(\nabla \times \mathbf{B}). \quad (2.25)$$

In order to compute $\mathbf{j}$, we would need to know the curl of the magnetic field. We have a time series of the vector magnetic field (all the three components) along the line of intercept for each event in our dataset. We can interpret the ∇ operator as the following:

$$\nabla \equiv \hat{x} \frac{\partial}{\partial x} + \hat{y} \frac{\partial}{\partial y} + \hat{z} \frac{\partial}{\partial z} = \hat{x} \frac{1}{v_{\text{sw}x}} \frac{\partial}{\partial t} + \hat{y} \frac{1}{v_{\text{sw}y}} \frac{\partial}{\partial t} + \hat{z} \frac{1}{v_{\text{sw}z}} \frac{\partial}{\partial t}, \quad (2.26)$$

where $v_{\text{sw}x}$, $v_{\text{sw}y}$, and $v_{\text{sw}z}$ are the x, y, and z components of the plasma velocity, respectively. This idea uses the usual Taylor hypothesis, whereby we can write $\partial/\partial x \rightarrow v_{\text{sw}x}^{-1} \partial/\partial t$ and so on. The temporal derivatives ($\partial/\partial t$) are estimated numerically from the time series data at our disposal. Since we have access to all components of $\mathbf{B}$ and all components of ∇ (Equation 2.26), we can compute $\nabla \times \mathbf{B}$ and consequently the current density $\mathbf{j}$ (Equation 2.25), at least along the line through which the spacecraft intercepts. The directions $\hat{x}$, $\hat{y}$ and $\hat{z}$ refer to the unit vectors of the Cartesian coordinate system used for measuring the plasma velocities and magnetic fields. For the WIND observations, they correspond to the geo-centered solar ecliptic (GSE) coordinate system (wind.nasa.gov/mfi_swe_plot.php), whereas for the events observed by Helios mission, they correspond to the spacecraft-centered solar ecliptic (SSE) coordinate system ([Di Matteo et al., 2019](#)). The noise in the measurements of plasma velocity can introduce errors in our estimate of the current density; in particular, the y and z components of the plasma velocity are found to be ≈ 1.4 to 1.9 times noisier than the x component. On the other hand, we note that the magnitude of $v_{\text{sw}x}$ is ≈ 100 times larger than that of the other two components. Errors can also be introduced by the numerical differentiation process. Notwithstanding these caveats, this method provides a practical and reliable means for evaluating the flux rope current, as we show herewith.

An estimate of the average current carried by an MC can be calculated by

$$\langle I \rangle = \langle \mathbf{j} \rangle \times (\pi/4) L_{\text{MC}}^2, \quad (2.27)$$

where the $\langle \rangle$ denotes temporal averaging over the MC. The mean, median, and most probable value of $\langle I \rangle$ for the events in WIND observations are 10^{11} A, 1.2×10^{10} A, and 8×10^8 A, respectively (top panel of Figure 2.5), while for the Helios events, the mean, median, and most probable value of $\langle I \rangle$ are 5.8×10^{10} A, 3×10^9 A, and 10^9 A, respectively (bottom panel of Figure 2.5). These numbers compare well with the estimate of $\approx 10^9$ A for the axial current carried by ICMEs in the near-Earth location (Vršnak et al., 2019). We also note that average current inside MCs does not vary significantly with the heliocentric distance. Hence, the amplitude of $\langle I \rangle$ for both WIND and Helios events are similar. Axial currents for flux rope CMEs closer to the Sun (in the field of view of the Large Angle and Spectrometric COronagraph (LASCO) instrument (lasco-www.nrl.navy.mil/) aboard the SOLar and Helispheric Observatory (SOHO) satellite) are somewhat larger; they are of the order of 10^{10} A (Subramanian and Vourlidis, 2009). We also compare our estimates of current density with the current densities estimated using the magnetic field model by Lepping et al. (1990). They computed $\mathbf{j}$ at 1 AU assuming that the magnetic field inside the near-Earth MCs is force-free. To compare our values with them, we have defined the following ratio:

$$j_R = \frac{\langle j \rangle_{MC}}{j_0}, \quad (2.28)$$

where $\langle j \rangle_{MC}$ is the average magnitude of $\mathbf{j}$ which we have calculated inside the MC and j_0 is the axial current density of flux rope estimated using the magnetic field model described in Lepping et al. (1990). The results are shown in Figure 2.6. The mean, median, and most probable value are 1.37, 0.61, and 0.49, respectively. Our estimates of the average axial current $[\langle I \rangle]$ are therefore in reasonable agreement with other independent computations. This supports our estimates of the current density $\mathbf{j}$ using Equations 2.25 and 2.26.

The average rate of energy dissipation per unit mass due to Joule heating inside the magnetic cloud is written as:

$$D_r = \left\langle \frac{j^2}{\rho\sigma} \right\rangle, \quad (2.29)$$

where $\langle \rangle$ denotes the temporal average inside the MC, σ is the total conductivity and is expressed as, $\sigma \equiv \sigma_0 + \sigma_P + \sigma_H$ (Equations 2.17 to 2.19) and $\rho \equiv n(m_p + m_e)$ is the total mass density, with m_e and m_p the electron mass, and proton mass, respectively, and n the proton number density (assumed to be equal to the electron number density). If the MC is composed of perfectly conducting plasma (i.e., $\sigma \rightarrow \infty$), the Joule heating rate (D_r) would become zero.

However, the collisional conductivities estimated in § 2.4 suggest a finite Joule

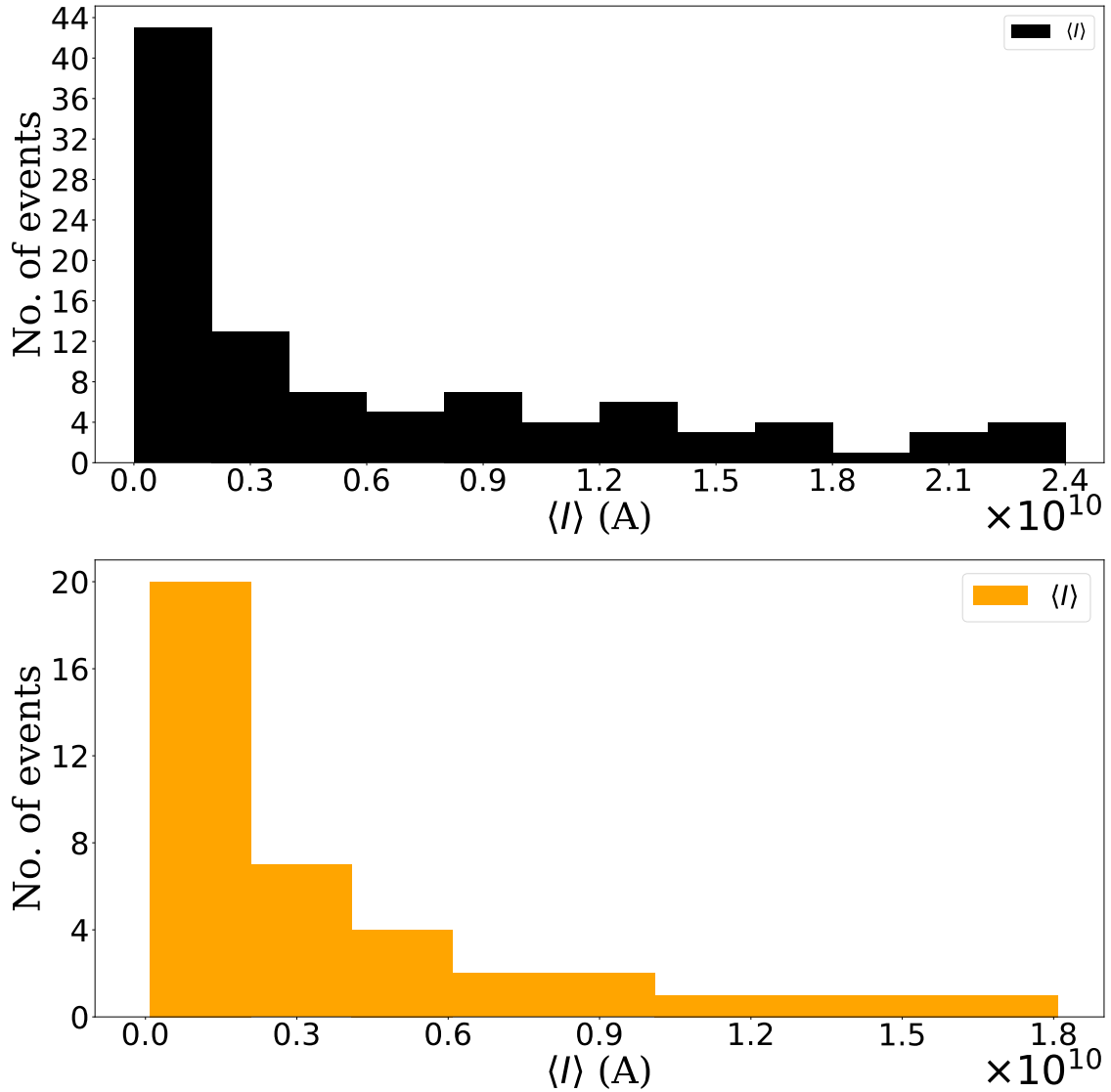


Figure 2.5: Histograms describing the average current (Equation 2.27) for the WIND (top panel) and Helios (bottom panel) events. The mean, median, and most probable values for the histogram of WIND events are 10^{11} A, 1.2×10^{10} A, and 8×10^8 A, respectively. The mean, median, and most probable values for the Helios events are 5.8×10^{10} A, 3×10^9 A, and 10^9 A, respectively.

heating rate D_r which is defined in Equation 2.29. We have plotted histograms of the Joule heating rate (D_r) in units of $\text{J kg}^{-1} \text{s}^{-1}$ in the histograms of the top and bottom panels of Figure 2.7. We now compare this heating rate with the expected estimates from different ICME models. If magnetic clouds expanded adiabatically, the proton temperatures inside them would likely be as low as a few Kelvins close to the Earth (Chen and Garren, 1993). On the contrary, proton temperatures inside MCs are measured to be as high as 10^5 K. This suggests either that MCs remain magnetically connected to the solar corona with a very high thermal conductivity along the magnetic field lines (Chen and Garren, 1993) or that there is substantial plasma heating inside MCs (Kumar and Rust, 1996a). Assuming that there is some

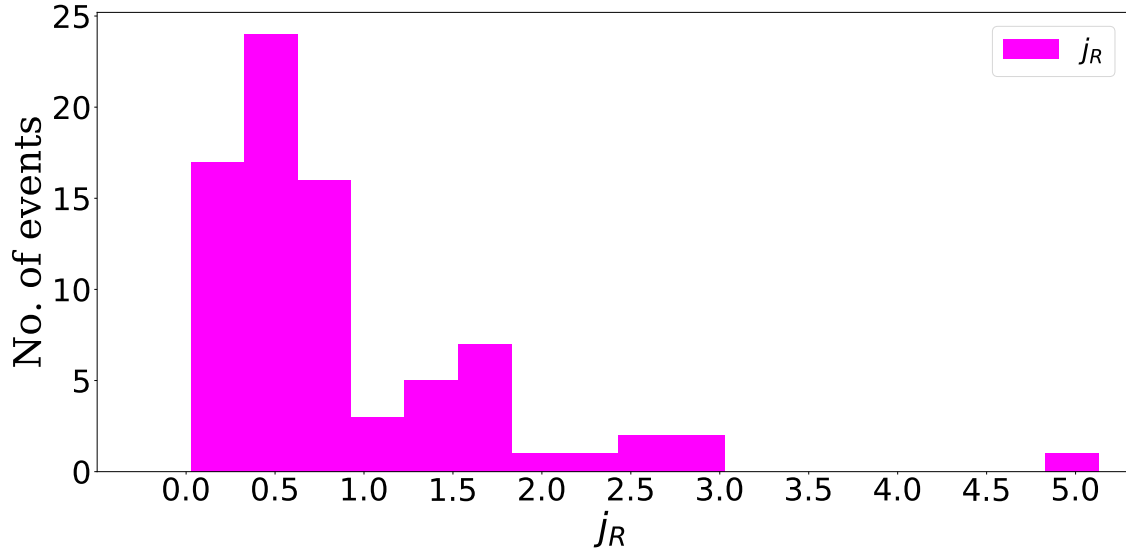


Figure 2.6: Histogram showing the behavior of j_R (Equation 2.28), the ratio between the current density ($\mathbf{j}$) estimated by our method and by the model in [Lepping et al. \(1990\)](#). The mean, median and most probable values are 1.37, 0.61, and 0.49, respectively.

kind of heating mechanism operating inside MCs, and using observations of the decrease in MC proton and alpha particle temperatures with the increasing heliocentric distance, [Liu et al. \(2006\)](#) estimate that the average required ICME heating rate at 1 AU is approximately $2550 \text{ J kg}^{-1} \text{ s}^{-1}$, of which $900 \text{ J kg}^{-1} \text{ s}^{-1}$ is accounted for by protons. By comparison, our estimates of the average Joule heating rate inside the near-Earth MCs are significantly smaller. The mean, median, and most probable value for the Joule heating rate for the events observed by the WIND spacecraft (top panel, Figure 2.7) are 1.1, 6×10^{-4} , and $8 \times 10^{-6} \text{ J kg}^{-1} \text{ s}^{-1}$, respectively. For the Helios events (bottom panel, Figure 2.7), the Joule heating rates are even smaller, the mean, median, and most probable value are 9×10^{-3} , 1.3×10^{-6} , and $2 \times 10^{-8} \text{ J kg}^{-1} \text{ s}^{-1}$, respectively. In both the cases, the mean values are biased by a few ($\approx 11\%$ for WIND measurements and $\approx 6\%$ for Helios measurements) events. This inadequacy of Joule heating is the key reason why turbulent dissipation and anomalous resistivity (a non-Spitzer resistivity which is clearly outside the purview of ideal MHD) are often invoked to account for the heating of protons (see, e.g., [Liu et al., 2006](#); [Verma, 1996](#)).

2.6 Conclusions and Final Remarks

ICMEs are generally modeled as static columns of plasma, in which the usual assumptions of magnetohydrodynamics are valid, and the plasma bulk velocity is assumed to be zero (Equation 2.12). While this approach is widely adopted, we are

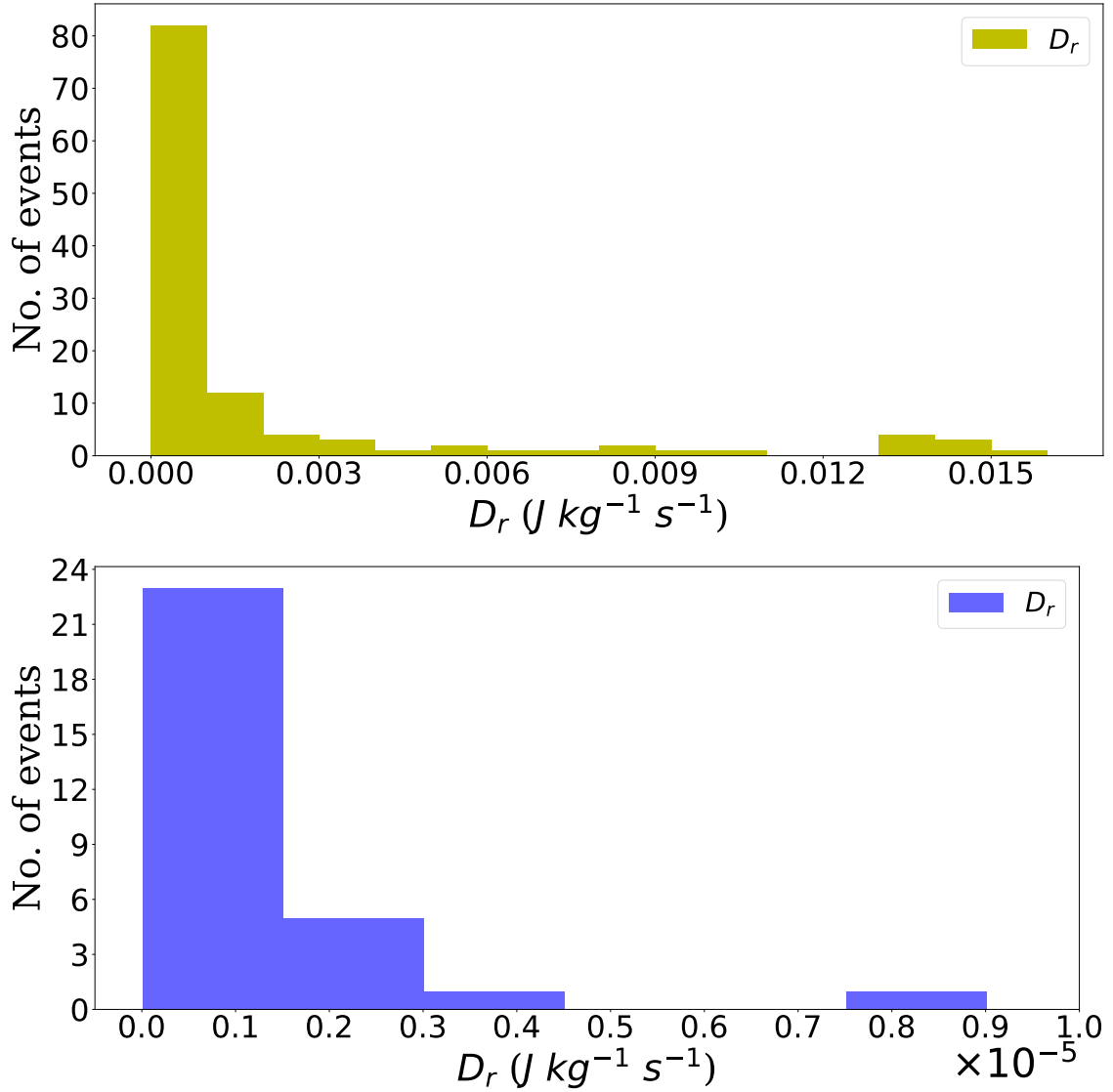


Figure 2.7: Histograms of the average Joule heating rate D_r (Equation 2.29). The top refers to the events listed in Table A.1.1 while the bottom refers to the events listed in Table A.1.2.

not aware of a systematic study using a large sample of ICMEs which examines the validity of these assumptions. The early study by [Klein and Burlaga \(1982\)](#) mentions that the expansion speeds of magnetic clouds are expected to be $\approx$ half the Alfvén speed in the ambient solar wind, and some other works ([Lugaz et al., 2017, 2020](#)) support this statement. While it seems that in these papers, the Alfvén speed refers to the medium surrounding the ICME, [Richardson and Cane \(2010\)](#) refer to the Alfvén speed inside the ICME and state that “the mean expansion speed is around half the Alfvén speed based on average ICME parameters”. Similarly, [Zurbuchen and Richardson \(2006\)](#) state “The expansion speed v_{exp} is typically around half the Alfvén speed in the ICME”. It is also recognized that the ICME expansion speed has to be less than the Alfvén speed in order for static assumptions to be valid for

describing the ICME cross-section, such as the ones that use the Grad-Shafranov reconstruction technique, to be valid (Farrugia et al., 2020). In this study, we use a sample of 151 well-observed ICMEs detected near the Earth by the WIND spacecraft and 45 well-observed MCs observed between 0.3 and 1 AU by the Helios spacecraft, to address the following questions (with a focus on the MC structures within the ICMEs):

1. It is well-known that ICMEs are observed to expand as they propagate, and yet their MC cross-sections are commonly modeled as static plasma columns. To what extent can the MC cross-sections be considered as static plasma columns?
2. Models of ICME and MC cross-sections assume the plasma to be a perfectly conducting fluid, which implies that the Lundquist number (the ratio of the magnetic field diffusion timescale to the Alfvén timescale) must go to infinity. How large are the Lundquist numbers inside the MC plasma?
3. How does the Joule heating rate in the ICME plasma match with the required heating rate which is mandated by the observed proton temperatures, and what does this suggest about departures from the ideal MHD framework?

The first question is addressed in § 2.3, where we note that MC expansion speeds are typically significantly smaller than Alfvén speeds (Figure 2.2). Although MC expansion speeds only indicate plasma velocities along the line of intercept by the spacecraft, our results show that the timescales for signals propagating from one end of the MC cross-section to the other are much smaller than those over which the cross-section expands, thus broadly supporting the notion of a static structure. We find that the ratio $R_A \equiv |v_{\text{exp}}|/\langle v_A \rangle$ (Equation 2.13) has a mean of 0.29, a median of 0.24, and a mode of 0.06, for all the events in our sample, which are observed at the position of WIND measurement. The mean, median, and most probable value of R_A for the events observed by the Helios mission are 0.28, 0.25, and 0.03, respectively. The Helios events are observed at various heliocentric distances, covering a range from 0.3 to 1 AU. We note that the mean, median, and most probable value of R_A in all these cases are below the frequently quoted value of 0.5.

The second question approaches the problem in a different way - one that is generally adopted in estimating the suitability of the MHD approach in analyzing the equilibrium configurations of plasma columns in laboratory settings. If the Lundquist number is large, it implies that the plasma is effectively non-diffusive, and the magnetic field is thus *frozen-in* which is a key assumption of the MHD framework. This question is addressed in § 2.4 of this chapter. We use the (electron-electron) Coulomb collision timescales and the associated electrical conductivity to

evaluate the Lundquist numbers, and find that they are large enough ($\gtrsim 10^{13}$) (Figure 2.4). Another way of appreciating the importance of large Lundquist numbers in the current situation is as follows (Boyd and Sanderson, 2003a): the MHD description technically mandates an infinite magnetic Reynolds number ($Re_m \equiv VL/\eta$ where V is a representative macroscopic plasma velocity, L is a representative macroscopic length-scale and η is the magnetic diffusivity). However, in the case of a static plasma column, $V \rightarrow 0$ and hence, the magnetic Reynolds number (Re_m) should also $\rightarrow 0$. The only way of legitimizing an MHD description is to show that the magnetic diffusivity is negligible; in other words, to show that the diffusion timescale is larger than any other timescale of interest (in our case, the Alfvén timescale). Large Lundquist numbers essentially ensure this fact.

The answer to the third question follows from § 2.5 of the current chapter; the large Lundquist numbers suggest that resistive dissipation in the ICME plasma ought to be very small. This is certainly the case, especially when we compare it with the plasma heating rate implied by the observed proton temperatures. Taken together, the answers to questions 1 to 3 offer a strong support for the magnetohydrostatic modeling of ICME cross-sections.

However, there are some caveats to this conclusion. The standard MHD description does not include any heating/dissipation at all. We have calculated the Joule dissipation rate inside the MCs arising out of electron-electron Coulomb collisions and found it to be several orders of magnitude smaller than the heating requirements suggested by the observed proton temperatures. Assuming an efficient electron-proton energy exchange, this argues for additional electron heating. There is a strong possibility that the protons could also be preferentially heated by processes such as turbulent fluctuations. Observations of noticeable plasma heating inside ICMEs at heliocentric distances about a few $R_\odot$ e.g., (Murphy et al., 2011; Wilson et al., 2021) argue for localized electron heating (unlike the uniform Joule dissipation scenario we consider), possibly at localized reconnection sites. In such a case, the bulk ICME plasma could be heated via thermal conduction from these localized heating sites. Either way, it is clear that the enhanced energy dissipation that is required inside ICMEs is a significant departure from the standard MHD framework, which requires a systematic study for a large sample of well-observed ICMEs. Conclusions from such a study could feed into the dynamical models of Sun-Earth propagation and consequently on estimates of the ICME arrival times at the Earth.

Chapter 3

Characterizing the specific energy and pressure in near-Earth magnetic clouds

A Brief Overview

Magnetic clouds (MCs) are magnetically structured plasmoids that expand as they propagate outwards from the solar corona. The pressure and energy density of the gas and magnetic field inside MCs (in relation to that in the ambient solar wind) is thought to play an important role in determining their dynamics. We compare the specific energy (erg g^{-1}) [comprising kinetic (H_k), thermal (H_{th}) and magnetic field (H_{mag}) contributions] inside MCs and the solar wind background. We then examine if the excess thermal + magnetic pressure and specific energy inside MCs (relative to the background) is correlated with their propagation and internal expansion speeds. Our study asks if the excess thermal + magnetic specific energy inside MCs might make them resemble rigid bodies in the context of aerodynamic drag. The in situ data from the WIND spacecraft helps us to identify a sample of 152 well-observed ICMEs and their MC counterparts. Using these data we estimate various metrics to address our questions. The outcomes show that the total specific energy (H) inside MCs is approximately equal to that in the background solar wind. We also find that the excess (thermal + magnetic) pressure and specific energy are not well correlated with the near-Earth MC propagation and expansion speeds. Finally, our study shows that the excess thermal+magnetic specific energy $\gtrsim$ the specific kinetic energy of the solar wind incident on 81–89 % of the MCs we study. This might explain how MCs retain their structural integrity and resist deformation by the solar wind bulk flow.

3.1 Introduction

It is now well-known that the Earth-directed Coronal mass ejections (CMEs) originating from the solar corona are the primary drivers of geomagnetic storms in the near-Earth space weather. It is therefore very important to have realistic estimations of Sun-Earth CME propagation times and the arrival velocities of the CMEs for accurate space weather forecasting. So, a clear understanding of the CME dynamics and the associated forces that govern their propagation and expansion during their motion through the solar wind plays a key role in the study of CMEs. Interplanetary counterparts of CMEs are termed as Interplanetary Coronal Mass Ejections or ICMEs. There are many approaches to studying this problem ranging from using the early analytical models for the entire Sun-Earth propagation (Chen, 1996; Kumar and Rust, 1996b), the semi-analytical models which only focus on the aerodynamic drag-dominated phase of the CME propagation (Cargill, 2004; Sachdeva et al., 2015; Vrřnak et al., 2013b) to detailed 3D MHD models (Keppens et al., 2020; Linker et al., 1999; Odstreil and Pizzo, 2009; Tóth et al., 2012). While some papers are focused on characterizing the internal structure of the interplanetary counterparts of CMEs (ICMEs) (Klein and Burlaga, 1982; Nieves-Chinchilla et al., 2016), some other studies have concentrated on a comprehensive understanding of various ICME properties (e.g.; see Forsyth et al., 2006; Richardson and Cane, 2010; Temmer, 2021).

In spite of all these advances, there are still some fairly crucial issues that remain to be addressed in this field. The issue of CME expansion provides a template for some of these issues. It is known that CMEs propagate as well as expand while they travel through the heliosphere - CMEs are observed to expand in typical coronagraph fields of view (St. Cyr et al., 2000) and beyond (Lugaz et al., 2010; Webb et al., 2009). The expansion of CMEs has also been established using in situ observations at various heliocentric distances (Bothmer and Schwenn, 1998; Wang and Richardson, 2004) and near the Earth (Dasso et al., 2007). This expansion is thought to occur because the CME interiors are overpressured with respect to the surrounding solar wind environments (e.g., Démoulin and Dasso, 2009; Scolini et al., 2019b; Verbeke et al., 2022; von Steiger and Richardson, 2006). However, some other studies argue that the expansion is a result of the rearrangement of the CME magnetic fields (Kumar and Rust, 1996b). Some researchers (e.g., Dagnew et al., 2022; Gopalswamy et al., 2014, 2015), ask whether the bounty of full halo CMEs with respect to the total number of halo CMEs (full+partial) during solar cycle 24 is because the ambient solar wind pressure is generally lower as compared to the previous cycles, causing CMEs to be more overpressured (with respect to their solar wind environment) than usual. CME expansion speeds are also found to be lower than the Alfvén speeds in

the ambient solar wind (Klein and Burlaga, 1982; Lugaz et al., 2020) - this is another case of comparing the properties of the CME plasma with those of the ambient solar wind. Moreover, the identification of CMEs using the in situ data also uses a comparison between the CME and the ambient solar wind plasma - one of the well-known criteria for identifying near-Earth magnetic clouds (MCs) is that they have a low plasma beta value with respect to the surrounding solar wind plasma (Klein and Burlaga, 1982; Lepping et al., 2003).

Evidently, a comparison of the thermal and magnetic pressure inside CMEs (relative to the background solar wind) is an issue of considerable interest. In this paper, we use near-Earth in situ data to compare the plasma inside a large sample of well-observed magnetic clouds (MCs) with respect to their surroundings. Besides comparing the thermal and magnetic pressures, we also compute the specific energy which is a conserved quantity in an ideal magnetized flow, and serves as a useful reference quantity.

To the best of our knowledge, we are not aware of any study which has addressed the above-mentioned issues so far, especially using a large sample of well-observed near-Earth ICMEs. The data used in this study are described in § 3.2 and the total specific energy for an ideal magnetized fluid is discussed in § 3.3. The total specific energy inside the MC is compared with that in the ambient solar wind in § 3.4.1, while the thermal+magnetic specific energy inside MCs is compared with that in the ambient solar wind in § 3.4.2. We compare the thermal+magnetic pressure inside MCs with that in the ambient solar wind in § 3.4.3. The role of the excess thermal+magnetic specific energy and pressure in influencing MC propagation and expansion is discussed in § 3.4.4. We speculate how the excess thermal+magnetic specific energy could contribute to maintaining the structural integrity of MCs in § 3.5 and we present our conclusions in § 3.6.

3.2 Data

3.2.1 Selecting the Magnetic Clouds

We use in situ data from the WIND (<https://wind.nasa.gov/>) spacecraft for the entire study described in this chapter. The WIND ICME catalog (<https://wind.nasa.gov/ICMEindex.php>) gives a large list of well-observed near-Earth ICMEs as detected by the WIND spacecraft (Nieves-Chinchilla et al., 2018b, 2019). As mentioned earlier in Section 3.1, we limit our study to the analysis of the magnetic clouds or MCs, which are the magnetically well-configured portions of ICMEs along with typically better-defined boundaries and expansion speeds (Klein and Burlaga, 1982). The MCs associated with these ICMEs are categorized into numerous types

based on how well the observed plasma data fit the assumptions of flux rope configurations. We first shortlist MCs that are categorized as F+ and Fr events, out of all the ICMEs that were observed during the years 1995 to 2015. The Fr and F+ events best meet the required expectations of the flux rope model (Nieves-Chinchilla et al., 2016, 2018b). Fr events are defined as MCs with a single magnetic field rotation between 90° and 180° , while F+ events imply MCs with a single magnetic field rotation greater than 180° . We further choose events which are neither preceded nor followed by any other ICMEs or ejecta inside a window of two days ahead of and after the event under consideration. This helps us exclude possibly interacting events. These chosen events must also be followed by a ‘smooth’ ambient solar wind background. The selection criteria for the background are described below.

3.2.2 Defining the Solar Wind Background

As our aim is to compare the pressure and specific energy inside the magnetic clouds with that in the ambient/background solar wind, we need concrete criteria to define the background. Ideally, the background solar wind must be quiet and should be in the vicinity of the MC. Accordingly, for this study, we consider two different solar wind backgrounds for each event. The first type of background, which is coined as BG1 in this chapter, is a 24-hour time window within 5 days preceding the event and satisfies the following conditions: a) the root mean square (rms) fluctuations of the solar wind velocity for this 24-hour period should not exceed 10% of the mean value b) the rms fluctuations of the total magnetic field for this 24-hour period should not exceed 20% of the mean value c) there must not be any magnetic field rotations. Following these criteria, we find that the average plasma beta in the background (BG1) is at least 1.5 times higher than that in the MC. Criteria a) and b) make sure that the background is sufficiently quiet. Criterion c) distinguishes between the background and the cloud since MCs are characterized by large rotations of magnetic field components (however, it depends on the location where the spacecraft is intersecting the CME) and low plasma beta. The second kind of solar wind background, which we call BG2, is a 24-hour period immediately preceding the event. We note that the term ‘solar wind’ is only used for the ambient/background solar wind throughout this study. Our final shortlist comprises 152 ICMEs, which are documented in Table A.3 of the appendix.

3.3 The Specific Energy for an Ideal Magnetized Fluid

Before delving into the estimation of the specific energy for a magnetized fluid, we first discuss the specific energy for unmagnetized fluids.

3.3.1 The Specific Energy for an Unmagnetized Fluid

A streamline in a steady flow is the curve that traces the local fluid velocity. It is exactly like a line of force in the domain of a force field (e.g.; magnetic force field). For a steady flow, a streamline bears an additional physical implication: it is the path that is traced out by a fluid element as a function of time (Choudhuri et al., 1998). The Bernoulli parameter (H_{BI}) represents the specific energy of a fluid parcel, and is conserved along a streamline. For an unmagnetized fluid, it is defined as:

$$H_{\text{BI}} = \frac{1}{2}v^2 + \int \frac{dP_{\text{th}}}{\rho} + \Phi \quad (3.1)$$

where, v , P_{th} and ρ are the velocity, thermal pressure and mass density of the fluid. Φ implies the potential associated with the conservative body force (e.g.; gravity). The integration is carried out along a streamline. One can write the thermal pressure, P_{th} , as, $P_{\text{th}} = nk_B T$, where, n , k_B and T are the number density, the Boltzmann's constant and absolute temperature of the fluid. The first term on the right-hand side (RHS) of Equation 3.1 represents the kinetic energy of the fluid flow, while the second indicates the energy from the thermal contribution. Φ is the potential due to conservative force field (such as gravity). H_{BI} is conserved along a streamline. If we neglect the gravitational potential energy (Φ), which is unimportant beyond a few solar radii above the solar surface (see Section 2 of Cargill, 2004), the Bernoulli parameter becomes

$$H_{\text{um}} \equiv \frac{1}{2}v^2 + \int \frac{dP_{\text{th}}}{\rho} \quad (3.2)$$

where, H_{um} is conserved along a streamline which is along the velocity vector, $\mathbf{v}$. 'um' refers to unmagnetized. If the pressure and mass density of the fluid are assumed to be related via a polytropic law like, $P_{\text{th}} \propto \rho^\gamma$ (where γ is the adiabatic index), Equation 3.2 shows that the specific energy (erg g^{-1}) of the unmagnetized fluid parcel is

$$H_{\text{um}} \equiv H_{\text{k}} + H_{\text{th}} = \frac{1}{2}v^2 + \frac{\gamma}{\gamma - 1} \frac{P_{\text{th}}}{\rho} \quad (3.3)$$

is conserved along a streamline. The quantity

$$H_{\text{k}} \equiv (1/2)v^2 \text{ erg g}^{-1} \quad (3.4)$$

is the (specific) kinetic energy of the fluid because of its bulk motion and

$$H_{\text{th}} \equiv [\gamma/(\gamma - 1)](P_{\text{th}}/\rho) \text{ erg g}^{-1} \quad (3.5)$$

is the (specific) thermal energy of the fluid.

3.3.2 The Specific Energy for a Magnetized Fluid

In a magnetized fluid, the situation is a little different. In the lab frame (Eulerian frame), the conservative form of the ideal MHD energy equation can be written as: [(Equation 65.10, Chapter 8, [Landau and Lifshitz, 1987](#)); (Chapter 4 of [Boyd and Sanderson, 2003b](#); [Kulsrud, 2005](#))]

$$\frac{\partial E}{\partial t} = -\nabla \cdot \left[\frac{\rho v^2}{2} \mathbf{v} + \frac{\gamma}{\gamma - 1} P_{\text{th}} \mathbf{v} - \frac{(\mathbf{v} \times \mathbf{B}) \times \mathbf{B}}{4\pi} \right], \quad (3.6)$$

where E is the energy density (erg cm^{-3}) of a parcel of magnetized fluid, $\mathbf{v}$ is the fluid velocity (cm s^{-1}), ρ is the mass density of the magnetized fluid (g cm^{-3}), P_{th} is the thermal pressure (including contributions from protons and electrons), γ is the polytropic index and $\mathbf{B}$ is the total magnetic field. The term inside the square brackets on the RHS of Equation 3.6 represents the total energy flux ($\text{erg cm}^{-2} \text{s}^{-1}$) of the magnetized fluid under ideal MHD formalism. We can write the energy flux as $\rho v H \hat{\mathbf{p}}$, where H is the total specific energy (erg g^{-1}) and $\hat{\mathbf{p}}$ is the unit vector directed along the total energy flux. H contains contributions from the bulk motion of the magnetized fluid (H_{k} , Equation 3.4), the thermal energy (H_{th} , Equation 3.5) and the magnetic field. In order to understand the contribution from the magnetic field to the total specific energy, we focus on the Poynting flux ($\mathbf{S}$), which is the energy flux ($\text{erg cm}^{-2} \text{s}^{-1}$) carried by the electromagnetic field, and is defined as:

$$\begin{aligned} \mathbf{S} &\equiv (c/4\pi) \mathbf{E} \times \mathbf{B} = (1/4\pi) \mathbf{B} \times (\mathbf{v} \times \mathbf{B}) = (1/4\pi) [\mathbf{v} \mathbf{B}^2 - \mathbf{B}(\mathbf{v} \cdot \mathbf{B})] \\ &= (1/4\pi) \mathbf{v}_{\perp} B^2 = (1/4\pi) v_{\perp} B^2 \hat{\mathbf{n}}, \end{aligned} \quad (3.7)$$

where $\mathbf{v}_{\perp}$ and $\mathbf{v}_{\parallel}$ are the components of the fluid velocity (v) perpendicular to and parallel to the total magnetic field (B) respectively and $\hat{\mathbf{n}}$ is the unit vector perpendicular to $\mathbf{B}$. Equation 3.7 is applicable for a magnetized fluid with an infinitely high conductivity and induction-only electric field. From Equation 3.7, it follows that the energy density (erg cm^{-3}) associated with the magnetic field is $B^2/4\pi$ ([Parker, 2009](#)). In the same way, we define the specific energy (erg g^{-1}) associated with the magnetic field as:

$$H_{\text{mag}} \equiv (B^2/4\pi\rho) \text{ erg g}^{-1} \quad (3.8)$$

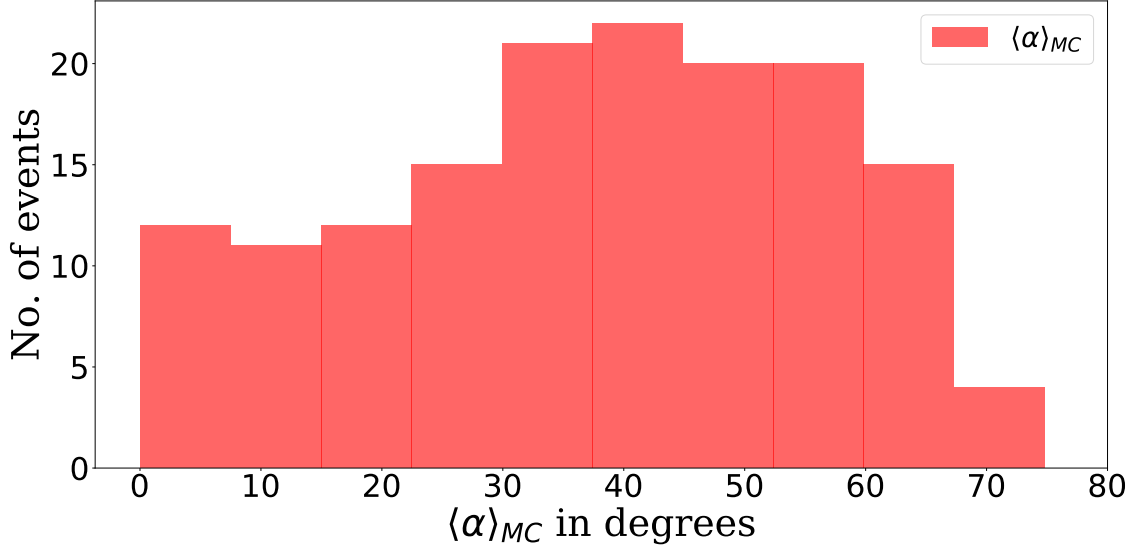


Figure 3.1: Histogram of $\langle \alpha \rangle$ (with $\gamma = 5/3$) inside the MC for all the events listed in Table A.3.

The quantity in the square brackets in Equation 3.6 becomes,

$$\begin{aligned} \rho(H_k + H_{th})(v_{||}\hat{\mathbf{b}} + v_{\perp}\hat{\mathbf{n}}) + \rho H_{mag}v_{\perp}\hat{\mathbf{n}} &= \rho v_{\perp}(H_k + H_{th} + H_{mag})\hat{\mathbf{n}} \\ &+ \rho v_{||}(H_k + H_{th})\hat{\mathbf{b}} = \rho v \hat{\mathbf{p}} [\cos^2 \theta (H_k + H_{th})^2 + \\ &\sin^2 \theta (H_k + H_{th} + H_{mag})^2]^{1/2} = \rho v \hat{\mathbf{p}} H, \end{aligned}$$

where $\sin \theta \equiv v_{\perp}/v$, $\cos \theta \equiv v_{||}/v$, $\hat{\mathbf{b}}$ is the unit vector along the total magnetic field, $\mathbf{B}$, and $\hat{\mathbf{p}}$ is a unit vector in the direction (which is neither along the fluid streamlines nor along the magnetic field), along which the total energy flux is directed and

$$H \equiv [\cos^2 \theta (H_k + H_{th})^2 + \sin^2 \theta (H_k + H_{th} + H_{mag})^2]^{1/2}. \quad (3.9)$$

α is the angle between $\hat{\mathbf{p}}$ and $\hat{\mathbf{b}}$ and it is given by:

$$\tan \alpha = \frac{v_{\perp}(H_k + H_{th} + H_{mag})}{v_{||}(H_k + H_{th})}. \quad (3.10)$$

Figure 3.1 shows the histogram of $\langle \alpha \rangle$ inside the MC for all the ICMEs enlisted in Table A.3. We can understand the significance of $\hat{\mathbf{p}}$ as follows: In the steady state, $\partial E / \partial t = 0$. This implies that the right-hand side of Equation 3.6 is zero. Using Equation 3.9, we can rewrite this statement as, $\nabla \cdot (\rho v \hat{\mathbf{p}} H) = 0$. This means, $H \nabla \cdot (\rho v \hat{\mathbf{p}}) + (\rho v \hat{\mathbf{p}}) \cdot \nabla H = 0$. In the steady state, the mass conservation (Equation 2.1) denotes $\nabla \cdot (\rho v \hat{\mathbf{p}}) = 0$ and that leads to $(\rho v \hat{\mathbf{p}}) \cdot \nabla H = 0$. Now, $\rho \neq 0$ and $v \neq 0$. In other words, $\nabla H \perp \hat{\mathbf{p}}$ and the total specific energy, H , is conserved along the direction of $\hat{\mathbf{p}}$.

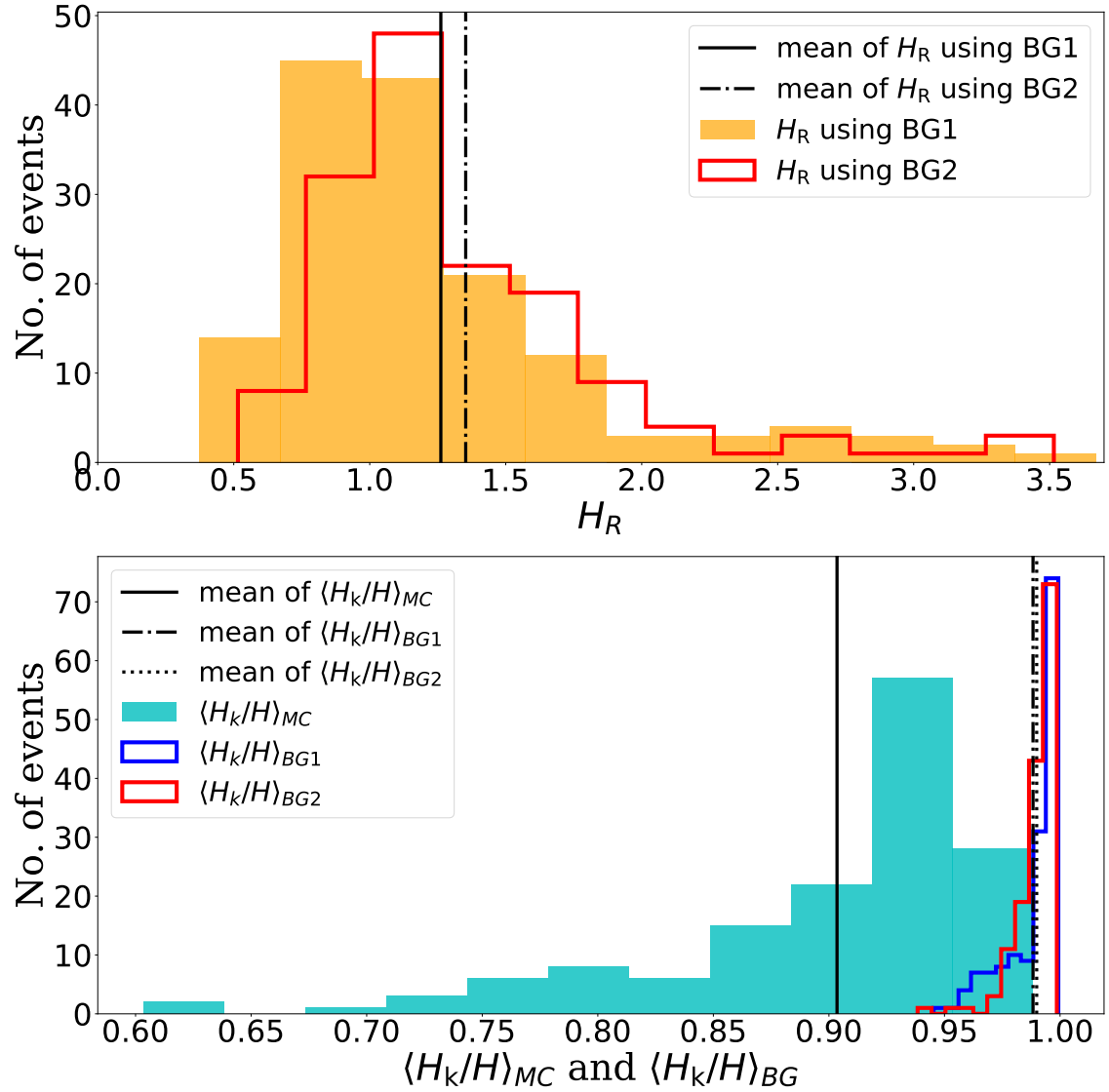


Figure 3.2: Histograms of H_R and $\langle H_k/H \rangle$ for all the events listed in Table A.3. Top panel shows the histograms for H_R (Equation 3.11) with $\gamma = 5/3$ using two different backgrounds, BG1 and BG2. The mean, median, and most probable value of H_R using BG1 are 1.26, 1.1, and 0.97, respectively. Using BG2, they are 1.36, 1.19, and 1.12, respectively. The histograms in the bottom panel display the ratio of H_k to H inside the MC ($\langle H_k/H \rangle_{MC}$) and in the backgrounds ($\langle H_k/H \rangle_{BG1}$, $\langle H_k/H \rangle_{BG2}$), using $\gamma = 5/3$. The mean, median, and the most probable value of $\langle H_k/H \rangle_{MC}$ are 0.90, 0.92, and 0.94, respectively. The mean, median, and the most probable value of $\langle H_k/H \rangle_{BG1}$ are 0.98, 0.99, and 0.995, respectively and those of $\langle H_k/H \rangle_{BG2}$ are 0.99, 0.99, and 0.996, respectively. The mean value of each histogram is marked by a vertical line.

In an unmagnetized fluid, we see that the total specific energy (The Bernoulli parameter, H_{um}) which is the summation of the thermal (H_{th}) and kinetic (H_k) terms is constant along the velocity streamline ($\mathbf{v}$) of the fluid. For a magnetized fluid which follows ideal MHD assumptions, in the steady state, $\hat{\mathbf{p}}$ is the direction along

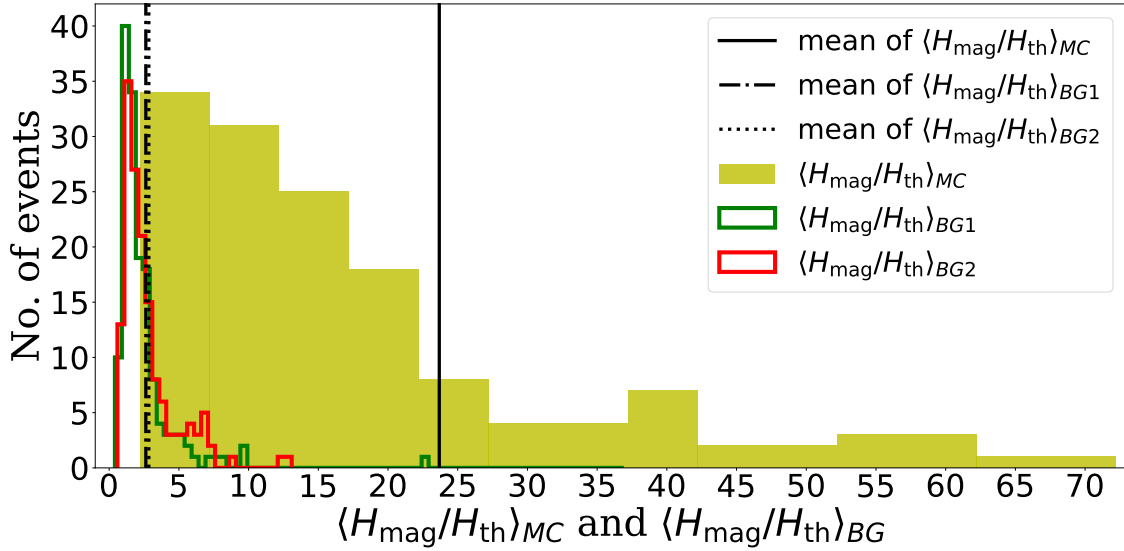


Figure 3.3: Histograms of $\langle H_{\text{mag}}/H_{\text{th}} \rangle$ (with $\gamma = 5/3$) inside the MC and in the two backgrounds, BG1 and BG2, for all the events listed in Table A.3. The mean, median and the most probable value of $\langle H_{\text{mag}}/H_{\text{th}} \rangle_{\text{MC}}$ are 23.68, 14.13, and 4.78, respectively. The mean, median, and most probable value of $\langle H_{\text{mag}}/H_{\text{th}} \rangle_{\text{BG1}}$ are 2.63, 1.73, and 1.10, respectively while for $\langle H_{\text{mag}}/H_{\text{th}} \rangle_{\text{BG2}}$ they are 2.84, 2.12, and 1.63, respectively. The mean value of each histogram is marked by a vertical line.

which the total specific energy (H , in Equation 3.9) is conserved. It is important to note that, $\hat{\mathbf{p}}$ is neither along the fluid streamlines, nor parallel or perpendicular to the direction of the magnetic field. Also, this direction does not have to coincide with the spacecraft passage.

Therefore, in this study, we only choose to compare the temporal average of H inside MCs with that in the background solar wind (defined in Section 3.2.2). This is in the same spirit when one compares the average pressure inside the MCs with that in the ambient solar wind. In this study, we are neglecting non-ideal effects like dissipation, resistive heating, viscosity, etc. Due to high magnetic Reynolds numbers, the bulk solar wind is often modeled using the ideal MHD framework. The plasma inside MCs also has significantly high Lundquist numbers (Bhattacharjee et al., 2022) which also justifies the MHD approach. The expression of H (Equation 3.9) depends on polytropic index, γ . The exact value to use for γ inside CMEs or in the solar wind is debatable. Considering a value of $5/3$ would mean that the MCs would expand adiabatically and a local heating mechanism would be required (Kumar and Rust, 1996b). On the other hand, if we choose $\gamma = 1.2$, that would imply that there is efficient thermal conduction from the corona to the interior of the MC. Thus, the MCs would be heated by the thermal conduction from the solar corona and a little additional heating would be required (Chen, 1996). A recent study using the observations from Helios and Parker Solar Probe (PSP) obtains a γ ranging from 1.35 to 1.57 for solar wind protons and a γ ranging from 1.21 to 1.29 for solar wind

electrons (Dakeyo et al., 2022). Another study using PSP data (Nicolaou et al., 2020) shows that for the solar wind plasma, $\gamma = 5/3$. Following Mishra and Wang (2018), the polytropic index of the CME plasma is thought to range from 1.35 to 1.8. Considering these views, we have used two values for γ ($5/3$ and 1.2) in this study.

3.4 Comparing H inside MCs and the background solar wind

The in situ data from the WIND spacecraft (<https://wind.nasa.gov/>) gives us a thorough time profile of the plasma velocity ($\mathbf{v}$), proton number density (n) and all components of the magnetic field ($\mathbf{B}$) in the reference frame of the spacecraft. Using this data, we also compute the angle (θ) between the plasma velocity $\mathbf{v}$ and the total magnetic field $\mathbf{B}$. We use the terms “plasma” and “magnetized fluid” interchangeably throughout this study; hence, the term “plasma velocity” can be considered to mean the quantity $\mathbf{v}$ introduced in § 3.3. This data also give the temporal distribution of the plasma thermal pressure (P_{th}), that includes both the proton and electron contributions (https://omniweb.gsfc.nasa.gov/ftpbrowser/bow_derivation.html). We assume the electron number density to be equal to the proton number density (so we can write, $\rho = n(m_p + m_e)$ where m_p and m_e are the proton and electron masses respectively) and we consider two values of the polytropic index, $\gamma = 5/3$ and 1.2. The in situ data available to us is along the line of spacecraft intercept, whose direction need not coincide with $\hat{p}$. We calculate H along the line of spacecraft intercept through the MC and estimate an average value for H inside the MC and in the ambient background.

3.4.1 $\langle H \rangle_{\text{MC}}$ vs $\langle H \rangle_{\text{BG}}$

We compare the average value of H inside an MC to that in the background solar wind using the following ratio

$$H_R \equiv \frac{\langle H \rangle_{\text{MC}}}{\langle H \rangle_{\text{BG}}} \quad (3.11)$$

where $\langle \rangle_{\text{MC}}$ and $\langle \rangle_{\text{BG}}$ represent the temporal average inside the MC and the background respectively. We estimate H_R using two different solar wind backgrounds (BG1 and BG2) which are described in § 3.2.2 and two different γ ($5/3$ and 1.2). At first, we describe the outcomes which are obtained using $\gamma = 5/3$. The histograms of H_R for all the ICMEs in our list are shown in the top panel of Figure 3.2. The mean, median, and the most probable value of H_R using BG1 are 1.26, 1.1, and 0.97,

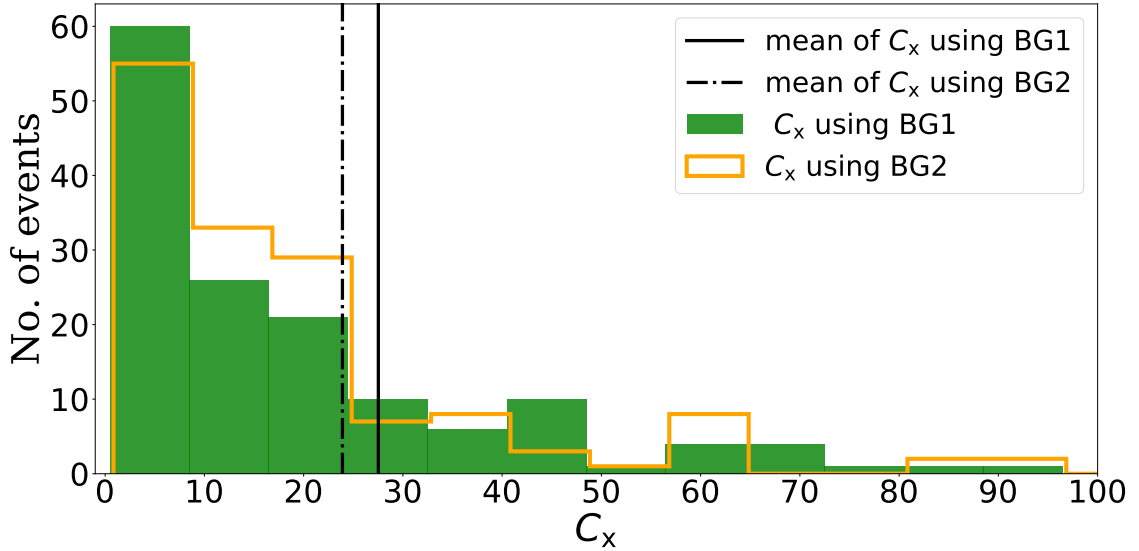


Figure 3.4: Histograms of C_x (Equation 3.12), with $\gamma = 5/3$ and using the two backgrounds, BG1 and BG2. The mean, median, and the most probable value of C_x using BG1 are 27.53, 11.09, and 2.48, respectively while for BG2, they are 23.91, 14.02, and 4.36 respectively. The mean value for each histogram is marked by a vertical line. The maximum value shown on the x-axis is limited to 100 for zooming in on the histogram peaks.

respectively. Using BG2 they are 1.36, 1.19, and 1.12, respectively. We next seek to quantify the contribution of the solar wind (specific) kinetic energy (H_k) to the total specific energy (H). The bottom panel of Figure 3.2 describes histograms of the ratio $\langle H_k/H \rangle$ inside the MC and in the two solar wind backgrounds, BG1 and BG2. The mean, median, and most probable value of $\langle H_k/H \rangle_{MC}$ are 0.90, 0.92, and 0.94, respectively. The mean, median, and the most probable values of $\langle H_k/H \rangle_{BG}$ are not that different: they are 0.98, 0.99, and 0.995, respectively, for BG1 and 0.99, 0.99, and 0.996 for BG2. We note that although we selected BG1 and BG2 based on two different criteria, the results are approximately similar. Next, we use, $\gamma = 1.2$. The mean, median, and most probable values of H_R for this case are 1.27, 1.09, and 0.93 (using BG1), respectively, and 1.36, 1.19, and 1.14 (using BG2), respectively. Using $\gamma = 1.2$, we find that the mean, median, and most probable value of $\langle H_k/H \rangle_{MC}$ are 0.89, 0.91, and 0.92, respectively. The mean, median, and most probable values of $\langle H_k/H \rangle_{BG}$ for both backgrounds are 0.98, 0.99, and 0.992, respectively. The main inferences we can draw from the study till now are that 1) the total specific energy, H , inside the MC is approximately the same as that in the solar wind background, 2) The kinetic energy (H_k) is the dominant contributor to H , $H_k \approx H$, both inside the MC and in the background; and, 3) These conclusions are approximately independent of the choice of the background and polytropic index, γ .

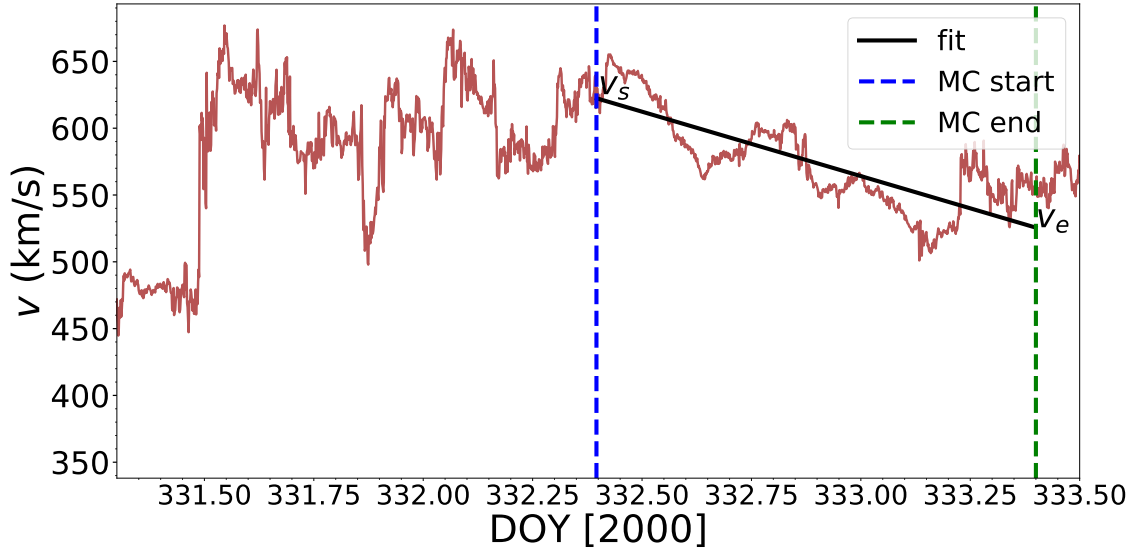


Figure 3.5: Velocity (v) profile as a function of time for event 54 in our dataset (Table A.3). The start time (t_s) and end time (t_e) of the MC are marked by blue and green dashed lines, respectively. The black solid line shows a linear fit to v . v_s and v_e denote the value of the fit at t_s and t_e , respectively. We compute the MC expansion speed, v_{exp} (Equation 2.13), using v_s and v_e .

3.4.2 Comparing the thermal+magnetic specific energy inside MCs and the background

In § 3.3, we have shown that the solar wind contribution (H_k) dominates the specific energy both in the background and inside the MC. In this section, our aim is to compare the specific energy due to the thermal and magnetic field, $H_{\text{th}} + H_{\text{mag}}$ between the MC and the solar wind background. For that, we define the following quantity

$$C_x \equiv \frac{\langle \epsilon \rangle_{\text{MC}}}{\langle \epsilon \rangle_{\text{BG}}}, \text{ where } \epsilon \equiv [H_{\text{th}}^2 \cos^2 \theta + (H_{\text{th}} + H_{\text{mag}})^2 \sin^2 \theta]^{1/2} \quad (3.12)$$

for all the MCs listed in Table A.3. The values of C_x are displayed in Table A.4. As mentioned earlier, $\langle \rangle_{\text{MC}}$ and $\langle \rangle_{\text{BG}}$ represent temporal averages inside the MC and the background solar wind respectively. The quantity ϵ represents the sum of thermal and magnetic contribution to the specific energy and it is often termed as the plasma enthalpy. We know that the thermal contribution to the specific energy for an unmagnetized fluid is $\gamma P_{\text{th}}/(\gamma - 1)$ (Equation 3.5). The expression for ϵ which is used in Equation 3.12 is written following the reasoning of Equation 3.9. The histograms of C_x using $\gamma = 5/3$ and two different backgrounds (BG1 and BG2) are shown in Figure 3.4. They have a mean, median, and most probable values of 27.53, 11.09, and 2.48, respectively (using BG1) and 23.91, 14.02, and 4.36, respectively (using BG2). The mean value (which is comparatively higher than the median

and mode) is biased by $\approx 40\%$ of the ICME events in our sample. To put it in other way, the thermal + magnetic specific energy contributions inside the MC is generally higher in comparison to that in the ambient solar wind background. If we use $\gamma = 1.2$ instead of $5/3$, we find the mean, median, and the most probable values of C_x are 18.48, 8.30, and 4.70, respectively (using BG1) and 16.51, 9.89, and 3.32, respectively (using BG2). The statistical picture of C_x thus does not differ significantly when using $\gamma = 1.2$. With $\gamma = 5/3$, the mean, median, and the most probable values of $\langle H_{\text{mag}}/H_{\text{th}} \rangle$ inside MCs are 23.68, 14.13, and 4.78, respectively; while it is only 2.63, 1.73, and 1.10, inside BG1, respectively and then 2.84, 2.12, and 1.63 inside BG2, respectively (Figure 3.3). Now, if we use $\gamma = 1.2$, $\langle H_{\text{mag}}/H_{\text{th}} \rangle$ becomes smaller (compared to the values with $\gamma = 5/3$) both inside the MC and in the two solar wind backgrounds. The mean, median and the most probable values of $\langle H_{\text{mag}}/H_{\text{th}} \rangle_{\text{MC}}$ are 9.87, 5.89, and 2.43, respectively; while it is 1.10, 0.72, and 0.46, respectively (for BG1) and 1.19, 0.88, and 0.59, respectively (for BG2). So, the increase of C_x inside MCs is mainly because of the magnetic fields.

3.4.3 Comparing the thermal+magnetic pressure inside MCs and the background

There are several studies care about the difference between total pressure (thermal+magnetic pressure, $P_{\text{th}} + P_{\text{mag}}$) inside CMEs and that in the the ambient solar wind (Burlaga et al., 1981; Démoulin and Dasso, 2009; Gopalswamy et al., 2015; Jian et al., 2005; Moldwin et al., 2000). It is often contemplated that ICME expansion is due to the fact that they are overpressured with respect to the ambient solar wind (Scolini et al., 2019b). Gopalswamy et al. (2015) and Mishra et al. (2021) studied whether ICMEs are more overpressured during relatively weaker solar cycles, which lead to more expansion of CMEs during those cycles.

Hence, we have defined the following coefficient and estimated it for the events in our sample using the two backgrounds, BG1 and BG2:

$$C_p \equiv \frac{\langle P_{\text{mag}} + P_{\text{th}} \rangle_{\text{MC}}}{\langle P_{\text{mag}} + P_{\text{th}} \rangle_{\text{BG}}} , \quad (3.13)$$

where $P_{\text{mag}} (= \mathbf{B}^2/8\pi)$ is the magnetic pressure and P_{th} is the thermal pressure of the plasma. We note that the thermal pressure, P_{th} , includes contributions from both protons and electrons. $\langle \rangle_{\text{MC}}$ and $\langle \rangle_{\text{BG}}$ carry their usual meanings. The C_p values are listed in Table A.4 and histograms for C_p are displayed in Figure 3.7. The mean, median, and the most probable value for C_p using BG1 are 5.90, 4.29, and 2.39, respectively. Using BG2, they are 4.76, 3.02, and 1.64, respectively. By comparison, Gopalswamy et al. (2015) investigated and found that the total pres-

sure (thermal + magnetic pressure) ratio between the MCs and the ambient solar wind background is ≈ 3 for their sample of near-Earth CMEs. The results, therefore, imply that the average magnetic+thermal pressure inside near-Earth MCs is significantly higher than that of the solar wind background. The polytropic index, γ has no bearing on the values of C_p .

3.4.4 Is the excess thermal+magnetic specific energy and pressure inside MCs correlated with near-Earth expansion and propagation speeds?

Several past studies have questioned whether the excess pressure inside ICMEs leads to their expansion (see e.g., Démoulin and Dasso, 2009; Scolini et al., 2019b; Verbeke et al., 2022; von Steiger and Richardson, 2006). In a similar way, one may contemplate that the enhanced thermal+magnetic specific energy inside the MCs would lead to its internal expansion (expansion of the MC width through which the spacecraft is intercepting) and propagation through the heliosphere. In order to understand this aspect, we estimate the MC expansion speed (v_{exp}) using the method of Nieves-Chinchilla et al. (2018b)

$$v_{exp} = \frac{1}{2}(v_s - v_e) \quad (3.14)$$

where v_s and v_e represent the speeds at the start and at the end of the magnetic cloud respectively and they are obtained using a linear fit to the temporal profile of the solar wind speed (v). An example of such a linear fit is shown in Figure 3.5. This method of evaluating the MC expansion speed (Equation 3.14) is also used in Section 2.3 of Chapter 2. We note that v_{exp} for $\approx 20\%$ of MCs in our event list is negative; which means, they contract rather than expand. Figure 3.6 shows scatter-plots between C_x (estimated using both the backgrounds) and the near-Earth MC propagation speed, $\langle v \rangle_{MC}$ (panel a), and, v_{exp} (panel b), for expanding MCs (that is, those for which $v_{exp} > 0$). The linear correlation coefficient (r) between C_x and the MC propagation speed ($\langle v \rangle_{MC}$) is 0.43, with a p-value of 3.5×10^{-8} for BG1 and $r = 0.51$, with $p = 1.8 \times 10^{-11}$ for BG2. The linear correlation coefficient (r) between C_x and v_{exp} for the expanding events is 0.50 and the corresponding p-value is 5.73×10^{-9} (using BG1) and $r = 0.63$, with $p = 1.9 \times 10^{-14}$ (using BG2). The correlation coefficient between C_x and $v_{exp}/\langle v \rangle$ (considering only expanding events, i.e, with positive v_{exp}), namely, $r = 0.40$, with a p-value 7.8×10^{-6} for BG1 and $r = 0.50$, with $p = 1.2 \times 10^{-8}$ for BG2. Our outcomes thus show that C_x is only moderately correlated with the near-Earth MC propagation and expansion speed.

3.5. DOES THE EXCESS THERMAL+MAGNETIC SPECIFIC ENERGY IN MCS MAKE THEM APPEAR “RIGID”?

The low values for p in all the cases indicate a high statistical significance for these findings.

Next, we investigate whether the overpressure parameter, C_p may be correlated with the near-Earth MC expansion and propagation speeds. Panel (a) of Figure 3.8 shows the scatter plot between C_p (with both BG1 and BG2) and the MC propagation speed. The correlation is low ($r = 0.18$, $p\text{-value} = 2 \times 10^{-2}$ using BG1 and $r = 0.15$, $p = 5 \times 10^{-2}$ using BG2). The correlation between C_p and the MC expansion speed of the expanding MCs ($v_{\text{exp}} > 0$) is also low (see panel b of Figure 3.8; $r = 0.25$, $p\text{-value} = 2 \times 10^{-3}$ using BG1 and $r = 0.25$ with $p = 5 \times 10^{-3}$). Finally, we note that the correlation coefficients between C_p and $v_{\text{exp}}/\langle v \rangle_{\text{MC}}$ for the expanding MCs (see panel c of Figure 3.8) are $r = 0.23$ and the p -value is 6×10^{-3} for BG1 and $r = 0.22$, with $p = 10^{-3}$ for BG2. From the findings, it is evident that C_p is rather poorly correlated with near-Earth MC expansion and propagation speeds. The correlation between expansion speed and Cx is not very significant either. The reason could be because we are using speeds measured at the position of the WIND observation, i.e., near the Earth. On the other hand, most of the CME expansion probably occurs closer to the Sun, and they have largely stopped expanding by the time we detect them near the Earth (Verbeke et al., 2022).

3.5 Does the excess thermal+magnetic specific energy in MCs make them appear “rigid”?

The main outcomes of this study that we have obtained so far are that 1) the total specific energy inside the MC is roughly equivalent to that of the solar wind background; and 2) the sum of the thermal and magnetic (specific) energies is higher within the MC as compared to the background.

In order to understand the second point in a better way, we now define the following coefficient:

$$C_r = \frac{\langle \epsilon \rangle_{\text{MC}} - \langle \epsilon \rangle_{\text{BG}}}{\langle (1/2)u^2 \rangle_{\text{BG}}}, \quad (3.15)$$

where ϵ has been defined in Equation 3.12 and $\mathbf{u} \equiv \mathbf{v} - \langle \mathbf{v} \rangle_{\text{MC}}$ is the solar wind velocity in the frame of the MC, while the other notations carry their usual meanings. This is akin to the pressure coefficient which is typically defined for unmagnetized fluids (Kundu and Cohen, 2008). For a particular event, the variation of $\mathbf{v}$ with time suggests that $\mathbf{u}$ also varies with time. Hence, $\langle u^2 \rangle_{\text{BG}}$ never goes to zero. The quantity $\langle (1/2)u^2 \rangle_{\text{BG}}$ represents the specific kinetic energy of the solar wind incident on the MC, as discerned by an observer who is moving at the average MC speed.

3.5. DOES THE EXCESS THERMAL+MAGNETIC SPECIFIC ENERGY IN MCS MAKE THEM APPEAR “RIGID”?

The quantity C_r defined in Equation 3.15, therefore compares the enhancement in thermal+magnetic specific energy inside the MC (relative to the background) with the specific kinetic energy of the solar wind incident on it. If $C_r \gtrsim 1$, it signifies that the excess thermal + magnetic specific energy in the MC is greater than or equal to the specific kinetic energy of the oncoming solar wind – leading to the suggestion that the MC can withstand deformation by the solar wind, somewhat akin to a rigid object. One way to understand C_r is as follows: we can imagine an inflated balloon that is placed in a stream of cold air. Let’s consider that there are no magnetic fields, and so $H_{\text{mag}} = 0$. Because the air stream is cold, we can neglect the thermal contribution, $\langle H_{\text{th}} \rangle_{\text{BG}} = 0$ and the only surviving term in the numerator of Equation 3.15 is $\langle H_{\text{th}} \rangle_{\text{MC}}$. The metric C_r therefore compares the thermal specific energy due to the gas inside balloon can better withstand deformation because of the air stream incident on it. So, if $C_r \gtrsim 1$, the balloon can withstand the deformation because of the incident air stream in a relatively better way. To put it another way, it behaves more like a well-inflated soccer ball than an inflated balloon (see Figure 3.10).

The C_r values for all the events in our sample are enlisted in Table A.4. The histogram of C_r for all the events using $\gamma = 5/3$ and both the backgrounds (BG1 and BG2) is described in Figure 3.9. Using BG1, we find that the mean, median, and most probable value of C_r histogram are 7.61, 3.33, and 1.16, respectively, with 81% of the events having $C_r \geq 1$. With BG2, the mean, median, and most probable value are 8.65, 4.66, and 2.25, respectively, with 89.5% of the events having $C_r \geq 1$. Instead of $\gamma = 5/3$, if we consider $\gamma = 1.2$, the mean, median, and most probable values of C_r become 8.09, 3.55, and 1.12, respectively with BG1, and 9.50, 5.29, and 2.29, respectively using BG2. Hence, our results are not significantly affected by the choice of polytropic index.

Furthermore, we note that the magnetic energy is generally higher than the thermal energy inside MCs, (Figure 3.3) leading to the fact that CME magnetic fields are primarily responsible for $C_r \geq 1$. In other words, the stronger the ICME magnetic field, the better it can resist the deformation of the ICME. Our outcomes are in agreement with those of [Lynnyk et al. \(2011\)](#) who stated that “if the magnetic field inside the ICME/MC is much stronger than that in the ambient solar wind, the ICME/MC cross-section is closer to circular.” Therefore, MCs with more circular cross-sections are probably those that behave relatively more like rigid bodies; they are probably characterized by $C_r \geq 1$, and have resisted deformation by the oncoming solar wind.

An issue that is associated to the rigidity of MCs is the widely used CME aero-

dynamic drag law (Cargill, 2004; Vrřnak et al., 2009b, 2013b)

$$F_D = C_D A \rho |u| u \quad (3.16)$$

which is a hydrodynamic drag law applicable to high Reynolds number (low viscosity) flows in the presence of *solid or rigid bodies* (Landau and Lifshitz, 1987). In the Equation 3.16, F_D is the drag force, u is the velocity of the background fluid with respect to an observer comoving with the solid body, A is the cross-sectional area subtended by the body to the flow, ρ is the mass density of the background fluid, and C_D is the drag coefficient, a dimensionless proportionality constant which depends on the shape of the object. By contrast, the high Reynolds number drag law for flows past deformable bubbles follows $F_D \propto u$ (Kang and Leal, 1988; Landau and Lifshitz, 1987; Moore, 1959, 1963). Although the $F_D \propto u$ looks like the well-known Stokes law, which is applicable for laminar or low Reynolds number flows past solid bodies, it is, in fact a high Reynolds number law for flows past deformable bubbles. Bubbles are different from solid bodies. The total velocity does not vanish on the surface of a bubble, as it does for solid bodies. We note that some investigations of CME dynamics have indeed adopted $F_D \propto u$ (Maloney and Gallagher, 2010; Vrřnak and Gopalswamy, 2002b). Although the form of the widely adopted CME aerodynamic drag law comes from a combination of various MHD effects (Lin and Chen, 2022), the simplest interpretation of Equation 3.16 is still that of a high Reynolds number, solid or rigid body law. The results of our study that indicate $C_r \gtrsim 1$ for over 89 % of the MCs of the total event number could be a possible justification for the solid body premise, even for CMEs, which are indeed far from solid bodies in the usual sense of the word.

3.6 Conclusions and discussion

CME evolution through the heliosphere is commonly thought to be strongly influenced by the difference in the (thermal + magnetic) pressures inside the CME and outside of it, that is, in the ambient solar wind. In this study, we compare the temporal average value of the total specific energy, H (Equation 3.9), inside MCs and in the background solar wind using the near-Earth in situ data from the WIND spacecraft for a sample of 152 well-observed events (described in Table A.3). The quantity H has contributions from the kinetic energy due to the bulk flow (H_k), the thermal energy (H_{th}), and the magnetic energy (H_{mag}). We also compare the total pressure (thermal+magnetic pressure) inside MCs with the background solar wind. In this analysis, we use two different ambient solar wind backgrounds for our

comparisons and also use two different values for the polytropic index γ . The main conclusions of this chapter are:

1. We find that the temporal average value of H inside MCs: $\langle H \rangle_{\text{MC}}$ is approximately equivalent to the average value in the ambient solar wind background, $\langle H \rangle_{\text{BG}}$ (§ 3.4.1, Figure 3.2). The bulk-flow kinetic energy (H_k) is the dominant contributor of H , that is, $H_k \approx H$, both inside the MCs and in the ambient solar wind. This is the primary reason for $\langle H \rangle_{\text{MC}} \approx \langle H \rangle_{\text{BG}}$.
2. The average thermal+magnetic specific energy inside near-Earth MCs significantly exceeds that of the background solar wind (§ 3.4.2). Similarly, the average of total pressure ($P_{\text{th}} + P_{\text{mag}}$) inside near-Earth MCs is also noticeably greater than that in the solar wind background (§ 3.4.3). These findings are generally consistent with the outcomes of [Gopalswamy et al. \(2015\)](#) and [Mishra et al. \(2021\)](#).
3. Finally, we find that the excess thermal+magnetic specific energy inside MC plasma $\gtrsim$ the specific kinetic energy of the solar wind impinging on them for 81–89% of the events in our sample (§ 3.5). This result sheds light on the ways in which MCs might be able to withstand the deformation caused by the oncoming solar wind. Additionally, this might suggest a justification for the widely used “rigid body” CME aerodynamic drag law (Equation 3.16).

We note that our conclusions are based solely on in situ data at the position of the WIND observations (i.e., at 1 AU). It would be interesting to carry out similar studies using in situ data closer to the Sun from the PSP ([Nieves-Chinchilla et al., 2022](#); [Weiss et al., 2020b](#)), which would potentially yield new insights into the evolution of CMEs throughout the heliosphere.

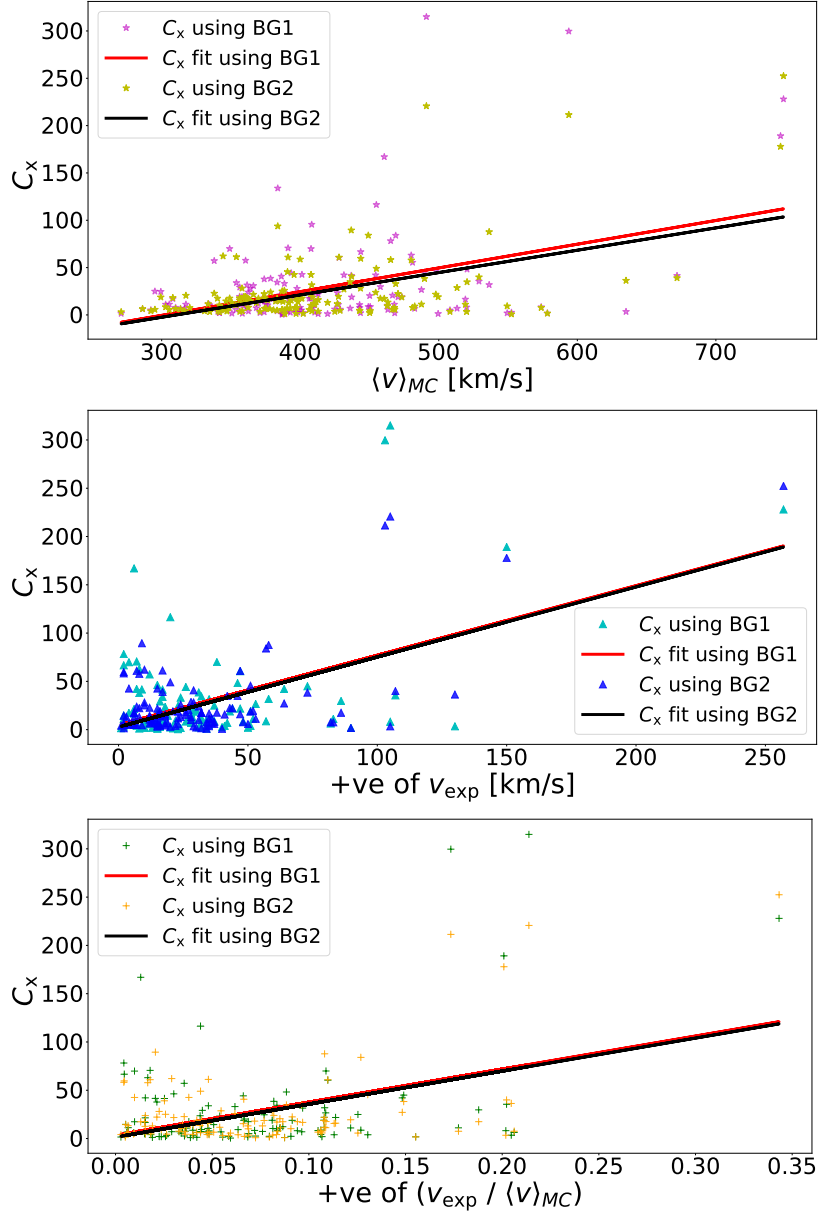


Figure 3.6: Scatter plots of C_x with MC propagation and expansion speeds for all the events listed in Table A.3. The top panel is the scatterplot between C_x (estimated using $\gamma = 5/3$; as in Equation 3.12) and the MC propagation speed ($\langle v \rangle_{MC}$). The correlation coefficient between C_x and $\langle v \rangle_{MC}$ are $r = 0.43$, with $p = 3.5 \times 10^{-8}$ (for BG1) and $r = 0.51$, with $p = 1.8 \times 10^{-11}$ (for BG2). The equations of the fitted lines corresponding to BG1 and BG2 are $y = 0.25x - 75.65$ and $y = 0.24x - 73.28$, respectively. The middle panel is the scatter plot between C_x (computed using $\gamma = 5/3$) and the MC expansion speed (v_{exp}), only for events with $v_{exp} > 0$. The correlation coefficients are $r = 0.50$, with $p = 5.73 \times 10^{-9}$ for BG1 and $r = 0.63$, with $p = 1.9 \times 10^{-14}$ for BG2. The equations of fitted lines are $y = 0.72x + 4.82$ and $y = 0.73x + 2.73$ corresponding to BG1 and BG2, respectively. The bottom panel is the scatter plot between C_x (calculated using $\gamma = 5/3$) and $v_{exp}/\langle v \rangle_{MC}$ (only for events with $v_{exp} > 0$). The correlation coefficients are $r = 0.40$, with $p = 7.8 \times 10^{-6}$ (for BG1) and $r = 0.50$, with $p = 1.2 \times 10^{-8}$ (for BG2). The equations of the fitted lines are $y = 342.6x + 3.36$ (for BG1) and $y = 341.71x + 1.46$ (for BG2). The small p-values imply a high statistical confidence in computing the r values in all three cases.

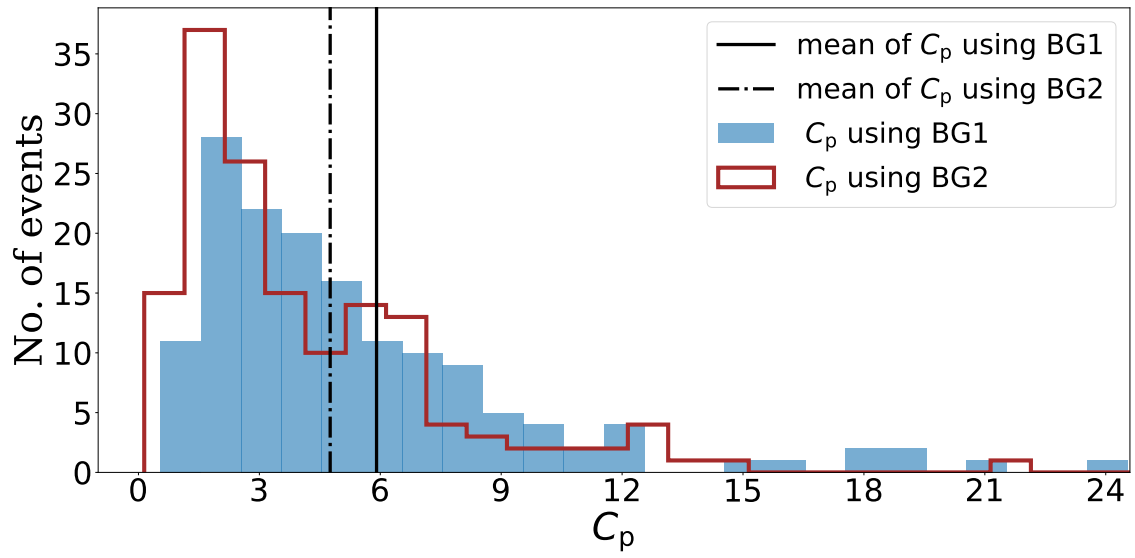


Figure 3.7: Histograms of C_p (Equation 3.13) using two different backgrounds, BG1 and BG2. The mean, median and the most probable values of C_p with BG1 are 5.90, 4.29, and 2.39, respectively and the mean, median, and the most probable value of C_p with BG2 are 4.76, 3.02, and 1.64, respectively. The mean value for each histogram is marked by a vertical line. The maximum value shown on the x-axis is limited to 24.5 in order to zoom in on the histogram peaks.

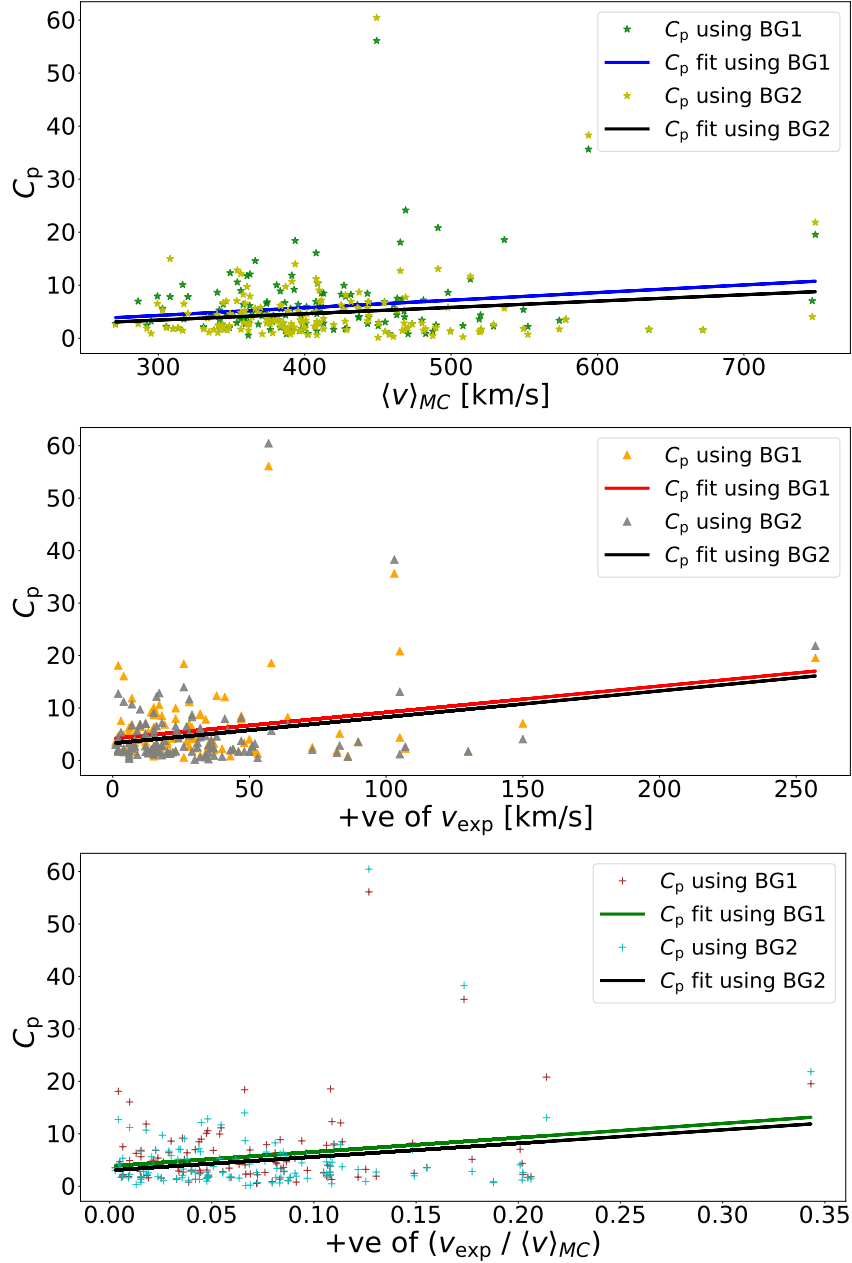


Figure 3.8: Scatter plots of C_p with MC propagation and expansion speeds for all the events listed in Table A.3. The top panel is the scatter plot between C_p (Equation 3.13 and the MC propagation speed ($\langle v \rangle_{MC}$)). The correlation coefficient between C_p and $\langle v \rangle_{MC}$ is $r = 0.18$, with $p = 2 \times 10^{-2}$ (for BG1) and $r = 0.15$, with $p = 5 \times 10^{-2}$ (for BG2). The equations of the fitted lines corresponding to BG1 and BG2 are $y = 0.01x - 0.004$ and $y = 0.01x - 0.1$, respectively. The middle panel is the scatter plot between C_p and the MC expansion speed (v_{exp}), only for events with $v_{exp} > 0$. The correlation coefficients are $r = 0.25$, with $p = 2 \times 10^{-3}$ for BG1 and $r = 0.25$, with $p = 5 \times 10^{-3}$ for BG2. The equations of the fitted lines are $y = 0.05x + 4.5$ and $y = 0.05x + 3.26$, for BG1 and BG2, respectively. The bottom panel is the scatter plot between C_p and $v_{exp}/\langle v \rangle_{MC}$, only for events with $v_{exp} > 0$. The correlation coefficients are $r = 0.23$, with $p = 6 \times 10^{-3}$ (for BG1) and $r = 0.22$, with $p = 10^{-3}$ (for BG2). The equations of the fitted lines are $y = 25.3x + 4.30$ (for BG1) and $y = 25.78x + 3.02$ (for BG2). The small p-values indicate a sufficiently high statistical confidence in estimating the r values for all three cases.

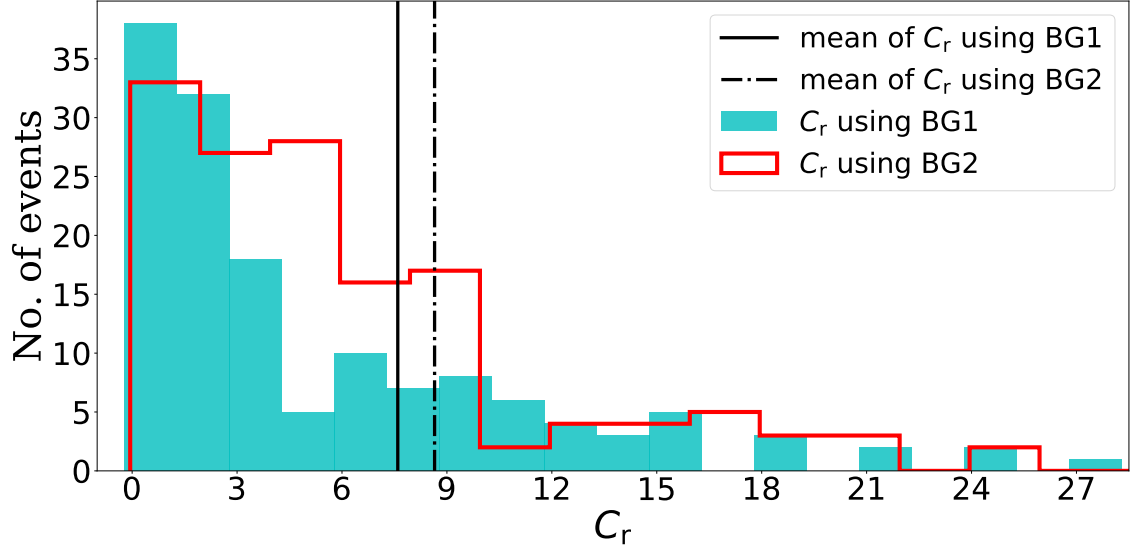


Figure 3.9: Histograms of C_r (Equation 3.15) with $\gamma = 5/3$ using both the backgrounds (BG1 and BG2). The mean, median, and the most probable values of C_r are 7.61, 3.33, and 1.16, respectively for BG1 and 8.65, 4.65, and 2.25, respectively for BG2. The mean value of each histogram is marked by a vertical line. The maximum value shown on the x-axis is limited to 28 for zooming in on the histogram peaks.

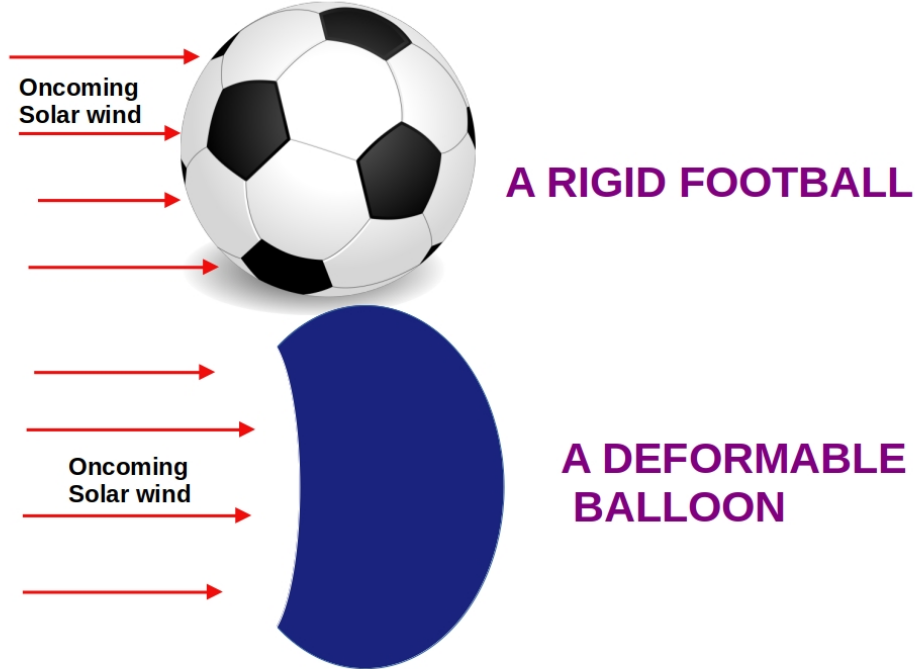


Figure 3.10: A cartoon describing whether MCs can withstand the effect of the oncoming solar wind's kinetic energy like a rigid 'football' or whether they get deformed like a 'balloon'. Our findings show that for most of the cases, MCs act like rigid footballs than deformable balloons.

Chapter 4

Turbulence and Anomalous Resistivity inside Near-Earth Magnetic Clouds

A Brief Overview

We use in situ data from the WIND spacecraft to survey the amplitude of turbulent fluctuations in proton density and total magnetic field in a large sample of well-observed near-earth MCs associated with interplanetary coronal mass ejections (ICMEs) from the Sun and compare them with the ambient solar wind background. We find that the most probable values of the modulation index for proton density fluctuations ($\delta n_p/n_p$) inside MCs range from 0.13 to 0.16. The most probable values of magnetic field fluctuation ($\delta B/B$) in MCs range from 0.04 to 0.05. We find that the most probable value of acoustic Mach number fluctuations (δM) inside MCs is ≈ 0.1 . Our findings show that the anomalous resistivity in MCs arising from electron scattering due to the fluctuations in the turbulent magnetic fields exceeds the (commonly used) Spitzer resistivity by a factor of $\approx 400 - 500$. The enhanced Joule heating arising from this anomalous resistivity could supplement to the ICME heating mechanism and help us better understand CME energetics.

4.1 Introduction

Turbulence is ubiquitous in everyday life as well as in astrophysical settings. The smoke from a chimney, the water flowing in a river, the wind in the atmosphere, the solar wind, nebula are some examples of turbulent flows. It is also one of the most

difficult genres of physics because it involves chaotic variations in fluid properties. Turbulence is sometimes called the frontier of classical mechanics. Though it is hard to define turbulence, it has some certain characteristics such as:

1. **Irregularity:** Turbulent flows are irregular, random and chaotic in nature. Though turbulence is chaotic, it is deterministic and can be described by the Navier-Stokes equation (Equation 2.3).
2. **Diffusivity:** Turbulent fluctuations also contribute to enhanced diffusivity and resistivity.
3. **High Reynolds number:** Generally, turbulent flows occur when the fluid Reynolds number (R_e , Equation 2.5) is large. For example, the transition from the linear flow to the turbulent flow inside pipes happens at, $R_e \approx 2300$, and in the pipe boundary layers, at $R_e \approx 10^5$.
4. **Dissipation:** Turbulent flows are characterized by a range of scales. The energy to the turbulent flow is typically fed at large scales. This energy is transferred via nonlinear interactions from large scales to progressively smaller ones until it is dissipated at the smallest scales.

Turbulence in astrophysical plasmas is typically studied in the context of MHD. An understanding of MHD turbulence is key to unraveling several astrophysical phenomena. The solar wind is a natural laboratory for studying MHD turbulence. A review of the early work on solar wind turbulence is documented in [Goldstein et al. \(1995\)](#) while more recent progress is reviewed in [Bruno and Carbone \(2013\)](#).

In this chapter, we pay attention to the interplanetary counterparts of solar coronal mass ejections called ICMEs. While the large-scale structure of ICMEs, their dynamics, and their impacts on space weather have been extensively studied, comparatively less attention has been paid to turbulent fluctuations of various plasma parameters inside them. [Ruzmaikin et al. \(1997\)](#) studied the nature of the magnetic energy spectra and helicity distribution inside 6 near-Earth MCs shortlisted by [Lepping et al. \(1990\)](#) using observations from the ISEE3 satellite. They show that the low-frequency spectral distribution of magnetic field energy differs substantially from that of the solar wind associated with coronal holes. This implies that the nature of turbulence which are coming from closed coronal regions (e.g.; inside MCs) is very different from the solar wind turbulence arising from the coronal holes. The detailed analysis of the Alfvén wave fluctuations inside a near-Earth MC (February 17 to 20, 2011) observed by the WIND spacecraft at 1 AU shows a more anisotropic power spectral density of magnetic field fluctuations inside the MC than in the quiet solar wind ([Liang et al., 2012](#)). [Li et al. \(2017\)](#) also inspected the

Alfvénic fluctuations inside the ICMEs, using the observations of Voyager 2 spacecraft in the heliocentric distance between 1 and 6 AU. Their results imply that the Alfvénic fluctuations can be a key factor in contributing to the local heating of the ICME plasma. While these studies focus on the magnetic field fluctuations inside ICMEs close to or beyond the Earth, [Lynch et al. \(2002\)](#) investigate the density fluctuations inside a CME at $10 R_{\odot}$. They studied the interplanetary scintillation (IPS) of the radio source 0854+201 at 8 GHz on 2nd August 2000 during the passage of a CME along the line of sight. They simulate the observations obtained from the LASCO (Large Angle and Spectrometric Coronagraph, aboard Solar and Heliospheric Observatory (SOHO)) C3 coronagraph and found that the electron density modulation index, $\delta n_e/n_e$, where n_e is the electron number density, shows a 19% drop inside the CME as compared to its magnitude in the pre-CME solar wind. Understanding the nature of turbulence in the ICME sheaths is also subject of recent interest. An extensive study of the evolution of magnetic field turbulence in the ICME sheath region has been conducted by [Good et al. \(2020\)](#) via tracking an ICME using the MESSENGER spacecraft at 0.47 AU and subsequently by the STEREO-B spacecraft at 1.08 AU while both the spacecraft were close to the radial alignment. [Kilpua et al. \(2021\)](#) reported a comprehensive statistical investigation of the magnetic field fluctuations of 79 well-observed ICME-driven sheath regions using the high-resolution magnetic field investigation (MFI) data from the WIND spacecraft in the near-Earth solar wind. They found that the characteristics of ICME-driven sheaths are noticeably different from the planetary magnetosheaths. The shocks associated with the ICMEs do not reset the solar wind turbulence, as appears to take place in the downstream of a bow shock. Magnetic turbulence in the ICME-driven shock was also studied by [Zhao et al. \(2021\)](#) where they recorded the ICME at 0.8 AU and 1 AU using the data from the Solar Orbiter and WIND missions. Their findings showed an enhancement in the power in the magnetic field fluctuations in the downstream of the shock. They also found that the frequency of the oblique kinetic Alfvén waves in the shock-downstream region is increased by a factor of $\approx 7 - 10$ times than the upstream due to shock compression and the Doppler effect. Magnetic field fluctuations in the ICME sheath have been found to influence characteristics of Forbush decreases (a transient decrease followed by a gradual recovery phase in the intensity of cosmic rays as detected at the Earth) and ICMEs ([Arunbabu et al., 2015](#)). Considering the magnetic field turbulence as a free parameter, [Arunbabu et al. \(2013\)](#) showed that it is the Earth-directed ICMEs (and not the shocks associated with them) that are the primary contributors to the Forbush decrease observed in high rigidity cosmic rays.

However, we are not aware of a large-sample study of fluctuations in the plasma properties inside the near-Earth magnetic clouds (MCs) associated with the ICMEs

using in situ data. A comprehensive study of turbulent fluctuation associated with Earth-directed ICMEs is also important because they are considered to be one of the primary drivers of the space weather disturbances (Gosling, 1993; Pulkkinen, 2007).

In the first half of this chapter, we seek to understand the statistics of the density, (total) magnetic field, and acoustic Mach number fluctuations inside a large sample of well-observed near-Earth MCs detected by the WIND satellite (<https://wind.nasa.gov/>). The second half is dedicated to analyzing the anomalous resistivity arising due to the non-Spitzer collisions of the electrons in the MCs. The data used in this paper are described in § 4.2 and all the required events are listed in Table A.3. In § 4.3 we inspect the amplitude of density and magnetic fluctuations inside the selected MCs and estimate the acoustic Mach number associated with these fluctuations. § 4.4 deals with the formulation of an anomalous resistivity mechanism which arises from the enhanced particle scattering caused by magnetic fluctuations inside MCs. This could contribute to enhanced plasma heating and increase our understanding of CME dynamics as they propagate through the heliosphere. § 4.5 describes the conclusions.

4.2 Data

We use the in situ data from the same sample set of 152 well-observed near-Earth ICMEs. These events are detected by the WIND spacecraft. The events we use are selected on the basis of the shortlisting procedure mentioned in § 3.2 of Chapter 3. The events are listed in Table A.3 of the appendix. The solar wind background used here is also defined in the § 3.2.2 of Chapter 3.

Here, we are interested in estimating the amplitude of turbulent fluctuations inside the magnetic clouds as their features and boundaries are relatively better defined (Klein and Burlaga, 1982). However, amplitudes of fluctuations signify only when they are compared with a suitable background/average value. We have defined the modulation index, which is basically the ratio of the fluctuation amplitude to the average. It provides an idea of the “strength” of the turbulent fluctuations of a certain parameter of interest. The choice of an average value is a subjective matter. In this study we use the WIND in situ data with a cadence of ≈ 1 minute. We then calculate rms fluctuations of the density, (total) magnetic field and velocity using running box averages using two temporal boxes: $t_{box} = 40$ minutes and 60 minutes. We note that with the use of $t_{box} = 40$ minutes, we have ≈ 38 boxes inside a typical MC while using $t_{box} = 60$ minutes yields ≈ 25 boxes inside a typical MC. By comparison, Bavassano et al. (1995) use three temporal box sizes ($t_{box} = 45, 90$ and 180 minutes) and Spangler and Spitler (2004) use $t_{box} = 60$ minutes in their

investigations of solar wind turbulence.

In this work, the running box average X (where X could represent the proton density, total magnetic field or velocity) is estimated using the exponentially weighted moving average (EWMA) formulation (Hunter, 1986). The EWMA is a quantitative or statistical measure used to model or describe a time series. It is designed as such that older observations are given lower weights. The weights fall exponentially as the data point gets older – hence the name is exponentially weighted.

The EWMA of a time series $\tilde{X}(i)$ is defined as

$$\begin{aligned} X(i) &= w \times \tilde{X}(i) + (1 - w) \times X(i - 1) , i > 1 \\ X(i) &= \tilde{X}(i) , i = 1 . \end{aligned} \quad (4.1)$$

where the quantity $\tilde{X}$ denotes the original one-minute resolution data (of the proton density or the total magnetic field or velocity) and X represents the exponentially weighted moving box average data. w is the weight ($0 \leq w \leq 1$) and we use $w = 1/l$, following Hunter (1986). The weight decides how important the current observation is in the calculation of the EWMA. The higher the value of w , the more closely the EWMA tracks the original time series. The quantity l represents the number of data points inside a certain t_{box} (so a box with $t_{box} = 40$ minutes would have $l = 40$, for instance) and i is an integer which runs from 1 to the length of the entire dataset. Since, in EWMA, the weights decline exponentially as the data points get older, this particular type of moving average emphasizes the newer data and thus better incorporates small variations compared to a simple moving average (SMA). An SMA provides equal weights to all data points in a particular time series (Lucas and Saccucci, 1990).

Then we estimate a quantity, δX that is the rms deviation of $\tilde{X}$ from its moving average, X for a particular time interval (t_{box}). Using these methodology, we form a time series of the modulation index $\delta X/X$. We then estimate the temporal average of this modulation index within the magnetic cloud (MC) and in the ambient (background) solar wind:

$$\begin{aligned} \left\langle \frac{\delta X}{X} \right\rangle_{MC} &\equiv \frac{1}{T_{MC}} \int_{t_s}^{t_e} \frac{\delta X}{X} dt \\ \left\langle \frac{\delta X}{X} \right\rangle_{BG} &\equiv \frac{1}{T_{BG}} \int_{BGs}^{BG e} \frac{\delta X}{X} dt , \end{aligned} \quad (4.2)$$

where T_{MC} and T_{BG} are the temporal extents of MC and background respectively.

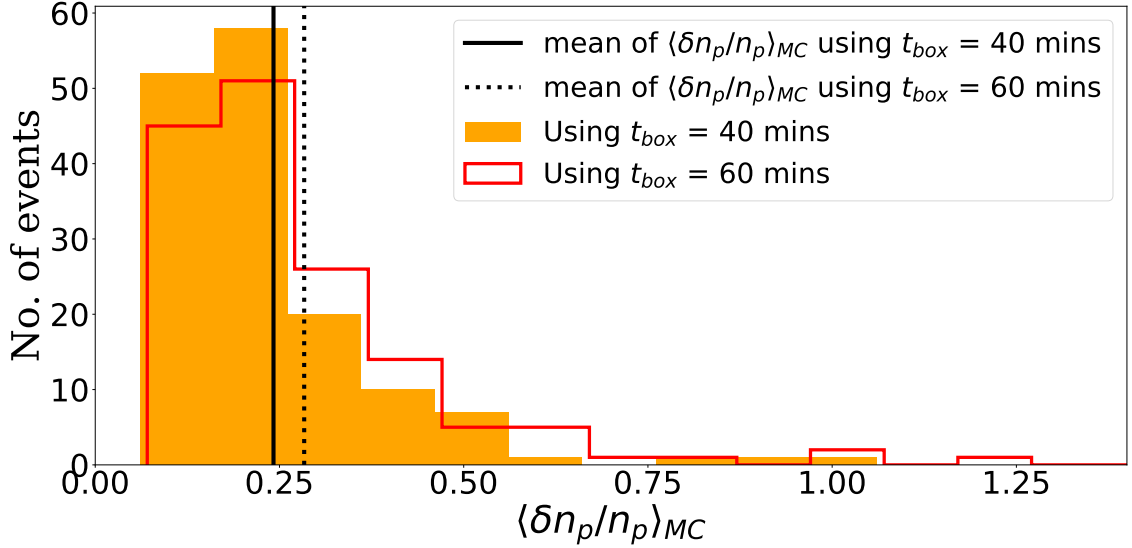


Figure 4.1: Histograms of the proton density modulation index inside the MCs ($\langle \delta n_p / n_p \rangle_{MC}$) for all the events listed in Table A.3. The vertical lines mark the mean values. With $t_{box} = 40$ minutes the mean, median and mode of $\langle \delta n_p / n_p \rangle_{MC}$ are 0.24, 0.2 and 0.13 respectively. The corresponding values for $t_{box} = 60$ minutes are 0.28, 0.23, and 0.16 respectively.

The quantities t_s and t_e represent the start and end times of each magnetic cloud (see Figure 1 of [Bhattacharjee et al., 2022](#)) and BG_s and BG_e represent the start and end times of the corresponding background solar wind.

4.3 Density, Magnetic field, and Acoustic Mach Number Fluctuations

The in situ data from the WIND spacecraft give us the temporal profiles of plasma velocity (v), proton number density (n_p), total magnetic field (B) along with its different components (B_x , B_y and B_z) and the proton thermal velocity (v_{th_p}) along the line of the spacecraft passage in the spacecraft frame of reference. We first pay attention to proton density (n_p) and total magnetic field (B) fluctuations by using $X \rightarrow n_p$ and $X \rightarrow B$ in Equations 4.1 and 4.2. We check the behavior of $\delta n_p / n_p$ and $\delta B / B$ inside near-Earth MCs and in the background solar wind. These denote the extent to which the proton density and magnetic field are modulated due to turbulent fluctuations. Therefore, they provide us an overall idea about the strength of density and magnetic turbulence. Based on these quantities, we also estimate the magnetic compressibility of the turbulent fluctuations and the acoustic Mach number of these fluctuations. We note that, the term ‘solar wind’ is only used for the ambient or background solar wind throughout this chapter.

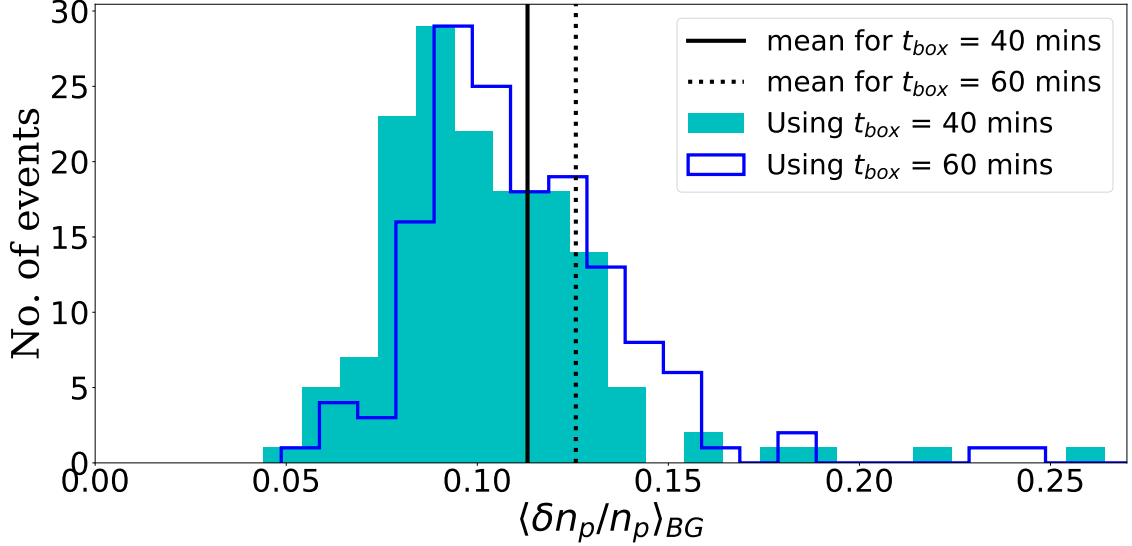


Figure 4.2: Histograms show the average of the proton density modulation index in the solar wind background, $\langle \delta n_p / n_p \rangle_{BG}$, for the events listed in Table A.3. The vertical lines represent the respective means of the histograms. With $t_{box} = 40$ minutes the mean, median and mode of $\langle \delta n_p / n_p \rangle_{MC}$ are 0.11, 0.10, and 0.08, respectively. The corresponding values for $t_{box} = 60$ minutes are 0.12, 0.11, and 0.09 respectively.

4.3.1 The density ($\delta n_p / n_p$) and magnetic field ($\delta B / B$) modulation index

Figure 4.1 shows histograms of the average proton density modulation index inside near-Earth MCs ($\langle \delta n_p / n_p \rangle_{MC}$) calculated following Equations 4.1 and 4.2 for all the events listed in Table A.3. The mean, median and the most probable value of $\langle \delta n_p / n_p \rangle_{MC}$ for $t_{box} = 40$ minutes are 0.24, 0.2 and 0.13 respectively; while for $t_{box} = 60$ minutes, they are 0.28, 0.23 and 0.16 respectively. A histogram of the average proton density modulation index in the background solar wind ($\langle \delta n_p / n_p \rangle_{BG}$) is shown in Figure 4.2. The mean, median, and most probable value of the average proton density modulation index in the background solar wind ($\langle \delta n_p / n_p \rangle_{BG}$) are 0.11, 0.1 and 0.08 respectively for $t_{box} = 40$ minutes and are 0.12, 0.11 and 0.09 respectively for $t_{box} = 60$ minutes. Our results for $\langle \delta n_p / n_p \rangle_{BG}$ are in broad agreement with the findings of [Bavassano et al. \(1995\)](#) who found that the density modulation index is a little less than 0.1 in the quiet solar wind, suggesting that the fluctuations are nearly incompressible. While the density modulation index is well below 1 both inside MCs and in the background solar wind, it is slightly higher inside MCs (as compared to the background).

Histograms of the temporal average of the total magnetic field modulation index inside MCs are shown in Figure 4.3. The mean, median, and most probable value of $\langle \delta B / B \rangle_{MC}$ with $t_{box} = 40$ minutes are 0.044, 0.042, and 0.038 respectively, and

4.3. DENSITY, MAGNETIC FIELD, AND ACOUSTIC MACH NUMBER FLUCTUATIONS

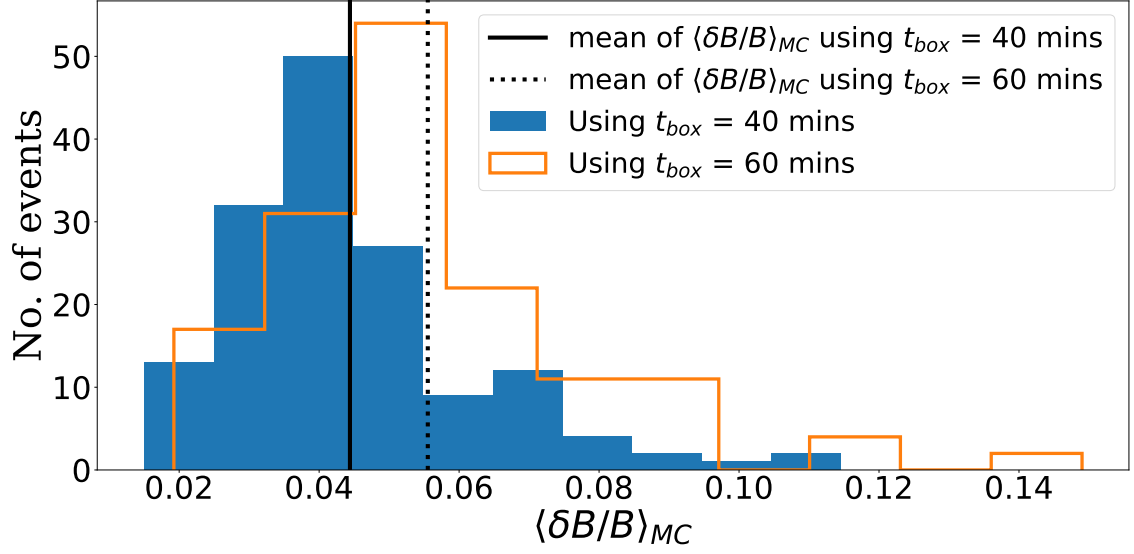


Figure 4.3: Histograms of the total magnetic field modulation index inside the MCs ($\langle \delta B/B \rangle_{MC}$) for all the events listed in Table A.3. The vertical lines mark the mean values. With $t_{box} = 40$ minutes the mean, median and mode of $\langle \delta B/B \rangle_{MC}$ are 0.044, 0.042 and 0.038 respectively. The corresponding values for $t_{box} = 60$ minutes are 0.056, 0.052 and 0.05 respectively.

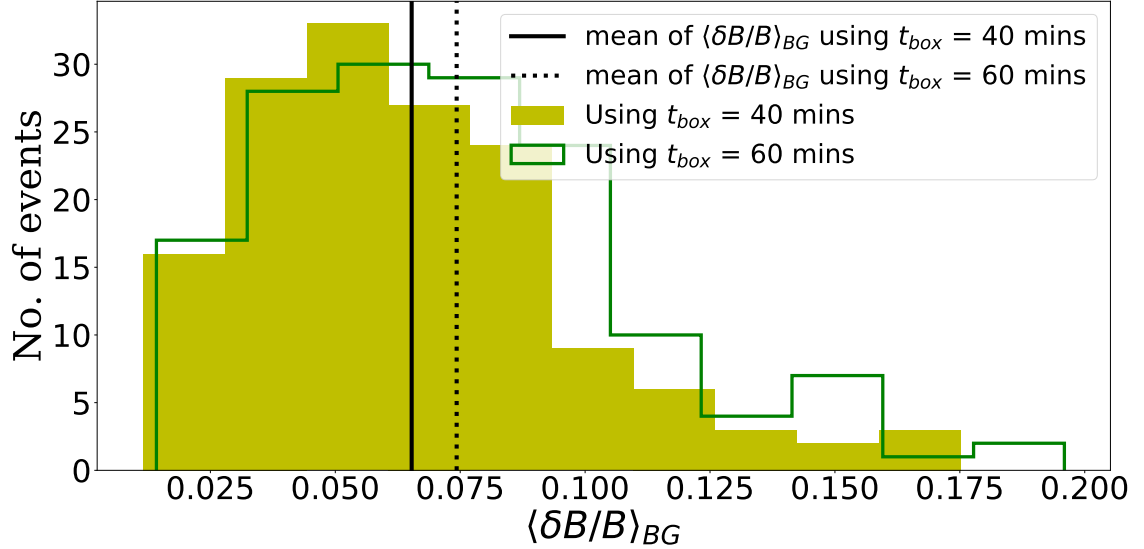


Figure 4.4: Histograms displaying the magnetic field modulation index ($\langle \delta B/B \rangle_{BG}$) in the background solar wind for all the events listed in Table A.3. The vertical lines represent the respective means of the histograms. With $t_{box} = 40$ minutes the mean, median and mode of $\langle \delta B/B \rangle_{MC}$ are 0.067, 0.060 and 0.059 respectively. The corresponding values for $t_{box} = 60$ minutes are 0.074, 0.068, and 0.063 respectively.

for $t_{box} = 60$ minutes, they are 0.056, 0.052 and 0.05 respectively. Histograms of the average value of the magnetic field modulation index in the background solar wind are shown in Figure 4.4. The mean, median, and most probable value of the temporal average of the magnetic field modulation index in the background solar

4.3. DENSITY, MAGNETIC FIELD, AND ACOUSTIC MACH NUMBER FLUCTUATIONS

wind ($\langle \delta B/B \rangle_{\text{BG}}$) are 0.067, 0.06 and 0.059 respectively for $t_{\text{box}} = 40$ minutes and 0.074, 0.068 and 0.063 respectively for $t_{\text{box}} = 60$ minutes. Our results indicate that the magnetic field modulation index in the background solar wind ($\langle \delta B/B \rangle_{\text{BG}}$) is slightly larger than the modulation index ($\langle \delta B/B \rangle_{\text{MC}}$) inside near-Earth MCs. The statistical picture of density and magnetic field fluctuations are enlisted in Table A.7 of the appendix. Density and magnetic field modulation indices inside MCs associated with each event in the Table A.3 are listed in Table A.5.

A comparison between Figures 4.1 and 4.3 shows that the density modulation index inside MCs is almost an order of magnitude larger than the magnetic field modulation index. We also find that the proton density modulation index is larger than the magnetic field modulation index in the background solar wind, although to a lesser extent.

4.3.2 Mach number fluctuations (δM)

The acoustic Mach number fluctuations is defined as (Bavassano et al., 1995):

$$\delta M \equiv \frac{\delta v}{c_s}, \quad (4.3)$$

where δv is the rms fluctuation in the plasma velocity (v) and c_s is the moving-average of the adiabatic sound speed. The adiabatic sound speed is defined as (Bavassano et al., 1995) $c_s \equiv [\gamma(n_e k_B T_e + n_p k_B T_p)/(n_p m_p + n_e m_e)]^{1/2}$ where n_e and n_p are the electron and proton number densities in cm^{-3} respectively, T_e and T_p are the electron and proton temperatures in the unit of Kelvin respectively, k_B is the Boltzmann constant, m_p and m_e are the proton and electron masses in g respectively, γ is the polytropic index. In this study, we have assumed $n_e = n_p$ and $T_e = 10T_p$ (Bhattacharjee et al., 2022). We estimate T_p from the proton thermal velocity (v_{th_p}) using $T_p = m_p v_{th_p}^2 / 3k_B$. We note that the expression for c_s uses a polytropic index γ . The appropriate value to use for γ inside ICMEs or MCs or in the solar wind is not clear. A value of 5/3 would suggest that the ICME plasma is cooling adiabatically and needs to be heated continuously to maintain its temperature (Kumar and Rust, 1996b). On the contrary, if we use a value of 1.2, it would imply efficient thermal conduction to the interior of the ICME from the solar corona and little additional heating (Chen, 1996). A recent study based on the data from Helios and Parker Solar Probe (PSP) postulates a polytropic index which ranges from 1.35 to 1.57 for solar wind protons and an index ranging from 1.21 to 1.29 for the solar wind electrons (Dakeyo et al., 2022). Another research work, Nicolaou et al. (2020), that

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uses PSP data, claims a polytropic index $\approx 5/3$ for the solar wind plasma. The polytropic index of the CME plasma is assumed to be in the range from 1.35 to 1.8 in the study by [Mishra and Wang \(2018\)](#). Therefore, we use two values for γ (5/3 and 1.2) in the calculations of this paper.

The mean, median, and most probable value of Mach number fluctuations in the background solar wind $\langle \delta M \rangle_{\text{BG}}$ using $\gamma = 5/3$ for $t_{\text{box}} = 40$ minutes are 0.84, 0.46 and 0.12 respectively while for $t_{\text{box}} = 60$ minutes they are 0.95, 0.52, and 0.14 respectively (see, histograms of Figure 4.6). Using $\gamma = 1.2$, the mean, median, and most probable values become 0.98, 0.54 and 0.14 respectively (for $t_{\text{box}} = 40$ minutes) and 1.09, 0.60 and 0.15 respectively (for $t_{\text{box}} = 60$ minutes). From these results, it can thus be argued that the velocity fluctuations in the background solar wind can often be marginally supersonic. Figure 4.5 shows histograms of $\langle \delta M \rangle_{\text{MC}}$ inside the MCs using $\gamma = 5/3$ for all the events listed in our sample (Table A.3) for two averaging time windows. The mean, median and the most probable value of $\langle \delta M \rangle_{\text{MC}}$ for $t_{\text{box}} = 40$ minutes are 0.15, 0.12 and 0.09 respectively. For $t_{\text{box}} = 60$ minutes, they are 0.17, 0.14 and 0.10 respectively. If instead of $\gamma = 5/3$, we use $\gamma = 1.2$, the mean, median and the most probable values are 0.17, 0.14 and 0.11 respectively (for $t_{\text{box}} = 40$ minutes) and 0.21, 0.16 and 0.12 respectively (for $t_{\text{box}} = 60$ minutes). Therefore, we find that the overall statistical behavior of $\langle \delta M \rangle$ does not depend significantly on the choice of the polytropic index γ . Our outcomes show that the mean, median and mode $\langle \delta M \rangle_{\text{MC}}$ are all considerably less than 1 (Figure 4.5) the turbulent plasma velocity fluctuations inside near-Earth MCs are clearly subsonic in nature.

On the other hand, the bulk motion of ICMEs is well-known to be supersonic. This finding leads us to the consideration of the Morokovin's hypothesis. According to this hypothesis, subsonic laws are adequate to describe the essential dynamics (such as aerodynamic drag, for instance) of an object moving at moderately supersonic speeds, as long as the turbulent fluctuations in the boundary layer of that object are fairly subsonic ([Duan et al., 2011](#); [Smits and Dussauge, 2006](#)). We need to define the boundaries of MCs. [Wei et al. \(2003a,b\)](#) estimate MC boundary layer widths using 80 well-observed MCs from 1996 to 2001. They show that the average thickness of the front boundary layer of the MC is ≈ 1.7 hours after the 'MC start' (inside the cloud) while the average thickness of the trailing boundary layer is ≈ 3.1 hours after the 'MC end' (outside the cloud). In order to get an adequate number of data points inside the boundaries, we choose the time window, $t_{\text{box}} = 10$ minutes. Using $\gamma = 5/3$, we find that the mean, median, and most probable value of $\langle \delta M \rangle$ inside the front boundary layer are 0.14, 0.07 and 0.05 respectively while they are 0.16, 0.05 and 0.04 respectively in the trailing boundary layer. If we consider $\gamma = 1.2$ (instead of 5/3), the mean, median, and most probable value become 0.17, 0.08 and 0.05

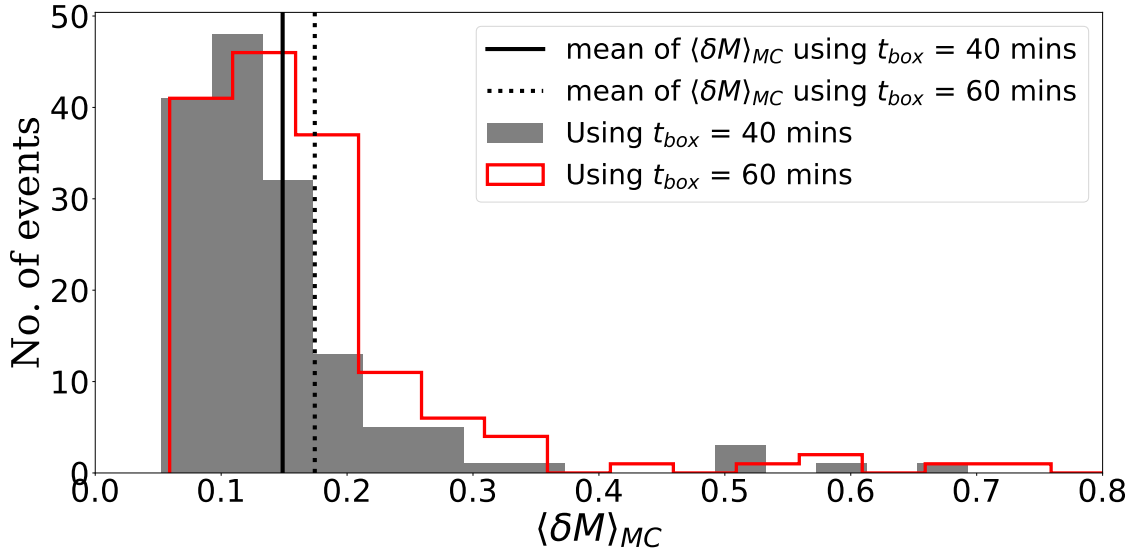


Figure 4.5: Histograms of the Mach number fluctuations inside the MCs ($\langle \delta M \rangle_{MC}$) using $\gamma = 5/3$ for all the events listed in Table A.3. The vertical lines mark the mean values. With $t_{box} = 40$ minutes the mean, median, and most probable value of $\langle \delta M \rangle_{MC}$ are 0.15, 0.12 and 0.09 respectively. The corresponding values for $t_{box} = 60$ minutes are 0.17, 0.14 and 0.10 respectively.

respectively in the front layer and 0.18, 0.06, and 0.04 respectively in the trailing layer. We again note that, the choice of γ does not affect the results substantially. The statistics for $\langle \delta M \rangle$ inside MCs, backgrounds, and boundary layers are enlisted in Table A.7. The values of $\langle \delta M \rangle_{MC}$ using both the polytropic indices for each event in Table A.3 are listed in Table A.6. Our results thus suggest that CME dynamics can be described adequately by subsonic laws.

It is interesting to note that, the widely used aerodynamic drag laws for CME propagation through the solar wind, both for the cases, when the drag force (F_D) is proportional to the square of the relative speed between the CME and the solar wind (V_{rel}), (Cargill, 2004; Vršnak et al., 2009a, 2010, 2013a) and when $F_D \propto V_{rel}$ (Borgazzi et al., 2009; Vršnak and Gopalswamy, 2002a), are subsonic drag laws. The results we find here, on the subsonic nature of δM in MC boundary layers could possibly be an explanation for why these subsonic aerodynamic drag laws work well for describing the dynamics of CMEs, even though it is well-known that their bulk motion is supersonic.

4.4 Anomalous resistivity inside MCs

Next, we ask whether the turbulent fluctuations inside magnetic clouds can contribute to an anomalous resistivity and associated Joule heating inside the plasma. We know that some source of heating is needed to account for the observed proton

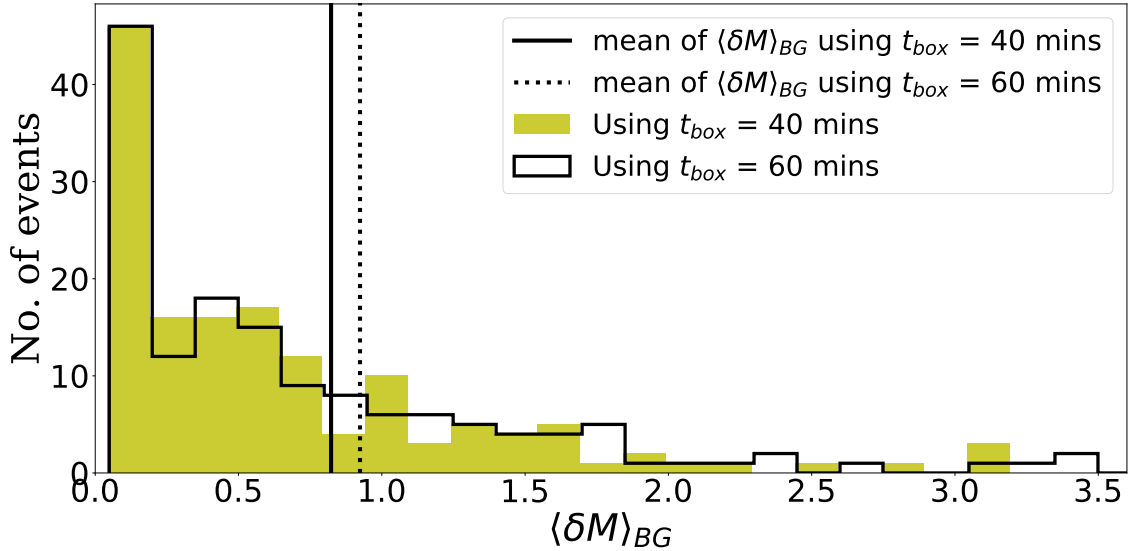


Figure 4.6: Histograms of the Mach number fluctuations inside the solar wind backgrounds ($\langle \delta M \rangle_{BG}$) using $\gamma = 5/3$ for all the events listed in Table A.3. The vertical lines mark the mean values. With $t_{box} = 40$ minutes the mean, median, and most probable value of $\langle \delta M \rangle_{BG}$ are 0.84, 0.46 and 0.12 respectively. The corresponding values for $t_{box} = 60$ minutes are 0.95, 0.52 and 0.14 respectively.

temperature profile in the solar wind (Verma et al., 1995). It is also well-known that the magnetic clouds associated with the ICMEs expand as they propagate through the solar wind. If MC expansion is happen to follow adiabatic process, the proton temperature inside them would have been as low as a few Kelvin near the Earth (Chen and Garren, 1993). However, the observed proton temperatures are $\approx 10^5$ K. Although here, we have only mentioned proton heating, we note that some semi-analytical treatments (Chen, 1996; Kumar and Rust, 1996b) and MHD simulations (Jin et al., 2017; Lionello et al., 2013; Manchester et al., 2008) of CME dynamics and propagation considers a single species fluid. The energy dissipation in such treatments is generally parameterized using a polytropic index. The energy dissipation here implies dissipation in the “plasma”, without distinguishing between protons and electrons. Some studies, which infer plasma heating rates using observations at various heliocentric distances (Ciaravella et al., 2001; Rakowski et al., 2007) implicitly refer to electron heating. On the other hand, some other treatments invoke turbulent dissipation mechanism to explain the proton heating (e.g., Liu et al., 2006). However, it is not clear if indirect electron heating via Coulomb coupling between protons and electrons is sufficient in this regard. Joule heating or Ohmic heating which is basically the $I^2 R$ (I is the current and R is the resistance) heating, is an important candidate for direct electron heating. Due to their lower mass, electrons are the primary current carriers, and will thus be the primary recipients of Joule heating. However, Joule heating due to Spitzer resistivity, which

is only due to Coulomb collisions of charged particles, is well-known to be quite inadequate (Bhattacharjee et al., 2022; Murphy et al., 2011). Therefore we focus on an anomalous (i.e., non-Spitzer), resistivity which can account for direct electron heating via Joule dissipation.

We can understand the MHD turbulence results small scale fluctuations riding on a large-scale background magnetic field. Charged particles that usually gyrate around the background magnetic field (and are therefore “tied” to them) are stochastically scattered by the turbulent fluctuations which are present in the magnetic field. We focus here only on electrons, since they are the primary current carriers, and are therefore relevant to Joule heating. Electrons effectively collide with the turbulent scattering centers, resulting in diffusion (parallel and perpendicular to the large-scale magnetic field). Therefore, they are undergoing diffusion parallel to and perpendicular to the background magnetic field. Here, we use the results of Candia and Roulet (2004), who report extensive simulations of charged particle dynamics in the presence of turbulence. They provide analytical fitting formulae for the particle diffusion coefficients due to such turbulent fluctuations. Their results are consistent with previous ones reported by Casse et al. (2001); Giacalone and Jokipii (1999) and are also valid for higher energy particles and stronger turbulence levels. These particle diffusion coefficients are generally used for high-energy cosmic rays. However, they are also technically valid for charged particles of any energy range, and thus are quite applicable to the regime which we study here. We use our method of estimating the turbulence amplitudes inside near-Earth MCs (§ 4.3.1) in these fitting formulae for finding the diffusion coefficients and extract effective (anomalous) collision timescales. Instead of the usual Spitzer or Coulomb collision timescales, we can now use these timescales to estimate an anomalous resistivity inside the MC plasma and also inside the background.

Candia and Roulet (2004) provide the following fitting formula for the spatial diffusion coefficient ($\text{cm}^2 \text{s}^{-1}$) parallel to the large-scale background magnetic field:

$$D_{\parallel} = v_{the} L_{max} \rho \times \frac{N_{\parallel}}{(\delta B/B)^2} \times \sqrt{\left(\frac{\rho}{\rho_{\parallel}}\right)^{2(1-\Gamma)} + \left(\frac{\rho}{\rho_{\parallel}}\right)^2} \quad (4.4)$$

where v_{the} is the electron thermal velocity and L_{max} is the largest turbulent length scale of the system of interest. We note that the corresponding formula mentioned in Candia and Roulet (2004) uses the speed of light (c) in place of the thermal velocity v_{the} , since their treatment addresses relativistic particles. The quantity $\delta B/B$ is the modulation index of the total magnetic fluctuations which is discussed in § 4.3.1, and it gives a quantification of the strength of turbulent fluctuations. The quantity ρ is the ratio of the electron gyroradius (r_L) to the maximum turbulent scale, L_{max} , and it represents how tightly the particle is bound to the background magnetic field.

The electron gyroradius (r_L) is defined by (Huba, 2013),

$$r_L = 2.38 \times T_{eV}^{1/2} \times B^{-1} \text{ cm} \quad (4.5)$$

where T_{eV} is the electron temperature in the unit of electronvolt (eV) and B is the total magnetic field in Gauss. Common choices for the maximum lengthscale L_{max} include the MC width (L_{MC}) (Arunbabu et al., 2013) and the outer scale of solar wind turbulence, which is $\approx 10^6$ km (Subramanian et al., 2009). In this study, we use both these prescriptions. The MC width, L_{MC} is estimated as (Bhattacharjee et al., 2022)

$$L_{max} = L_{MC} \equiv \int_{t_s}^{t_e} |v(t)| dt. \quad (4.6)$$

where v is the plasma velocity measured in the spacecraft frame of reference, t_s and t_e denote the start and end time of the MC (see Figure 1 of Bhattacharjee et al., 2022). The quantities Γ , $N_{\parallel}$ and $\rho_{\parallel}$ are fitting parameters that depend upon the type of the turbulent energy spectra, we would like to consider (Kolmogorov, Kraichnan or Bykov-Toptygin) in the system. The energy spectrum for magnetic fluctuations in MHD turbulence usually follows the Kraichnan scaling: $E(k) \propto k^{-3/2}$ (Biskamp, 1993; Kraichnan, 1965). This is because several solar wind turbulence observations show evidence for this (Borovsky, 2012; Podesta and Borovsky, 2010; Podesta et al., 2007; Vasquez et al., 2007). Therefore, we use $\Gamma = 3/2$, $N_{\parallel} = 2$ and $\rho_{\parallel} = 0.22$ which are appropriate for the Kraichnan turbulence (see Table 1 of Candia and Roulet, 2004). We further note that there is evidence for velocity fluctuations in the solar wind to follow the Kraichnan spectrum, while the magnetic field fluctuations obey the Kolmogorov's 5/3 scaling (Alexandrova et al., 2013; Roberts, 2010; Salem et al., 2009). Hence, we also briefly outline how the results change if we use parameters which are appropriate to Kolmogorov turbulence.

The anomalous electron diffusion timescale (in seconds) parallel to the magnetic field is given by

$$t_{\parallel} = \frac{D_{\parallel}}{v_{the}^2}, \quad (4.7)$$

and this can be used to determine the anomalous electron resistivity $\eta_{\parallel}$ which is given as

$$\eta_{\parallel} = \frac{m_e}{t_{\parallel} n_e e^2}. \quad (4.8)$$

The quantities m_e , e and n_e are electron mass in g, electron charge in esu, and electron number density in cm^{-3} . Here we have assumed n_e to be the same as the proton number density n_p . The expression for the anomalous resistivity which is described in Eq 4.8 is in exact analogy with that for the collisional (Spitzer) resistivity η_{coll} . The Spitzer resistivity is because of Coulomb collisions between

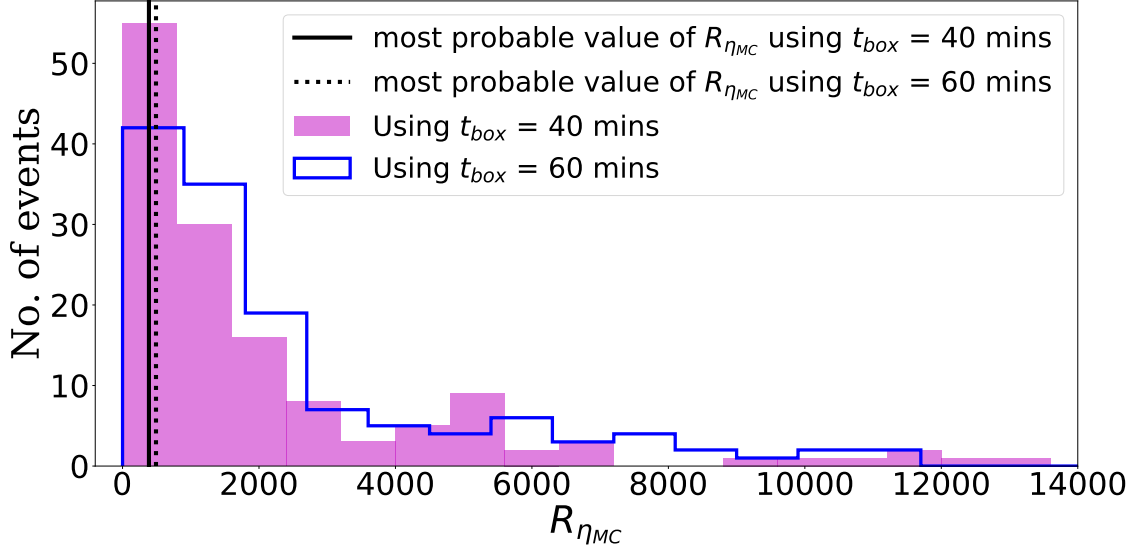


Figure 4.7: Histograms of $R_{\eta_{MC}}$ (Equation 4.11) for all the MCs listed in Table A.3 with $L_{max} = L_{MC}$ and parameters appropriate to the Kraichnan turbulence spectrum. The vertical lines indicate the most probable value. With $t_{box} = 40$ minutes the mean, median, and most probable value of $R_{\eta_{MC}}$ are 7068, 1258 and 387 respectively. The corresponding values for $t_{box} = 60$ minutes are 10157, 1780, and 490 respectively.

charged particles in an unmagnetized plasma, and it is defined as,

$$\eta_{coll} = \frac{m_e}{t_{coll} n_e e^2}, \quad (4.9)$$

where the electron-electron Coulomb collisional timescale (in seconds) is given by (Huba, 2013),

$$t_{coll} = \left[2.91 \times 10^{-6} n_e \ln \Lambda T_e^{-3/2} \right]^{-1}. \quad (4.10)$$

The quantity $\ln \Lambda$ is the Coulomb logarithm and we have taken it to be 20 for this study. We use $T_e = 10T_p$ following Bhattacharjee et al. (2022). In this study, we concentrate only on $\eta_{\parallel}$. We can now compare the anomalous resistivity with the Coulomb collisional (Spitzer) resistivity using the following ratio

$$R_{\eta_{MC}} = \frac{\langle \eta_{\parallel} \rangle_{MC}}{\langle \eta_{coll} \rangle_{MC}} \quad (4.11)$$

where, as previously mentioned, $\langle \rangle_{MC}$ represents the temporal average inside the MC. The ratio $R_{\eta_{MC}}$ for all the MCs listed in Table A.3 are shown in Figure 4.7. The mean, median, and most probable value are 7×10^3 , 1.25×10^3 and 387 respectively for $t_{box} = 40$ minutes. For $t_{box} = 60$ minutes, they are 10^4 , 1.8×10^3 and 490 respectively. Instead of using L_{MC} , if we use $L_{max} = 10^6$ km (Subramanian et al., 2009), we find that the mean, median, and most probable value of $R_{\eta_{MC}}$ are 3.7×10^4 ,

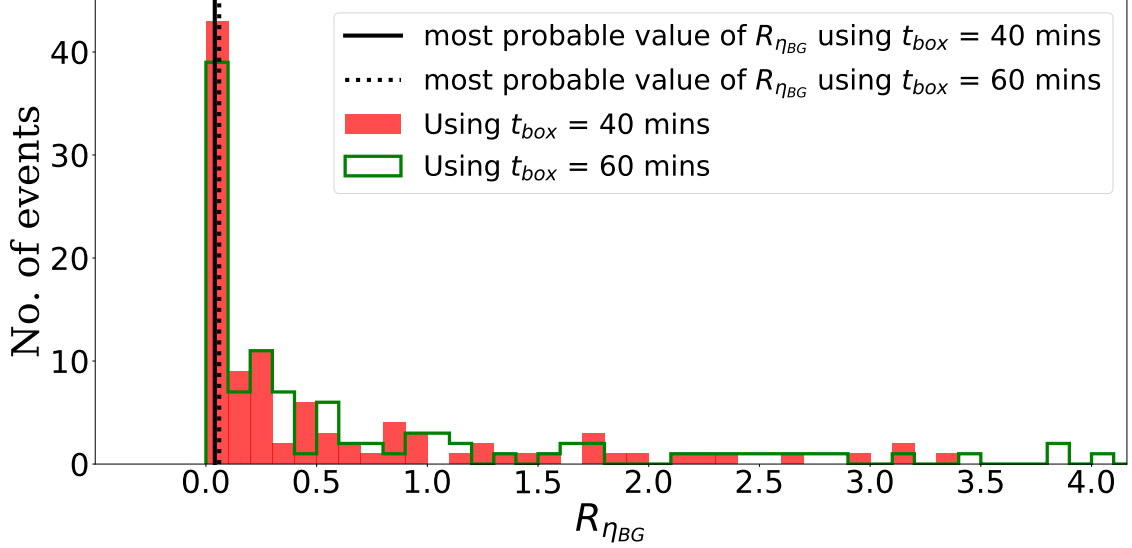


Figure 4.8: Histograms of $R_{\eta_{MC}}$ (Equation 4.11) for all the MCs listed in Table A.3 with $L_{max} = L_{MC}$ and parameters appropriate to the Kraichnan turbulence spectrum. The vertical lines indicate the most probable value. With $t_{box} = 40$ minutes the mean, median, and most probable value of $R_{\eta_{MC}}$ are 7068, 1258, and 387 respectively. The corresponding values for $t_{box} = 60$ minutes are 10157, 1780, and 490 respectively.

7.2×10^3 and 2×10^3 (for $t_{box} = 40$ minutes) respectively and 5.3×10^4 , 10^4 and 2770 (for $t_{box} = 60$ minutes) respectively.

In a similar approach, We can construct the ratio between the anomalous and Spitzer resistivity in the ambient solar wind background as follows,

$$R_{\eta_{BG}} = \frac{\langle \eta_{\parallel} \rangle_{BG}}{\langle \eta_{coll} \rangle_{BG}} \quad (4.12)$$

where $\langle \rangle_{BG}$ denotes the temporal average in the solar wind background. The ratio $R_{\eta_{BG}}$ for all the events we have studied are displayed in Figure 4.8. The mean, median, and most probable value of $R_{\eta_{BG}}$ for $t_{box} = 40$ minutes are 1175, 0.68 and 0.04 respectively. For $t_{box} = 60$ minutes, the corresponding values are 1400, 0.88 and 0.06 respectively. With $L_{max} = 10^6$ km, the mean, median, and most probable value of $R_{\eta_{BG}}$ are 5.7×10^3 , 4.05 and 0.32 respectively for $t_{box} = 40$ minutes and 6900, 4.75 and 0.52 respectively for $t_{box} = 60$ minutes. In this study, the mean values are biased by $\approx 22\%$ of the background solar wind periods associated with the 152 events listed in Table A.3.

To summarize, the anomalous resistivity arising out of turbulent fluctuations can be two to four orders of magnitude higher than the collisional (Spitzer) resistivity inside near-Earth MCs. On the other hand, the anomalous resistivity is generally lower than the Coulomb collisional resistivity in the ambient solar wind. The sheath regions in front of ICMEs are known to be significantly more turbulent than the

ICME interiors Kilpua et al. (2021). Our preliminary estimates using values for $\delta B/B$ appropriate for the ICME sheath regions imply that the anomalous resistivity can exceed the collisional one by as much as 4 to 5 orders of magnitude in the ICME sheath regions. This particular aspect deserves further study. If we assume a Kolmogorov spectrum for the magnetic fluctuations (which amounts to using $\Gamma = 5/3$, $N_{\parallel} = 1.7$ and $\rho_{\parallel} = 0.2$) for the turbulent fluctuations, $R_{\eta_{\text{MC}}}$ and $R_{\eta_{\text{BG}}}$ are lower by a factor of ≈ 10 .

4.5 Summary and Conclusions

It is well-known that solar wind turbulence is an extensively studied subject. However, not much attention has been devoted to the turbulent fluctuations inside CMEs. In this chapter, we have surveyed the turbulence amplitudes of density and total magnetic field fluctuations inside a large and well-observed sample of near-Earth magnetic clouds using in situ data from the WIND spacecraft. To estimate the fluctuation amplitudes, we divide the one-minute resolution data into temporal boxes of the time window, t_{box} . Here, we use $t_{\text{box}} = 40$ and 60 minutes. We have estimated the average density and magnetic field for each t_{box} and have compared it with the corresponding rms deviation in order to obtain the modulation indices of the proton density ($\delta n_p/n_p$) and total magnetic field ($\delta B/B$). We have also estimated the fluctuations of the acoustic Mach number inside MCs. The magnetic field fluctuations scatter electrons and therefore, they mimic collisions. Finally, we have calculated the anomalous resistivity arising out of such collisions. Our main results are:

- The most probable value of the average density modulation index inside near-Earth MCs ($\langle \delta n_p/n_p \rangle_{\text{MC}}$), ranges from 0.13 to 0.16 depending on the size of the time window, t_{box} used. This is slightly larger than the density modulation index in the solar wind background ($\langle \delta n_p/n_p \rangle_{\text{BG}}$) which is ≈ 0.08 to 0.09 (depending on the t_{box} used). On the other hand, the most probable value of the $\langle \delta B/B \rangle_{\text{MC}}$, ranges from 0.04 to 0.05. We find that the average magnetic field modulation index in the background solar wind ($\langle \delta B/B \rangle_{\text{BG}}$) is comparatively larger (≈ 0.06). We further note that $\langle \delta B/B \rangle_{\text{MC}}$ is smaller than $\langle \delta n_p/n_p \rangle_{\text{MC}}$. This indicates that the magnetic fluctuations in MCs are probably associated with magnetosonic modes of the plasma. Our findings show that the most probable value for fluctuations in the Mach number (δM) inside near-Earth magnetic clouds is ≈ 0.1 . The corresponding value within the leading and trailing boundary layers of the ICME is around an order of magnitude smaller. Putting it in another way, although ICMEs propagate supersonically

through the background solar wind, the turbulent fluctuations inside them are quite subsonic. Using the Morokovin hypothesis, this suggests that the characteristics of the bulk ICME dynamics (such as the aerodynamic drag) will be governed by subsonic laws, although the ICME itself moves supersonically.

- The turbulent magnetic field fluctuations act as effective scattering centers for electrons. We estimate an anomalous resistivity arising from this process. Our findings show that this anomalous resistivity can be $\approx 500 - 1000$ times as large as the Spitzer resistivity inside near-Earth MCs. This will therefore, enhance the Joule heating in MCs. It is not clear if this level of enhanced Joule heating will significantly impact the overall energetics associated with CME propagation. It is also well-known that magnetic reconnections are one of the important mechanisms for the conversion of magnetic energy to kinetic and thermal energy. Using high-resolution WIND data, [Feng and Wang \(2014\)](#) suggested that magnetic reconnections can lead to the possible enhancement of proton temperature locally inside near-Earth MCs. The acceleration of energetic electrons driven by magnetic reconnection in the boundary of near-Earth MCs was also noted by [Wang et al. \(2010\)](#).

CME sheaths, are characterized by much stronger turbulence. A dedicated study of such anomalous resistivity and attendant Joule heating in sheaths might yield interesting results that impact on our understanding of CME energetics and plasma heating. As suggested previously, magnetic reconnection and thermal conduction from the reconnection sites can also contribute to electron heating inside CME plasma.

Chapter 5

Future Research

A Brief Overview

In this chapter, we outline a plan for our future research. Here, we concentrate on three problems related to heliophysics – the CME heating mechanism, CME aerodynamic drag, and the coupling between the CME and Earth’s magnetosphere. These three problems aim at quantifying turbulent fluctuations and turbulent transport properties in the collisionless plasma of the ambient solar wind and CMEs. Turbulence analysis can provide us with a wide richness of physics at different scales. We will use in situ observations to characterize these turbulent fluctuations. This study builds a bridge between the micro-physics of turbulent dissipations and macroscopic MHD modeling, leading to an overall understanding of CME dynamics and geo-effectiveness related to them. We expect that our findings will also help in building realistic estimates of space weather predictions that will protect the ground based technology and the space exploration.

5.1 Introduction

The Sun often expels massive blobs of coronal plasma and magnetic fields into interplanetary space. Such Coronal Mass Ejections (CMEs), when directed towards the Earth, are the primary drivers of geomagnetic storms that lead to space weather disturbances in the near-Earth space environment. Space weather disturbances affect a wide range of technologies and communication systems we rely on. Furthermore, CMEs are often accompanied by solar energetic particles, which pose significant health hazards to astronauts. A good understanding of CME dynamics and energetics is essential for space weather forecasting, which relies on realistic estimates

of Earth arrival times and speeds. Despite considerable progress, reliable and accurate estimates of CME Sun-Earth propagation times and Earth arrival speeds are still elusive. This is primarily because there are uncertainties in some basic issues associated with magnetohydrodynamic (MHD) models for CME dynamics. It is broadly recognized that Lorentz self-forces associated with the magnetic fields and currents carried by CMEs are responsible for their propagation and expansion. However, it is not clear what fraction of the magnetic energy is dissipated in heating the CME plasma, and what fraction is expended in overcoming the aerodynamic drag resistance CMEs experience as they travel through the background solar wind. In another way of looking at it, the values of transport coefficients such as viscosity, electrical and thermal conductivities in the collisionless solar wind plasma are uncertain. Given the ubiquity of turbulence in the solar wind and inside CMEs, it is reasonable to expect that these transport coefficients will be mediated by turbulent fluctuations.

Turbulence in the solar wind has been a subject of considerable interest for several decades; comprehensive reviews include [Goldstein et al. \(1995\)](#) and [Bruno and Carbone \(2013\)](#). However, not as much attention has been devoted to investigating turbulent transport coefficients in the context of CMEs. Turbulent fluctuations (and the associated anomalous resistivity) have been found to substantially enhance electron heating inside CMEs ([Bhattacharjee et al., 2023a](#)) (see Figure 4.7). The anomalous resistivity comes from the charged particles (tied to the magnetic field) which are stochastically scattered due to the turbulent fluctuations in the magnetic field; like the electrons are undergoing collisions via these scattering centers. In Figure 4.7, $R_{\eta_{MC}}$ is defined as the ratio between the anomalous resistivity and Spitzer resistivity as used in the study by [Bhattacharjee et al. \(2023a\)](#). They estimated $R_{\eta_{MC}}$ using two different time windows (40 and 60 minutes), which were used to compute the moving average and root-mean-square fluctuations of the magnetic field. However, these results are only suggestive, and we are far from a comprehensive understanding. There are unresolved issues with regard to electron-proton coupling, direct turbulent heating of protons, and turbulent suppression of thermal conduction that can impinge on CME energetics. Mass entrainment and viscous dissipation in the turbulent boundary layer between CMEs and the ambient solar wind is also expected to affect CME dynamics.

The direction of the large-scale magnetic field in the leading part of CMEs impacting the Earth's magnetosphere is generally thought to be the primary factor that decides the magnitude of geomagnetic storms. However, there is some evidence that turbulent density fluctuations in the CME sheath can also play an important role in CME-magnetosphere coupling. Understanding this aspect could help us develop better models for predicting the geoeffectiveness of Earth-impacting CMEs.

These issues can be addressed using in situ observations from the PSP and WIND and theoretical interpretation.

5.2 Future work: Statements and Research Methodology

5.2.1 Problem 1: CME heating

The heating of CME and solar wind plasma is among the most important, unsolved problems in heliophysics. The problem of energy dissipation inside CMEs is often couched in terms of determining the appropriate value for the polytropic index. The “right” value to use for the polytropic index is not obvious, however. In the absence of thermal coupling to the solar corona, if a parcel of solar wind plasma is assumed to expand adiabatically (i.e., with a polytropic index of $5/3$), the proton temperature should be as low as a few Kelvin by the time it reaches the Earth (Chen and Garren, 1993). Detailed in situ observations show, however, that the near-Earth temperature of CME protons is $\approx 10^5$ K. This discrepancy can be reconciled either by assuming that the CME interior is thermally connected to the solar corona via magnetic field lines (Chen, 1996) or by postulating a local heating mechanism inside the plasma (Kumar and Rust, 1996b). The problem is often posed using the polytropic equation of state, which is essentially a simple and convenient substitute for a full energy equation. If the CME plasma is thermally connected to the solar corona, there is no need for substantial CME heating, and the effective polytropic index would be close to the isothermal value of 1. If it is not, the polytropic index would be close to the adiabatic value of $5/3$ and high proton temperatures imply substantial heating inside the CME. While the appropriate value to use for the polytropic index in the interior of CMEs is not clear, there is some more attention devoted to the polytropic index for the solar wind plasma. Using in situ data from Helios and the Parker Solar Probe (PSP), (Dakeyo et al., 2022) show that the polytropic index for solar wind electrons ranges from 1.21 to 1.29, while that for protons ranges from 1.35 to 1.57. Another study (Nicolaou et al., 2020) claims $\gamma \approx 5/3$ for solar wind protons.

Although the polytropic index is a convenient parameter, it masks some important issues. Since the plasma in the ambient solar wind as well as the CME interior is collisionless, conventional estimates of plasma heating or thermal conductivity based on Coulomb collisions are not valid. Coulomb collisions in such situations will be substantially mediated by turbulence, and this needs to be taken into account in any realistic estimate of dissipation.

Problem 1 can be addressed using the following steps:

1. Obtain estimates of the modulation index of density, magnetic field and velocity fluctuations ($\delta n/n$, $\delta B/B$ and $\delta v/v$) using in situ data from the PSP, Helios and WIND spacecraft. This exercise would involve a careful selection of events and of solar wind intervals that are representative of the quiet/ambient solar wind and of CME interiors. The first products from such an exercise could possibly reveal the heliocentric evolution of turbulent fluctuations in the solar wind, which would be interesting in its own right.
2. Use the modulation indices to build models for turbulence-modified transport coefficients such as thermal and electrical conductivity and viscosity. There are different prescriptions for constructing these turbulent transport coefficients (e.g., [Bhattacharjee et al., 2023a](#); [Bian et al., 2016](#)), and we would have to compare their results.
3. We could use the results from item 1 to develop sub-grid prescriptions for viscous and resistive dissipation to be incorporated in 3D MHD codes. For instance, the well established k-epsilon prescription (e.g., [Scott-Pomerantz, 2004](#)) has been used in MHD codes for studying ram pressure stripping in galaxies ([Close et al., 2013](#)) – we could follow a similar approach. The advantage with such an approach is twofold - first, it uses the k-epsilon formalism, which is a well empirical characterization that has been used to study turbulent flows for a long time. Secondly, sub-grid transport coefficients have been in use in solar MHD (in studies of the solar dynamo) for a long while. This approach is therefore well known in the MHD modeling community. We would have to collaborate with other groups that have working MHD codes in this regard.

5.2.2 Problem 2: Aerodynamic drag on CMEs

As CMEs propagate through the heliosphere, they also expend energy in overcoming aerodynamic drag, causing them to slow down. Needless to say, a good understanding of the drag force is essential to have reliable estimates of CME Sun-Earth travel times. There are several treatments of the aerodynamic drag force in the literature, but all of them employ ad-hoc parametrizations of the drag coefficient that are tuned to match observations. We note that [Subramanian et al. \(2012\)](#) used a microphysical prescription for viscosity in the turbulent solar wind to obtain an analytical model for the drag coefficient. In this project, we will be using estimates of turbulent viscosity to compute energy dissipation and mass entrainment in CME boundary layers using approaches similar to those that have been adopted to address the deceleration of astrophysical jets ([Panferov, 2017](#)). We anticipate that insights

from such efforts could help us better address the CME slowdown.

5.2.3 Problem 3: CME-magnetosphere coupling

The third area we address to work on concerns estimates of the geoeffectiveness of Earth-directed CMEs. As per our current understanding, the main determinant of CME geoeffectiveness is the direction of the large-scale magnetic field in the leading edge of the CME magnetic field; if it is anti-parallel to the Earth’s magnetic field, it favors reconnection and enhances the geoeffectiveness of CMEs. The other commonly acknowledged determinant of geoeffectiveness is the ram pressure exerted by the CME on the Earth’s magnetosphere. On the other hand, we note that turbulent density fluctuations and boundary layer viscosity are known to influence solar wind-magnetosphere coupling ([Axford and Hines, 1961](#); [Borovsky, 2021](#); [Farrugia et al., 2001](#)), although the details are still somewhat uncertain. It is therefore reasonable to expect that the turbulent density fluctuations in the CME sheath region and the associated viscosity will play a role in coupling between the CME and the Earth’s magnetosphere. We will use in situ measurements of the density modulation index and estimates of boundary layer turbulent viscosity to better characterize CME-magnetosphere coupling, and therefore CME geoeffectiveness.

5.3 Conclusion

The three problems outlined in the previous section center around the theme of turbulent fluctuations in the collisionless plasma of the ambient solar wind and CMEs. We propose to use detailed in situ observations to characterize these fluctuations. Inputs from the analysis of the observational data will be used to estimate transport coefficients, which will inform CME propagation models. Our approaches for estimating transport coefficients will borrow from related research applicable to situations ranging from solar flares to astrophysical jets. The resulting improvements can positively impact key aspects of space weather prediction, such as Earth arrival times, and geoeffectiveness of CMEs.

Appendix A

Appendix

A.1 Data Tables for Chapter 02:

This section displays the in situ data which are described in Chapter 2 and used in the paper: [Bhattacharjee et al. \(2022\)](#). The data from 151 well-observed events observed by the WIND spacecraft are described in the Table A.1.1. The data consisting of 45 well-observed events observed by the pair of Helios spacecraft and selected by [Bothmer and Schwenn \(1998\)](#) are shown in Table A.1.2.

A.1.1 Events from the WIND Observation

Table A.1: The list of the 151 WIND ICME events we use in this study (Chapter 2 and [Bhattacharjee et al. \(2022\)](#)). The arrival date and time of the ICME at the position of the WIND measurement and the arrival and departure dates & times of the associated magnetic clouds (MCs) are taken from the WIND ICME catalogue (wind.nasa.gov/ICMEindex.php). The 15 events marked with an asterisk (*) coincide with the near-Earth counterparts of 15 CMEs listed in [Sachdeva et al. \(2017\)](#).

CME event number	CME Arrival date and time [UT] (1AU)	MC start date and time [UT]	MC end date and time [UT]	Flux rope type
1	1995 03 04 , 00:36	1995 03 04 , 11:23	1995 03 05 , 03:06	Fr
2	1995 04 03 , 06:43	1995 04 03 , 12:45	1995 04 04 , 13:25	F+
3	2010 06 30 , 09:21	1995 06 30 , 14:23	1995 07 02 , 16:47	Fr
4	1995 08 22 , 12:56	1995 08 22 , 22:19	1995 08 23 , 18:43	Fr
5	1995 09 26 , 15:57	1995 09 27 , 03:36	1995 09 27 , 21:21	Fr

A.1. DATA TABLES FOR CHAPTER 02:

CME event number	CME Arrival date and time [UT] (1AU)	MC start date and time [UT]	MC end date and time [UT]	Flux rope type
6	1995 10 18 , 10:40	1995 10 18 , 19:11	1995 10 20 , 02:23	Fr
7	1996 02 15 , 15:07	1996 02 15 , 15:07	1996 02 16 , 08:59	F+
8	1996 04 04 , 11:59	1996 04 04 , 11:59	1996 04 04 , 21:36	Fr
9	1996 05 16 , 22:47	1996 05 17 , 01:36	1996 05 17 , 11:58	F+
10	1996 05 27 , 14:45	1996 05 27 , 14:45	1996 05 29 , 02:22	Fr
11	1996 07 01 , 13:05	1996 07 01 , 17:16	1996 07 02 , 10:17	Fr
12	1996 08 07 , 08:23	1996 08 07 , 11:59	1996 08 08 , 13:12	Fr
13	1996 12 24 , 01:26	1996 12 24 , 03:07	1996 12 25 , 11:44	F+
14	1997 01 10 , 00:52	1997 01 10 , 04:47	1997 01 11 , 03:36	F+
15	1997 04 10 , 17:02	1997 04 11 , 05:45	1997 04 11 , 19:10	Fr
16	1997 04 21 , 10:11	1997 04 21 , 11:59	1997 04 23 , 07:11	F+
17	1997 05 15 , 01:15	1997 05 15 , 10:00	1997 05 16 , 02:37	F+
18	1997 05 26 , 09:09	1997 05 26 , 15:35	1997 05 28 , 00:00	Fr
19	1997 06 08 , 15:43	1997 06 09 , 06:18	1997 06 09 , 23:01	Fr
20	1997 06 19 , 00:00	1997 06 19 , 05:31	1997 06 20 , 22:29	Fr
21	1997 07 15 , 03:10	1997 07 15 , 06:48	1997 07 16 , 11:16	F+
22	1997 08 03 , 10:10	1997 08 03 , 13:55	1997 08 04 , 02:23	Fr
23	1997 08 17 , 01:56	1997 08 17 , 06:33	1997 08 17 , 20:09	Fr
24	1997 09 02 , 22:40	1997 09 03 , 08:38	1997 09 03 , 20:59	Fr
25	1997 09 18 , 00:30	1997 09 18 , 04:07	1997 09 19 , 23:59	F+
26	1997 10 01 , 11:45	1997 10 01 , 17:08	1997 10 02 , 23:15	Fr
27	1997 10 10 , 03:08	1997 10 10 , 15:33	1997 10 11 , 22:00	F+
28	1997 11 06 , 22:25	1997 11 07 , 06:00	1997 11 08 , 22:46	F+
29	1997 11 22 , 09:12	1997 11 22 , 17:31	1997 11 23 , 18:43	F+
30	1997 12 30 , 01:13	1997 12 30 , 09:35	1997 12 31 , 08:51	Fr
31	1998 01 06 , 13:29	1998 01 07 , 02:23	1998 01 08 , 07:54	F+
32	1998 01 28 , 16:04	1998 01 29 , 13:12	1998 01 31 , 00:00	F+
33	1998 03 25 , 10:48	1998 03 25 , 14:23	1998 03 26 , 08:57	Fr
34	1998 03 31 , 07:11	1998 03 31 , 11:59	1998 04 01 , 16:18	Fr
35	1998 05 01 , 21:21	1998 05 02 , 11:31	1998 05 03 , 16:47	Fr
36	1998 06 02 , 10:28	1998 06 02 , 10:28	1998 06 02 , 09:16	Fr
37	1998 06 24 , 10:47	1998 06 24 , 13:26	1998 06 25 , 22:33	F+
38	1998 07 10 , 22:36	1998 07 10 , 22:36	1998 07 12 , 21:34	F+
39	1998 08 19 , 18:40	1998 08 20 , 08:38	1998 08 21 , 20:09	F+
40	1998 10 18 , 19:30	1998 10 19 , 04:19	1998 10 20 , 07:11	F+
41	1999 02 11 , 17:41	1999 02 11 , 17:41	1999 02 12 , 03:35	Fr
42	1999 07 02 , 00:27	1999 07 03 , 08:09	1999 07 05 , 13:13	Fr
43	1999 09 21 , 18:57	1999 09 21 , 18:57	1999 09 22 , 11:31	Fr
44	2000 02 11 , 23:34	2000 02 12 , 12:20	2000 02 13 , 00:35	Fr
45	2000 03 01 , 01:58	2000 03 01 , 03:21	2000 03 02 , 03:07	Fr
46	2000 07 01 , 07:12	2000 07 01 , 07:12	2000 07 02 , 03:34	Fr
47	2000 07 11 , 22:35	2000 07 11 , 22:35	2000 07 13 , 04:33	Fr
48	2000 07 28 , 06:38	2000 07 28 , 14:24	2000 07 29 , 10:06	F+
49	2000 09 02 , 23:16	2000 09 02 , 23:16	2000 09 03 , 22:32	Fr
50	2000 10 03 , 01:02	2000 10 03 , 09:36	2000 10 05 , 03:34	F+

A.1. DATA TABLES FOR CHAPTER 02:

CME event number	CME Arrival date and time [UT] (1AU)	MC start date and time [UT]	MC end date and time [UT]	Flux rope type
51	2000 10 12 , 22:33	2000 10 13 , 18:24	2000 10 14 , 19:12	Fr
52	2000 11 06 , 09:30	2000 11 06 , 23:05	2000 11 07 , 18:05	Fr
53	2000 11 26 , 11:43	2000 11 27 , 09:30	2000 11 28 , 09:36	Fr
54	2001 04 21 , 15:29	2001 04 22 , 00:28	2001 04 23 , 01:11	Fr
55	2001 10 21 , 16:39	2001 10 22 , 01:17	2001 10 23 , 00:47	Fr
56	2001 11 24 , 05:51	2001 11 24 , 15:47	2001 11 25 , 13:17	Fr
57	2001 12 29 , 05:16	2001 12 30 , 03:24	2001 12 30 , 19:10	Fr
58	2002 02 28 , 05:06	2002 02 28 , 19:11	2002 03 01 , 23:15	Fr
59	2002 03 18 , 13:14	2002 03 19 , 06:14	2002 03 20 , 15:36	Fr
60	2002 03 23 , 11:24	2002 03 24 , 13:11	2002 03 25 , 21:36	Fr
61	2002 04 17 , 11:01	2002 04 17 , 21:36	2002 04 19 , 08:22	F+
62	2002 07 17 , 15:56	2002 07 18 , 13:26	2002 07 19 , 09:35	Fr
63	2002 08 18 , 18:40	2002 08 19 , 19:12	2002 08 21 , 13:25	Fr
64	2002 08 26 , 11:16	2002 08 26 , 14:23	2002 08 27 , 10:47	Fr
65	2002 09 30 , 07:54	2002 09 30 , 22:04	2002 10 01 , 20:08	F+
66	2002 12 21 , 03:21	2002 12 21 , 10:20	2002 12 22 , 15:36	Fr
67	2003 01 26 , 21:43	2003 01 27 , 01:40	2003 01 27 , 16:04	Fr
68	2003 02 01 , 13:06	2003 02 02 , 19:11	2003 02 03 , 09:35	Fr
69	2003 03 20 , 04:30	2003 03 20 , 11:54	2003 03 20 , 22:22	Fr
70	2003 06 16 , 22:33	2003 06 16 , 17:48	2003 06 18 , 08:18	Fr
71	2003 08 04 , 20:23	2003 08 05 , 01:10	2003 08 06 , 02:23	Fr
72	2003 11 20 , 08:35	2003 11 20 , 11:31	2003 11 21 , 01:40	Fr
73	2004 04 03 , 09:55	2004 04 04 , 01:11	2004 04 05 , 19:11	F+
74	2005 05 15 , 02:10	2005 05 15 , 05:31	2005 05 16 , 22:47	F+
75	2005 05 20 , 04:47	2005 05 20 , 09:35	2005 05 22 , 02:23	F+
76	2005 07 17 , 14:52	2005 07 17 , 14:52	2005 07 18 , 05:59	Fr
77	2005 10 31 , 02:23	2005 10 31 , 02:23	2005 10 31 , 18:42	Fr
78	2006 02 05 , 18:14	2006 02 05 , 20:23	2006 02 06 , 11:59	F+
79	2006 09 30 , 02:52	2006 09 30 , 08:23	2006 09 30 , 22:03	F+
80	2006 11 18 , 07:11	2006 11 18 , 07:11	2006 11 20 , 04:47	Fr
81	2007 05 21 , 22:40	2007 05 21 , 22:45	2007 05 22 , 13:25	Fr
82	2007 06 08 , 05:45	2007 06 08 , 05:45	2007 06 09 , 05:15	Fr
83	2007 11 19 , 17:22	2007 11 20 , 00:33	2007 11 20 , 11:31	Fr
84	2008 05 23 , 01:12	2008 05 23 , 01:12	2008 05 23 , 10:46	F+
85	2008 09 03 , 16:33	2008 09 03 , 16:33	2008 09 04 , 03:49	F+
86	2008 09 17 , 00:43	2008 09 17 , 03:57	2008 09 18 , 08:09	Fr
87	2008 12 04 , 11:59	2008 12 04 , 16:47	2008 12 05 , 10:47	Fr
88	2008 12 17 , 03:35	2008 12 17 , 03:35	2008 12 17 , 15:35	Fr
89	2009 02 03 , 19:21	2009 02 03 , 01:12	2009 02 04 , 19:40	F+
90	2009 03 11 , 22:04	2009 03 12 , 01:12	2009 03 13 , 01:40	F+
91	2009 04 22 , 11:16	2009 04 22 , 14:09	2009 04 22 , 20:37	Fr
92	2009 06 03 , 13:40	2009 06 03 , 20:52	2009 06 05 , 05:31	Fr
93	2009 06 27 , 11:02	2009 06 27 , 17:59	2009 06 28 , 20:24	F+
94	2009 07 21 , 02:53	2009 07 21 , 04:48	2009 07 22 , 03:36	Fr
95	2009 09 10 , 10:19	2009 09 10 , 10:19	2009 09 10 , 19:26	Fr

A.1. DATA TABLES FOR CHAPTER 02:

CME event number	CME Arrival date and time [UT] (1AU)	MC start date and time [UT]	MC end date and time [UT]	Flux rope type
96	2009 09 30 , 00:44	2009 09 30 , 06:59	2009 09 30 , 19:11	Fr
97	2009 10 29 , 01:26	2009 10 29 , 01:26	2009 10 29 , 23:45	F+
98	2009 11 14 , 10:47	2009 11 14 , 10:47	2009 11 15 , 11:45	Fr
99	2009 12 12 , 04:47	2009 12 12 , 19:26	2009 12 14 , 04:47	Fr
100	2010 01 01 , 22:04	2010 01 02 , 00:14	2010 01 03 , 09:06	Fr
101	2010 02 07 , 18:04	2010 02 07 , 19:11	2010 02 09 , 05:42	Fr
102*	2010 03 23 , 22:29	2010 03 23 , 22:23	2010 03 24 , 15:36	Fr
103*	2010 04 05 , 07:55	2010 04 05 , 11:59	2010 04 06 , 16:48	Fr
104*	2010 04 11 , 12:20	2010 04 11 , 21:36	2010 04 12 , 14:12	Fr
105	2010 05 28 , 01:55	2010 05 29 , 19:12	2010 05 29 , 17:58	Fr
106*	2010 06 21 , 03:35	2010 06 21 , 06:28	2010 06 22 , 12:43	Fr
107*	2010 09 15 , 02:24	2010 09 15 , 02:24	2010 09 16 , 11:58	Fr
108*	2010 10 31 , 02:09	2010 10 30 , 05:16	2010 11 01 , 20:38	Fr
109	2010 12 19 , 00:35	2010 12 19 , 22:33	2010 12 20 , 22:14	F+
110	2011 01 24 , 06:43	2011 01 24 , 10:33	2011 01 25 , 22:04	F+
111*	2011 03 29 , 15:12	2011 03 29 , 23:59	2011 04 01 , 14:52	Fr
112	2011 05 28 , 00:14	2011 05 28 , 05:31	2011 05 28 , 22:47	F+
113	2011 06 04 , 20:06	2011 06 05 , 01:12	2011 06 05 , 18:13	Fr
114	2011 07 03 , 19:12	2011 07 03 , 19:12	2011 07 04 , 19:12	Fr
115*	2011 09 17 , 02:57	2011 09 17 , 15:35	2011 09 18 , 21:07	Fr
116	2012 02 14 , 07:11	2012 02 14 , 20:52	2012 02 16 , 04:47	Fr
117	2012 04 05 , 14:23	2012 04 05 , 19:41	2012 04 06 , 21:36	Fr
118	2012 05 03 , 00:59	2012 05 04 , 03:36	2012 05 05 , 11:22	Fr
119	2012 05 16 , 12:28	2012 05 16 , 16:04	2012 05 18 , 02:11	Fr
120	2012 06 11 , 02:52	2012 06 11 , 11:31	2012 06 12 , 05:16	Fr
121*	2012 06 16 , 09:03	2012 06 16 , 22:01	2012 06 17 , 11:23	F+
122*	2012 07 14 , 17:39	2012 07 15 , 06:14	2012 07 17 , 03:22	Fr
123	2012 08 12 , 12:37	2012 08 12 , 19:12	2012 08 13 , 05:01	Fr
124	2012 08 18 , 03:25	2012 08 18 , 19:12	2012 08 19 , 08:22	Fr
125*	2012 10 08 , 04:12	2012 10 08 , 15:50	2012 10 09 , 17:17	Fr
126	2012 10 12 , 08:09	2012 10 12 , 18:09	2012 10 13 , 09:14	Fr
127*	2012 10 31 , 14:28	2012 10 31 , 23:35	2012 11 02 , 05:21	F+
128*	2012 11 12 , 22:12	2012 11 13 , 08:23	2012 11 14 , 08:09	F+
129*	2013 03 17 , 05:21	2013 03 17 , 14:09	2013 03 19 , 16:04	Fr
130*	2013 04 13 , 22:13	2013 04 14 , 17:02	2013 04 17 , 05:30	F+
131	2013 04 30 , 08:52	2013 04 30 , 12:00	2013 05 01 , 07:12	Fr
132	2013 05 14 , 02:23	2013 05 14 , 06:00	2013 05 15 , 06:28	Fr
133	2013 06 06 , 02:09	2013 06 06 , 14:23	2013 06 08 , 00:00	F+
134	2013 06 27 , 13:51	2013 06 28 , 02:23	2013 06 29 , 11:59	Fr
135	2013 09 01 , 06:14	2013 09 01 , 13:55	2013 09 02 , 01:56	Fr
136	2013 10 30 , 18:14	2013 10 30 , 18:14	2013 10 31 , 05:30	Fr
137	2013 11 08 , 21:07	2013 11 08 , 23:59	2013 11 09 , 06:14	Fr
138	2013 11 23 , 00:14	2013 11 23 , 04:47	2013 11 23 , 15:35	Fr
139	2013 12 14 , 16:47	2013 12 15 , 16:47	2013 12 16 , 05:30	Fr
140	2013 12 24 , 20:36	2013 12 25 , 04:47	2013 12 25 , 17:59	F+

CME event number	CME Arrival date and time [UT] (1AU)	MC start date and time [UT]	MC end date and time [UT]	Flux rope type
141	2014 04 05 , 09:58	2014 04 05 , 22:18	2014 04 07 , 14:24	Fr
142	2014 04 11 , 06:57	2014 04 11 , 06:57	2014 04 12 , 20:52	F+
143	2014 04 14 , 10:20	2014 04 21 , 07:41	2014 04 22 , 06:12	Fr
144	2014 04 29 , 19:11	2014 04 29 , 19:11	2014 04 30 , 16:33	Fr
145	2014 06 29 , 04:47	2014 06 29 , 20:53	2014 06 30 , 11:15	Fr
146	2014 08 19 , 05:49	2014 08 19 , 17:59	2014 08 21 , 19:09	F+
147	2014 08 26 , 02:40	2014 08 27 , 03:07	2014 08 27 , 21:49	Fr
148	2015 01 07 , 05:38	2015 01 07 , 06:28	2015 01 07 , 21:07	F+
149	2015 09 07 , 13:05	2015 09 07 , 23:31	2015 09 09 , 14:52	F+
150	2015 10 06 , 21:35	2015 10 06 , 21:35	2015 10 07 , 10:03	Fr
151	2015 12 19 , 15:35	2015 12 20 , 13:40	2015 12 21 , 23:02	Fr

A.1.2 Events from the Helios Observation

Table A.2: The list of 45 magnetic clouds (MCs) shortlisted by [Bothmer and Schwenn \(1998\)](#) using in situ data from the Helios 1 and 2 spacecraft for the period December 1974–July 1981. This data is used in Chapter 2 of this thesis and in ([Bhattacharjee et al., 2022](#)). The columns show the year, time duration, heliocentric distance and the spacecraft by which observed the MC.

Magnetic Cloud serial number	Year	Time duration		Heliocentric distance (AU)	Observed by
		Days	Hours		
1	1975	7	00 – 10	0.92	Helios 1
2		63,64	16 – 05	0.39	Helios 1
3		92	06 – 16	0.48	Helios 1
4		313	03 – 18	0.81	Helios 1
5		321	06 – 18	0.87	Helios 1
6	1976	90	09 – 21	0.47	Helios 2
7		187	03 – 21	0.98	Helios 1
8	1977	29,30	10 – 10	0.95	Helios 1
9		76	05 – 20	0.71	Helios 2
10		78,79	22 – 08	0.57	Helios 1
11		159,160	18 – 13	0.86	Helios 1
12		240,241	14 – 10	0.84	Helios 1
13		268,269	14 – 12	0.57	Helios 1
14		335	14 – 00	0.75	Helios 1
15		3,4	15 – 17	0.95	Helios 1
16		4,5	08 – 10	0.94	Helios 2
17		6	01 – 13	0.95	Helios 2
18	1978	17	01 – 23	0.98	Helios 2
19		29,30	12 – 01	0.98	Helios 2
20		37,38	16 – 16	0.98	Helios 2
21		46,47	14 – 20	0.95	Helios 1
22		47,48	03 – 09	0.95	Helios 2
23		61,62	01 – 01	0.87	Helios 1
24		92	02 – 07	0.61	Helios 2
25		114	12 – 19	0.32	Helios 2
26		189,190	22 – 22	0.94	Helios 1
27		292,293	01 – 14	0.47	Helios 1
28	1979	358,359	15 – 15	0.85	Helios 2
29		363,364	09 – 14	0.85	Helios 1
30		58,59	15 – 15	0.96	Helios 1

Magnetic Cloud serial number	Year	Time duration		Heliocentric distance (AU)	Observed by
		Days	Hours		
31		62	09 – 17	0.94	Helios 1
32		93	02 – 18	0.68	Helios 2
33		129	06 – 12	0.30	Helios 2
34		148,149	23 – 07	0.43	Helios 1
35		305	03 – 19	0.50	Helios 1
36	1980	82,83	17 – 12	0.92	Helios 1
37		90	01 – 15	0.88	Helios 1
38		162,163	17 – 01	0.41	Helios 1
39		172	02 – 20	0.53	Helios 1
40		175	05 – 17	0.57	Helios 1
41	1980	231	00 – 18	0.97	Helios 1
42		117,118	09 – 03	0.79	Helios 1
43		131,132	15 – 03	0.66	Helios 1
44		146,147	03 – 07	0.48	Helios 1
45		170	03 – 09	0.34	Helios 1

A.2 Tables for Chapter 03:

A.2.1 Data Table for Chapter 03:

This section displays the in situ data used for the analysis in Chapters 3 and 4, and used in the papers: [Bhattacharjee et al. \(2023a,b\)](#). The ICME selection process is described in § 3.2 of Chapter 3.

Table A.3: The list of the 152 WIND ICME events we use in Chapters 3 and 4 of this thesis. The arrival date and time of the ICME at the position of WIND measurement and the arrival and departure dates & times of the associated magnetic clouds (MCs) are taken from WIND ICME catalogue (<https://wind.nasa.gov/ICMEindex.php>). The 14 events marked with an asterisk (*) coincide with the near earth counterparts of 14 CMEs listed in [Sachdeva et al. \(2017\)](#).

CME event number	CME Arrival date and time [UT] (1AU)	MC start date and time [UT]	MC end date and time [UT]	Flux rope type
1	1995 03 04 , 00:36	1995 03 04 , 11:23	1995 03 05 , 03:06	Fr
2	1995 04 03 , 06:43	1995 04 03 , 12:45	1995 04 04 , 13:25	F+
3	1995 06 30 , 09:21	1995 06 30 , 14:23	1995 07 02 , 16:47	Fr
4	1995 08 22 , 12:56	1995 08 22 , 22:19	1995 08 23 , 18:43	Fr
5	1995 09 26 , 15:57	1995 09 27 , 03:36	1995 09 27 , 21:21	Fr
6	1995 10 18 , 10:40	1995 10 18 , 19:11	1995 10 20 , 02:23	Fr
7	1996 02 15 , 15:07	1996 02 15 , 15:07	1996 02 16 , 08:59	F+
8	1996 04 04 , 11:59	1996 04 04 , 11:59	1996 04 04 , 21:36	Fr
9	1996 05 16 , 22:47	1996 05 17 , 01:36	1996 05 17 , 11:58	F+
10	1996 05 27 , 14:45	1996 05 27 , 14:45	1996 05 29 , 02:22	Fr
11	1996 07 01 , 13:05	1996 07 01 , 17:16	1996 07 02 , 10:17	Fr
12	1996 08 07 , 08:23	1996 08 07 , 11:59	1996 08 08 , 13:12	Fr
13	1996 12 24 , 01:26	1996 12 24 , 03:07	1996 12 25 , 11:44	F+
14	1997 01 10 , 00:52	1997 01 10 , 04:47	1997 01 11 , 03:36	F+
15	1997 04 10 , 17:02	1997 04 11 , 05:45	1997 04 11 , 19:10	Fr
16	1997 04 21 , 10:11	1997 04 21 , 11:59	1997 04 23 , 07:11	F+
17	1997 05 15 , 01:15	1997 05 15 , 10:00	1997 05 16 , 02:37	F+
18	1997 05 26 , 09:09	1997 05 26 , 15:35	1997 05 28 , 00:00	Fr
19	1997 06 08 , 15:43	1997 06 09 , 06:18	1997 06 09 , 23:01	Fr
20	1997 06 19 , 00:00	1997 06 19 , 05:31	1997 06 20 , 22:29	Fr
21	1997 07 15 , 03:10	1997 07 15 , 06:48	1997 07 16 , 11:16	F+
22	1997 08 03 , 10:10	1997 08 03 , 13:55	1997 08 04 , 02:23	Fr
23	1997 08 17 , 01:56	1997 08 17 , 06:33	1997 08 17 , 20:09	Fr
24	1997 09 02 , 22:40	1997 09 03 , 08:38	1997 09 03 , 20:59	Fr
25	1997 09 18 , 00:30	1997 09 18 , 04:07	1997 09 19 , 23:59	F+

A.2. TABLES FOR CHAPTER 03:

CME event number	CME Arrival date and time [UT] (1AU)	MC start date and time [UT]	MC end date and time [UT]	Flux rope type
26	1997 10 01 , 11:45	1997 10 01 , 17:08	1997 10 02 , 23:15	Fr
27	1997 10 10 , 03:08	1997 10 10 , 15:33	1997 10 11 , 22:00	F+
28	1997 11 06 , 22:25	1997 11 07 , 06:00	1997 11 08 , 22:46	F+
29	1997 11 22 , 09:12	1997 11 22 , 17:31	1997 11 23 , 18:43	F+
30	1997 12 30 , 01:13	1997 12 30 , 09:35	1997 12 31 , 08:51	Fr
31	1998 01 06 , 13:29	1998 01 07 , 02:23	1998 01 08 , 07:54	F+
32	1998 01 28 , 16:04	1998 01 29 , 13:12	1998 01 31 , 00:00	F+
33	1998 03 25 , 10:48	1998 03 25 , 14:23	1998 03 26 , 08:57	Fr
34	1998 03 31 , 07:11	1998 03 31 , 11:59	1998 04 01 , 16:18	Fr
35	1998 05 01 , 21:21	1998 05 02 , 11:31	1998 05 03 , 16:47	Fr
36	1998 06 02 , 10:28	1998 06 02 , 10:28	1998 06 02 , 09:16	Fr
37	1998 06 24 , 10:47	1998 06 24 , 13:26	1998 06 25 , 22:33	F+
38	1998 07 10 , 22:36	1998 07 10 , 22:36	1998 07 12 , 21:34	F+
39	1998 08 19 , 18:40	1998 08 20 , 08:38	1998 08 21 , 20:09	F+
40	1998 10 18 , 19:30	1998 10 19 , 04:19	1998 10 20 , 07:11	F+
41	1999 02 11 , 17:41	1999 02 11 , 17:41	1999 02 12 , 03:35	Fr
42	1999 07 02 , 00:27	1999 07 03 , 08:09	1999 07 05 , 13:13	Fr
43	1999 09 21 , 18:57	1999 09 21 , 18:57	1999 09 22 , 11:31	Fr
44	2000 02 11 , 23:34	2000 02 12 , 12:20	2000 02 13 , 00:35	Fr
45	2000 02 20 , 21:03	2000 02 21 , 14:24	2000 02 22 , 13:16	Fr
46	2000 03 01 , 01:58	2000 03 01 , 03:21	2000 03 02 , 03:07	Fr
47	2000 07 01 , 07:12	2000 07 01 , 07:12	2000 07 02 , 03:34	Fr
48	2000 07 11 , 22:35	2000 07 11 , 22:35	2000 07 13 , 04:33	Fr
49	2000 07 28 , 06:38	2000 07 28 , 14:24	2000 07 29 , 10:06	F+
50	2000 09 02 , 23:16	2000 09 02 , 23:16	2000 09 03 , 22:32	Fr
51	2000 10 03 , 01:02	2000 10 03 , 09:36	2000 10 05 , 03:34	F+
52	2000 10 12 , 22:33	2000 10 13 , 18:24	2000 10 14 , 19:12	Fr
53	2000 11 06 , 09:30	2000 11 06 , 23:05	2000 11 07 , 18:05	Fr
54	2000 11 26 , 11:43	2000 11 27 , 09:30	2000 11 28 , 09:36	Fr
55	2001 04 21 , 15:29	2001 04 22 , 00:28	2001 04 23 , 01:11	Fr
56	2001 10 21 , 16:39	2001 10 22 , 01:17	2001 10 23 , 00:47	Fr
57	2001 11 24 , 05:51	2001 11 24 , 15:47	2001 11 25 , 13:17	Fr
58	2001 12 29 , 05:16	2001 12 30 , 03:24	2001 12 30 , 19:10	Fr
59	2002 02 28 , 05:06	2002 02 28 , 19:11	2002 03 01 , 23:15	Fr
60	2002 03 18 , 13:14	2002 03 19 , 06:14	2002 03 20 , 15:36	Fr
61	2002 03 23 , 11:24	2002 03 24 , 13:11	2002 03 25 , 21:36	Fr
62	2002 04 17 , 11:01	2002 04 17 , 21:36	2002 04 19 , 08:22	F+
63	2002 07 17 , 15:56	2002 07 18 , 13:26	2002 07 19 , 09:35	Fr
64	2002 08 18 , 18:40	2002 08 19 , 19:12	2002 08 21 , 13:25	Fr
65	2002 08 26 , 11:16	2002 08 26 , 14:23	2002 08 27 , 10:47	Fr
66	2002 09 30 , 07:54	2002 09 30 , 22:04	2002 10 01 , 20:08	F+
67	2002 12 21 , 03:21	2002 12 21 , 10:20	2002 12 22 , 15:36	Fr
68	2003 01 26 , 21:43	2003 01 27 , 01:40	2003 01 27 , 16:04	Fr
69	2003 02 01 , 13:06	2003 02 02 , 19:11	2003 02 03 , 09:35	Fr
70	2003 03 20 , 04:30	2003 03 20 , 11:54	2003 03 20 , 22:22	Fr

A.2. TABLES FOR CHAPTER 03:

CME event number	CME Arrival date and time [UT] (1AU)	MC start date and time [UT]	MC end date and time [UT]	Flux rope type
71	2003 06 16 , 22:33	2003 06 16 , 17:48	2003 06 18 , 08:18	Fr
72	2003 08 04 , 20:23	2003 08 05 , 01:10	2003 08 06 , 02:23	Fr
73	2003 11 20 , 08:35	2003 11 20 , 11:31	2003 11 21 , 01:40	Fr
74	2004 04 03 , 09:55	2004 04 04 , 01:11	2004 04 05 , 19:11	F+
75	2004 09 17 , 20:52	2004 09 18 , 12:28	2004 09 19 , 16:58	Fr
76	2005 05 15 , 02:10	2005 05 15 , 05:31	2005 05 16 , 22:47	F+
77	2005 05 20 , 04:47	2005 05 20 , 09:35	2005 05 22 , 02:23	F+
78	2005 07 17 , 14:52	2005 07 17 , 14:52	2005 07 18 , 05:59	Fr
79	2005 10 31 , 02:23	2005 10 31 , 02:23	2005 10 31 , 18:42	Fr
80	2006 02 05 , 18:14	2006 02 05 , 20:23	2006 02 06 , 11:59	F+
81	2006 09 30 , 02:52	2006 09 30 , 08:23	2006 09 30 , 22:03	F+
82	2006 11 18 , 07:11	2006 11 18 , 07:11	2006 11 20 , 04:47	Fr
83	2007 05 21 , 22:40	2007 05 21 , 22:45	2007 05 22 , 13:25	Fr
84	2007 06 08 , 05:45	2007 06 08 , 05:45	2007 06 09 , 05:15	Fr
85	2007 11 19 , 17:22	2007 11 20 , 00:33	2007 11 20 , 11:31	Fr
86	2008 05 23 , 01:12	2008 05 23 , 01:12	2008 05 23 , 10:46	F+
87	2008 09 03 , 16:33	2008 09 03 , 16:33	2008 09 04 , 03:49	F+
88	2008 09 17 , 00:43	2008 09 17 , 03:57	2008 09 18 , 08:09	Fr
89	2008 12 04 , 11:59	2008 12 04 , 16:47	2008 12 05 , 10:47	Fr
90	2008 12 17 , 03:35	2008 12 17 , 03:35	2008 12 17 , 15:35	Fr
91	2009 02 03 , 19:21	2009 02 03 , 01:12	2009 02 04 , 19:40	F+
92	2009 03 11 , 22:04	2009 03 12 , 01:12	2009 03 13 , 01:40	F+
93	2009 04 22 , 11:16	2009 04 22 , 14:09	2009 04 22 , 20:37	Fr
94	2009 06 03 , 13:40	2009 06 03 , 20:52	2009 06 05 , 05:31	Fr
95	2009 06 27 , 11:02	2009 06 27 , 17:59	2009 06 28 , 20:24	F+
96	2009 07 21 , 02:53	2009 07 21 , 04:48	2009 07 22 , 03:36	Fr
97	2009 09 10 , 10:19	2009 09 10 , 10:19	2009 09 10 , 19:26	Fr
98	2009 09 30 , 00:44	2009 09 30 , 06:59	2009 09 30 , 19:11	Fr
99	2009 10 29 , 01:26	2009 10 29 , 01:26	2009 10 29 , 23:45	F+
100	2009 11 14 , 10:47	2009 11 14 , 10:47	2009 11 15 , 11:45	Fr
101	2009 12 12 , 04:47	2009 12 12 , 19:26	2009 12 14 , 04:47	Fr
102	2010 01 01 , 22:04	2010 01 02 , 00:14	2010 01 03 , 09:06	Fr
103	2010 02 07 , 18:04	2010 02 07 , 19:11	2010 02 09 , 05:42	Fr
104*	2010 03 23 , 22:29	2010 03 23 , 22:23	2010 03 24 , 15:36	Fr
105*	2010 04 05 , 07:55	2010 04 05 , 11:59	2010 04 06 , 16:48	Fr
106*	2010 04 11 , 12:20	2010 04 11 , 21:36	2010 04 12 , 14:12	Fr
107	2010 05 28 , 01:55	2010 05 29 , 19:12	2010 05 29 , 17:58	Fr
108*	2010 06 21 , 03:35	2010 06 21 , 06:28	2010 06 22 , 12:43	Fr
109*	2010 09 15 , 02:24	2010 09 15 , 02:24	2010 09 16 , 11:58	Fr
110*	2010 10 31 , 02:09	2010 10 30 , 05:16	2010 11 01 , 20:38	Fr
111	2010 12 19 , 00:35	2010 12 19 , 22:33	2010 12 20 , 22:14	F+
112	2011 01 24 , 06:43	2011 01 24 , 10:33	2011 01 25 , 22:04	F+
113*	2011 03 29 , 15:12	2011 03 29 , 23:59	2011 04 01 , 14:52	Fr
114	2011 05 28 , 00:14	2011 05 28 , 05:31	2011 05 28 , 22:47	F+
115	2011 06 04 , 20:06	2011 06 05 , 01:12	2011 06 05 , 18:13	Fr

CME event number	CME Arrival date and time [UT] (1AU)	MC start date and time [UT]	MC end date and time [UT]	Flux rope type
116	2011 07 03 , 19:12	2011 07 03 , 19:12	2011 07 04 , 19:12	Fr
117*	2011 09 17 , 02:57	2011 09 17 , 15:35	2011 09 18 , 21:07	Fr
118	2012 02 14 , 07:11	2012 02 14 , 20:52	2012 02 16 , 04:47	Fr
119	2012 04 05 , 14:23	2012 04 05 , 19:41	2012 04 06 , 21:36	Fr
120	2012 05 03 , 00:59	2012 05 04 , 03:36	2012 05 05 , 11:22	Fr
121	2012 05 16 , 12:28	2012 05 16 , 16:04	2012 05 18 , 02:11	Fr
122	2012 06 11 , 02:52	2012 06 11 , 11:31	2012 06 12 , 05:16	Fr
123*	2012 06 16 , 09:03	2012 06 16 , 22:01	2012 06 17 , 11:23	F+
124*	2012 07 14 , 17:39	2012 07 15 , 06:14	2012 07 17 , 03:22	Fr
125	2012 08 12 , 12:37	2012 08 12 , 19:12	2012 08 13 , 05:01	Fr
126	2012 08 18 , 03:25	2012 08 18 , 19:12	2012 08 19 , 08:22	Fr
127*	2012 10 08 , 04:12	2012 10 08 , 15:50	2012 10 09 , 17:17	Fr
128	2012 10 12 , 08:09	2012 10 12 , 18:09	2012 10 13 , 09:14	Fr
129*	2012 10 31 , 14:28	2012 10 31 , 23:35	2012 11 02 , 05:21	F+
130*	2013 03 17 , 05:21	2013 03 17 , 14:09	2013 03 19 , 16:04	Fr
131*	2013 04 13 , 22:13	2013 04 14 , 17:02	2013 04 17 , 05:30	F+
132	2013 04 30 , 08:52	2013 04 30 , 12:00	2013 05 01 , 07:12	Fr
133	2013 05 14 , 02:23	2013 05 14 , 06:00	2013 05 15 , 06:28	Fr
134	2013 06 06 , 02:09	2013 06 06 , 14:23	2013 06 08 , 00:00	F+
135	2013 06 27 , 13:51	2013 06 28 , 02:23	2013 06 29 , 11:59	Fr
136	2013 09 01 , 06:14	2013 09 01 , 13:55	2013 09 02 , 01:56	Fr
137	2013 10 30 , 18:14	2013 10 30 , 18:14	2013 10 31 , 05:30	Fr
138	2013 11 08 , 21:07	2013 11 08 , 23:59	2013 11 09 , 06:14	Fr
139	2013 11 23 , 00:14	2013 11 23 , 04:47	2013 11 23 , 15:35	Fr
140	2013 12 14 , 16:47	2013 12 15 , 16:47	2013 12 16 , 05:30	Fr
141	2013 12 24 , 20:36	2013 12 25 , 04:47	2013 12 25 , 17:59	F+
142	2014 04 05 , 09:58	2014 04 05 , 22:18	2014 04 07 , 14:24	Fr
143	2014 04 11 , 06:57	2014 04 11 , 06:57	2014 04 12 , 20:52	F+
144	2014 04 14 , 10:20	2014 04 21 , 07:41	2014 04 22 , 06:12	Fr
145	2014 04 29 , 19:11	2014 04 29 , 19:11	2014 04 30 , 16:33	Fr
146	2014 06 29 , 04:47	2014 06 29 , 20:53	2014 06 30 , 11:15	Fr
147	2014 08 19 , 05:49	2014 08 19 , 17:59	2014 08 21 , 19:09	F+
148	2014 08 26 , 02:40	2014 08 27 , 03:07	2014 08 27 , 21:49	Fr
149	2015 01 07 , 05:38	2015 01 07 , 06:28	2015 01 07 , 21:07	F+
150	2015 09 07 , 13:05	2015 09 07 , 23:31	2015 09 09 , 14:52	F+
151	2015 10 06 , 21:35	2015 10 06 , 21:35	2015 10 07 , 10:03	Fr
152	2015 12 19 , 15:35	2015 12 20 , 13:40	2015 12 21 , 23:02	Fr

A.2.2 List of C_x , C_p , and C_r for all Events in our Sample

Table A.4: C_x (Equation 3.12), C_p (Equation 3.13), and C_r (Equation 3.15) for all events in Chapter 3. The 14 events marked with and asterisk (*) coincide with the near-Earth counterparts of 14 CMEs listed in [Sachdeva et al. \(2017\)](#).

CME event number	Using BG1			Using BG2		
	C_x	C_p	C_r	C_x	C_p	C_r
1	2.11	6.85	1.78	28.08	6.89	3.34
2	24.93	3.23	0.52	5.71	0.91	2.95
3	6.35	1.82	3.47	7.62	1.42	4.16
4	9.36	2.68	2.29	19.19	6.56	8.23
5	11.35	4.14	7.55	7.09	4.42	2.52
6	69.85	16.07	15.37	42.55	11.20	7.23
7	0.49	1.65	-0.20	5.68	1.80	0.26
8	4.79	1.74	3.22	4.94	1.82	10.74
9	1.16	1.62	0.29	13.06	2.55	18.30
10	7.35	2.63	2.17	13.03	4.78	4.13
11	5.65	2.90	5.80	10.37	7.06	4.82
12	6.53	1.70	2.36	5.08	1.72	4.80
13	8.77	1.96	1.70	7.80	2.34	2.38
14	18.79	4.08	18.01	40.73	8.69	8.38
15	5.62	7.52	7.08	13.68	5.35	1.06
16	3.94	12.08	3.48	15.62	7.96	9.40
17	83.94	24.15	1.88	32.90	7.72	2.01
18	4.69	2.14	24.73	4.06	1.74	4.50
19	37.80	4.98	11.83	22.26	4.01	30.68
20	11.57	3.84	15.12	11.57	3.84	15.12
21	13.06	3.61	9.08	12.89	5.15	4.86
22	7.01	6.34	10.06	34.91	5.75	12.53
23	7.07	1.35	4.12	7.63	1.41	4.87
24	7.87	10.35	9.93	18.73	10.51	2.35
25	4.23	7.82	15.08	7.60	4.65	13.96
26	20.23	2.32	10.74	2.24	0.15	0.30
27	10.62	2.78	35.34	11.12	2.89	30.14
28	21.81	8.47	3.23	15.95	3.71	4.32
29	46.27	8.62	1.95	21.75	5.84	1.66
30	30.85	14.60	4.16	21.60	5.63	7.22
31	34.43	8.88	21.85	17.12	6.18	4.05
32	10.44	1.60	1.57	15.60	2.73	3.71
33	17.38	4.91	1.03	5.52	2.27	4.65
34	1.06	1.06	0.01	0.96	1.10	-0.03
35	8.15	4.37	0.16	3.41	1.18	0.31

CME event number	Using BG1			Using BG2		
	C_x	C_p	C_r	C_x	C_p	C_r
36	2.88	3.05	2.15	13.91	3.07	4.65
37	1.97	4.01	1.72	5.76	1.66	1.07
38	40.72	6.69	50.49	16.17	2.24	6.40
39	11.18	3.60	3.26	20.53	6.48	9.92
40	17.51	6.37	6.66	42.52	5.20	14.20
41	10.79	8.44	7.76	4.74	5.71	1.43
42	29.70	0.82	1.15	17.42	0.67	1.63
43	1.56	3.52	3.96	4.12	2.98	9.42
44	1.94	5.38	2.80	9.30	1.81	1.30
45	38.53	4.29	19.14	23.95	3.40	12.96
46	19.02	2.69	1.07	18.73	2.68	1.20
47	1.18	2.83	0.69	3.79	1.74	1.85
48	5.04	2.35	1.77	3.55	0.23	1.52
49	10.12	4.39	1.01	9.48	5.30	1.04
50	10.11	1.36	0.32	4.08	0.63	0.69
51	17.47	6.91	6.55	10.04	4.95	9.27
52	5.09	2.81	2.33	17.54	3.37	4.06
53	31.83	18.57	3.61	87.69	5.66	14.80
54	8.37	3.36	0.16	7.67	1.71	0.33
55	18.96	6.35	9.46	28.15	8.26	24.59
56	1.77	3.58	0.04	1.68	3.50	0.04
57	189.13	7.05	1.40	177.90	4.06	2.15
58	42.62	5.95	60.55	17.51	4.67	32.86
59	4.05	2.04	1.65	4.75	2.29	1.35
60	133.84	5.51	22.01	93.76	6.20	19.50
61	41.65	3.89	47.33	84.49	5.60	34.64
62	44.67	2.48	3.51	38.32	2.01	3.27
63	116.44	3.04	13.85	49.05	1.29	68.57
64	18.86	0.81	1.25	21.38	1.94	3.73
65	3.16	4.67	1.05	1.44	3.45	0.17
66	17.37	10.03	11.50	5.07	3.36	3.74
67	5.90	1.86	1.95	4.66	1.58	0.57
68	48.21	1.64	0.86	34.78	1.71	1.43
69	6.77	0.85	1.05	9.15	1.76	0.24
70	41.44	1.56	13.90	39.08	1.57	8.93
71	55.44	7.18	9.34	7.72	1.48	5.16
72	7.63	2.71	0.04	4.49	3.29	0.32
73	299.67	35.64	12.01	211.51	38.28	8.27
74	42.12	8.24	27.90	27.12	6.92	9.22
75	2.31	0.88	0.06	1.46	0.65	0.06

CME event number	Using BG1			Using BG2		
	C_x	C_p	C_r	C_x	C_p	C_r
76	228.01	19.54	2.54	252.44	21.85	2.32
77	10.97	1.75	1.43	19.42	3.18	5.24
78	23.28	9.95	4.86	11.68	5.32	2.52
79	14.42	6.83	14.05	6.63	3.75	3.17
80	7.29	2.46	5.57	5.97	2.35	8.63
81	44.21	18.40	2.87	15.35	13.98	1.49
82	7.80	1.88	13.10	58.77	2.01	21.42
83	42.13	6.85	0.85	23.76	6.67	3.49
84	23.96	6.14	12.48	7.88	2.81	7.85
85	78.21	18.09	3.95	58.24	12.72	3.60
86	1.28	1.33	0.36	18.99	1.31	1.76
87	20.65	7.36	0.59	6.09	1.44	0.86
88	21.97	2.14	0.54	22.01	2.17	0.55
89	21.43	5.62	1.03	7.17	0.76	1.26
90	57.20	4.35	61.71	22.71	1.63	34.01
91	29.19	8.97	7.29	15.22	12.15	6.30
92	57.55	11.76	15.98	19.02	9.73	8.38
93	0.97	0.78	-0.03	14.13	1.14	6.47
94	6.72	1.89	10.43	6.07	1.98	7.64
95	33.10	5.15	4.08	25.83	5.18	16.91
96	6.92	10.10	15.12	4.12	1.47	6.78
97	11.24	2.23	1.89	5.50	1.99	18.23
98	10.49	4.64	1.25	14.59	7.01	6.45
99	27.84	4.77	7.78	14.93	3.98	16.30
100	10.48	4.28	3.07	3.28	1.14	2.29
101	1.46	2.77	0.60	3.10	2.57	8.72
102	6.34	6.97	32.60	6.36	2.70	20.34
103	31.52	3.03	3.42	16.72	1.49	9.87
104*	5.15	2.46	2.26	4.14	1.86	4.52
105*	3.47	1.65	1.09	36.34	1.73	1.87
106	23.62	8.48	4.92	13.53	7.17	4.01
107	33.93	10.58	9.87	61.34	12.83	17.35
108*	8.41	0.55	0.63	18.10	2.63	12.23
109*	2.37	4.20	2.52	3.67	0.81	2.84
110*	2.31	5.31	0.60	10.17	2.49	6.58
111	21.07	2.83	0.56	14.96	2.90	4.01
112	8.28	2.65	0.38	6.80	2.51	6.06
113*	7.09	6.40	33.30	62.10	6.70	175.26
114	16.49	3.59	0.86	11.06	1.29	1.73
115	6.90	11.13	1.70	28.72	11.68	0.80

CME event number	Using BG1			Using BG2		
	C_x	C_p	C_r	C_x	C_p	C_r
116	16.61	1.60	11.74	12.66	1.26	16.99
117*	66.65	3.93	24.50	59.62	4.27	17.83
118	17.09	3.08	10.92	6.30	0.98	7.28
119	2.25	3.47	10.35	2.99	1.69	9.29
120	7.82	1.81	6.17	6.61	1.83	3.14
121	3.01	6.54	2.01	17.14	2.84	10.32
122	95.55	4.59	0.56	31.61	3.10	24.51
123*	8.68	56.12	5.93	84.04	60.46	2.50
124	314.97	20.82	8.30	220.67	13.09	6.22
125	14.69	3.44	5.16	14.44	3.35	4.52
126	1.98	4.34	0.89	25.11	9.73	4.38
127*	27.89	4.23	10.20	17.13	3.38	8.68
128	63.11	3.40	18.11	57.82	2.83	13.88
129*	8.10	8.64	8.01	17.45	4.46	4.86
130*	35.51	2.26	3.64	39.95	2.62	3.29
131*	3.88	1.92	4.45	45.50	2.71	21.16
132	2.64	9.18	0.68	6.94	2.07	4.54
133	10.42	4.57	0.80	3.57	1.68	3.15
134	60.52	7.87	3.75	60.83	8.14	4.25
135	70.57	11.85	6.38	60.93	10.70	30.87
136	26.59	1.30	1.46	11.22	0.47	2.26
137	3.24	4.63	2.49	4.56	1.05	5.80
138	2.72	6.16	0.94	11.38	6.84	4.85
139	19.44	3.57	6.46	17.86	4.86	4.74
140	167.01	6.27	2.72	17.32	0.33	4.11
141	24.61	7.93	8.90	18.73	6.53	9.87
142	12.24	4.65	2.51	17.41	5.81	1.91
143	1.68	4.68	1.88	13.04	4.24	5.25
144	2.58	2.19	0.02	0.84	0.72	-0.05
145	11.09	5.61	1.37	8.38	5.30	6.93
146	9.25	4.18	7.89	3.90	1.55	3.03
147	69.95	12.32	54.23	17.57	4.58	8.12
148	16.97	7.82	8.60	18.11	14.99	6.20
149	8.60	2.94	1.68	4.33	2.82	2.16
150	11.09	5.12	6.40	7.57	2.83	4.65
151	6.06	8.26	1.38	3.61	6.24	2.08
152	10.81	5.11	2.08	12.09	9.06	5.98

A.3 Tables for Chapter 04:

A.3.1 List of $\langle \delta n_p/n_p \rangle_{MC}$, and $\langle \delta B/B \rangle_{MC}$ for all Events in our Sample

Table A.5: The list of $\langle \delta n_p/n_p \rangle_{MC}$ and $\langle \delta B/B \rangle_{MC}$ using both the time windows ($t_{\text{box}} = 40$ and 60 mins) for all events in Chapter 4. The 14 events marked with and asterisk (*) coincide with the near-Earth counterparts of 14 CMEs listed in [Sachdeva et al. \(2017\)](#).

CME event number	Using $t_{\text{box}} = 40$ mins		Using $t_{\text{box}} = 60$ mins	
	$\langle \delta n_p/n_p \rangle_{MC}$	$\langle \delta B/B \rangle_{MC}$	$\langle \delta n_p/n_p \rangle_{MC}$	$\langle \delta B/B \rangle_{MC}$
1	0.186	0.064	0.214	0.082
2	0.125	0.022	0.133	0.028
3	0.159	0.043	0.186	0.053
4	0.201	0.034	0.248	0.043
5	0.112	0.066	0.133	0.086
6	0.218	0.033	0.270	0.041
7	0.169	0.092	0.207	0.112
8	0.128	0.114	0.154	0.146
9	0.101	0.053	0.108	0.140
10	0.110	0.085	0.125	0.101
11	0.112	0.084	0.127	0.094
12	0.061	0.053	0.071	0.060
13	0.160	0.024	0.198	0.029
14	0.311	0.087	0.392	0.095
15	0.273	0.142	0.296	0.153
16	0.142	0.063	0.158	0.070
17	0.272	0.120	0.314	0.131
18	0.191	0.087	0.232	0.104
19	0.371	0.035	0.423	0.040
20	0.101	0.029	0.108	0.036
21	0.169	0.042	0.183	0.052
22	0.243	0.017	0.298	0.022
23	0.118	0.047	0.131	0.060
24	0.216	0.051	0.253	0.059
25	0.124	0.025	0.134	0.029
26	0.161	0.024	0.179	0.029
27	0.167	0.035	0.191	0.041
28	0.362	0.048	0.419	0.062
29	0.263	0.048	0.285	0.064
30	0.172	0.047	0.197	0.055

CME event number	Using $t_{\text{box}} = 40$ mins		Using $t_{\text{box}} = 60$ mins	
	$\langle \delta n_p / n_p \rangle_{MC}$	$\langle \delta B / B \rangle_{MC}$	$\langle \delta n_p / n_p \rangle_{MC}$	$\langle \delta B / B \rangle_{MC}$
31	0.221	0.015	0.240	0.019
32	0.124	0.040	0.142	0.048
33	0.155	0.043	0.179	0.051
34	0.105	0.047	0.115	0.059
35	0.374	0.057	0.415	0.071
36	0.109	0.061	0.126	0.082
37	0.210	0.046	0.254	0.058
38	0.166	0.071	0.187	0.093
39	0.143	0.035	0.155	0.046
40	0.283	0.038	0.347	0.048
41	0.214	0.110	0.272	0.149
42	0.932	0.021	1.066	0.025
43	0.121	0.044	0.133	0.052
44	0.238	0.080	0.247	0.091
45	0.323	0.028	0.360	0.033
46	0.194	0.054	0.212	0.062
47	0.127	0.047	0.146	0.054
48	0.529	0.041	0.566	0.051
49	0.213	0.041	0.242	0.049
50	0.164	0.044	0.183	0.055
51	0.139	0.035	0.160	0.045
52	0.214	0.027	0.245	0.031
53	0.260	0.025	0.315	0.036
54	0.210	0.094	0.252	0.101
55	0.132	0.031	0.152	0.043
56	0.152	0.066	0.166	0.077
57	0.531	0.050	0.607	0.065
58	0.235	0.042	0.265	0.052
59	0.160	0.049	0.179	0.061
60	0.357	0.055	0.438	0.068
61	0.236	0.031	0.291	0.039
62	0.314	0.035	0.395	0.042
63	1.488	0.044	1.770	0.049
64	0.198	0.040	0.229	0.054
65	0.086	0.045	0.096	0.058
66	0.160	0.041	0.195	0.056
67	0.140	0.043	0.166	0.058
68	0.387	0.022	0.402	0.028
69	0.131	0.032	0.142	0.041
70	0.499	0.027	0.586	0.031
71	0.197	0.071	0.219	0.096
72	0.099	0.041	0.103	0.052
73	0.540	0.089	0.678	0.114
74	0.198	0.021	0.227	0.029
75	0.098	0.025	0.107	0.031

CME event number	Using $t_{\text{box}} = 40$ mins		Using $t_{\text{box}} = 60$ mins	
	$\langle \delta n_p / n_p \rangle_{MC}$	$\langle \delta B / B \rangle_{MC}$	$\langle \delta n_p / n_p \rangle_{MC}$	$\langle \delta B / B \rangle_{MC}$
76	0.313	0.038	0.337	0.055
77	0.217	0.058	0.255	0.072
78	0.232	0.073	0.275	0.086
79	0.173	0.066	0.204	0.086
80	0.176	0.048	0.205	0.060
81	0.210	0.043	0.251	0.053
82	0.208	0.022	0.242	0.027
83	0.220	0.047	0.263	0.059
84	0.104	0.037	0.129	0.047
85	0.272	0.026	0.338	0.036
86	0.840	0.028	1.047	0.035
87	0.246	0.049	0.282	0.057
88	0.170	0.027	0.183	0.037
89	0.490	0.037	0.572	0.046
90	0.380	0.036	0.482	0.043
91	0.272	0.050	0.320	0.058
92	0.370	0.041	0.462	0.052
93	0.072	0.065	0.076	0.084
94	0.226	0.040	0.266	0.047
95	0.382	0.063	0.433	0.072
96	0.153	0.066	0.205	0.087
97	0.119	0.069	0.151	0.084
98	0.163	0.059	0.170	0.075
99	0.199	0.065	0.230	0.083
100	0.195	0.038	0.240	0.047
101	0.178	0.054	0.204	0.064
102	0.252	0.037	0.307	0.046
103	0.262	0.038	0.321	0.049
104*	0.079	0.043	0.099	0.051
105*	0.255	0.042	0.284	0.054
106	0.302	0.044	0.348	0.052
107	0.195	0.022	0.231	0.028
108*	0.182	0.038	0.218	0.046
109*	0.160	0.056	0.186	0.072
110*	0.290	0.041	0.336	0.051
111	0.175	0.050	0.211	0.057
112	0.227	0.048	0.281	0.056
113*	0.343	0.023	0.400	0.028
114	0.247	0.035	0.280	0.043
115	0.404	0.076	0.497	0.093

CME event number	Using $t_{\text{box}} = 40$ mins		Using $t_{\text{box}} = 60$ mins	
	$\langle \delta n_p / n_p \rangle_{MC}$	$\langle \delta B / B \rangle_{MC}$	$\langle \delta n_p / n_p \rangle_{MC}$	$\langle \delta B / B \rangle_{MC}$
116	0.147	0.025	0.157	0.033
117*	0.221	0.044	0.244	0.057
118	0.127	0.026	0.150	0.033
119	0.255	0.038	0.281	0.047
120	0.140	0.027	0.165	0.032
121	0.162	0.032	0.189	0.041
122	0.209	0.031	0.248	0.039
123*	0.257	0.060	0.305	0.083
124	0.476	0.033	0.571	0.047
125	0.128	0.042	0.151	0.050
126	0.249	0.046	0.263	0.053
127*	0.285	0.022	0.338	0.028
128	1.001	0.037	1.212	0.054
129*	0.369	0.029	0.501	0.038
130*	0.206	0.036	0.233	0.0451
131*	0.323	0.029	0.393	0.037
132	0.132	0.027	0.143	0.032
133	0.131	0.047	0.146	0.056
134	0.309	0.045	0.372	0.058
135	0.327	0.032	0.384	0.039
136	0.087	0.043	0.095	0.053
137	0.660	0.039	0.813	0.047
138	0.245	0.083	0.287	0.111
139	0.145	0.067	0.158	0.080
140	0.366	0.043	0.483	0.057
141	0.197	0.043	0.226	0.051
142	0.127	0.029	0.148	0.037
143	0.463	0.024	0.603	0.030
144	0.090	0.030	0.096	0.042
145	0.149	0.053	0.168	0.063
146	0.100	0.039	0.112	0.047
147	0.258	0.031	0.302	0.041
148	0.324	0.037	0.382	0.043
149	0.126	0.051	0.141	0.062
150	0.109	0.034	0.124	0.049
151	0.192	0.069	0.208	0.085
152	0.143	0.041	0.169	0.051

A.3.2 List of $\langle \delta M \rangle_{MC}$ for all Events in our Sample

Table A.6: The list of $\langle \delta M \rangle_{MC}$ (Equation 4.3) using two different polytropic indices ($\gamma = 5/3$ and 1.2) and using both the time windows ($t_{\text{box}} = 40$ and 60 mins) for all events in Chapter 4. The 14 events marked with and asterisk (*) coincide with the near-Earth counterparts of 14 CMEs listed in [Sachdeva et al. \(2017\)](#).

CME event number	$\langle \delta M \rangle_{MC}$ (Using $t_{\text{box}} = 40$ mins)		$\langle \delta M \rangle_{MC}$ (Using $t_{\text{box}} = 60$ mins)	
	using $\gamma = 5/3$	using $\gamma = 1.2$	using $\gamma = 5/3$	using $\gamma = 1.2$
1	0.275	0.324	0.320	0.378
2	0.365	0.430	0.410	0.470
3	0.228	0.268	0.278	0.327
4	0.167	0.197	0.199	0.232
5	0.334	0.394	0.409	0.482
6	0.264	0.311	0.303	0.357
7	0.196	0.231	0.247	0.290
8	0.177	0.209	0.191	0.225
9	0.151	0.177	0.175	0.204
10	0.303	0.356	0.336	0.397
11	0.128	0.150	0.146	0.171
12	0.162	0.191	0.185	0.218
13	0.228	0.269	0.269	0.317
14	0.205	0.241	0.250	0.295
15	0.235	0.277	0.283	0.333
16	0.209	0.246	0.245	0.288
17	0.312	0.367	0.376	0.443
18	0.273	0.320	0.324	0.382
19	0.258	0.304	0.296	0.348
20	0.330	0.389	0.389	0.458
21	0.166	0.196	0.186	0.219
22	0.440	0.518	0.530	0.624
23	0.212	0.249	0.240	0.282
24	0.252	0.296	0.277	0.326
25	0.349	0.411	0.382	0.450
26	0.240	0.282	0.271	0.319
27	0.279	0.328	0.323	0.382
28	0.246	0.290	0.290	0.340
29	0.412	0.486	0.482	0.569
30	0.384	0.452	0.468	0.551
31	0.277	0.326	0.313	0.368
32	0.184	0.216	0.208	0.245
33	0.279	0.327	0.321	0.379
34	0.430	0.506	0.529	0.623
35	0.533	0.628	0.710	0.835

CME event number	$\langle \delta M \rangle_{MC}$ (Using $t_{\text{box}} = 40$ mins)		$\langle \delta M \rangle_{MC}$ (Using $t_{\text{box}} = 60$ mins)	
	using $\gamma = 5/3$	using $\gamma = 1.2$	using $\gamma = 5/3$	using $\gamma = 1.2$
36	0.203	0.239	0.239	0.281
37	0.293	0.344	0.378	0.445
38	0.229	0.269	0.259	0.304
39	0.167	0.196	0.196	0.230
40	0.423	0.533	0.517	0.609
41	0.602	0.709	0.636	0.749
42	0.649	0.765	0.753	0.887
43	0.173	0.204	0.190	0.224
44	0.254	0.299	0.277	0.323
45	0.338	0.397	0.395	0.465
46	0.316	0.372	0.385	0.453
47	0.272	0.321	0.320	0.377
48	0.439	0.517	0.505	0.595
49	0.185	0.217	0.207	0.244
50	0.227	0.267	0.274	0.322
51	0.292	0.344	0.359	0.423
52	0.378	0.445	0.431	0.508
53	0.507	0.597	0.530	0.698
54	0.307	0.361	0.382	0.450
55	0.147	0.173	0.181	0.212
56	1.201	1.414	1.409	1.661
57	0.545	0.642	0.661	0.778
58	0.317	0.374	0.370	0.435
59	0.233	0.274	0.262	0.309
60	0.382	0.450	0.457	0.538
61	0.283	0.333	0.341	0.402
62	0.414	0.488	0.487	0.573
63	1.567	1.848	1.695	1.997
64	0.310	0.365	0.379	0.446
65	1.173	1.383	1.369	1.613
66	0.371	0.437	0.439	0.517
67	0.364	0.429	0.473	0.556
68	0.347	0.408	0.436	0.513
69	0.339	0.401	0.384	0.452
70	0.379	0.446	0.440	0.518
71	0.313	0.369	0.356	0.419
72	0.599	0.706	0.711	0.837
73	0.394	0.463	0.464	0.546
74	0.296	0.349	0.357	0.420
75	0.845	0.996	0.971	1.144

CME event number	$\langle \delta M \rangle_{MC}$ (Using $t_{\text{box}} = 40$ mins)		$\langle \delta M \rangle_{MC}$ (Using $t_{\text{box}} = 60$ mins)	
	using $\gamma = 5/3$	using $\gamma = 1.2$	using $\gamma = 5/3$	using $\gamma = 1.2$
76	0.647	0.762	0.744	0.877
77	0.245	0.289	0.292	0.344
78	0.176	0.207	0.210	0.247
79	0.252	0.297	0.303	0.357
80	0.188	0.221	0.225	0.265
81	0.257	0.302	0.315	0.371
82	0.374	0.441	0.428	0.503
83	0.207	0.243	0.235	0.277
84	0.180	0.213	0.197	0.231
85	0.256	0.301	0.324	0.382
86	0.146	0.172	0.164	0.193
87	0.383	0.450	0.478	0.563
88	0.208	0.244	0.273	0.321
89	0.510	0.601	0.605	0.713
90	0.212	0.249	0.245	0.288
91	0.226	0.262	0.258	0.304
92	0.225	0.264	0.256	0.302
93	0.156	0.184	0.187	0.221
94	0.656	0.773	0.752	0.885
95	0.317	0.373	0.378	0.446
96	0.350	0.411	0.421	0.496
97	0.124	0.146	0.139	0.163
98	0.160	0.188	0.189	0.222
99	0.228	0.267	0.267	0.314
100	0.231	0.273	0.303	0.357
101	0.373	0.439	0.438	0.516
102	0.172	0.203	0.199	0.234
103	0.231	0.273	0.283	0.333
104*	0.216	0.254	0.273	0.321
105*	0.496	0.584	0.635	0.747
106	0.373	0.440	0.426	0.502
107	0.184	0.216	0.216	0.254
108*	0.207	0.244	0.244	0.287
109*	0.188	0.222	0.225	0.265
110*	0.290	0.341	0.329	0.387
111	0.202	0.238	0.242	0.284
112	0.299	0.352	0.374	0.440
113*	0.498	0.586	0.567	0.668
114	0.497	0.585	0.570	0.671
115	0.345	0.408	0.395	0.464

CME event number	$\langle \delta M \rangle_{MC}$ (Using $t_{\text{box}} = 40$ mins)		$\langle \delta M \rangle_{MC}$ (Using $t_{\text{box}} = 60$ mins)	
	using $\gamma = 5/3$	using $\gamma = 1.2$	using $\gamma = 5/3$	using $\gamma = 1.2$
116	0.443	0.521	0.483	0.569
117*	0.380	0.448	0.432	0.508
118	0.232	0.273	0.269	0.316
119	0.329	0.387	0.375	0.442
120	0.224	0.263	0.249	0.294
121	0.239	0.281	0.291	0.342
122	0.283	0.333	0.325	0.383
123*	0.311	0.366	0.386	0.455
124	0.466	0.548	0.561	0.661
125	0.165	0.194	0.181	0.212
126	0.298	0.351	0.332	0.390
127*	0.692	0.815	0.799	0.942
128	0.380	0.448	0.426	0.502
129*	0.218	0.257	0.268	0.315
130*	0.540	0.635	0.632	0.744
131*	0.318	0.374	0.376	0.442
132	0.312	0.368	0.357	0.420
133	0.205	0.241	0.251	0.296
134	0.226	0.266	0.264	0.311
135	0.439	0.517	0.537	0.632
136	0.188	0.221	0.233	0.275
137	0.168	0.198	0.190	0.224
138	0.219	0.257	0.228	0.268
139	0.169	0.199	0.193	0.227
140	0.399	0.470	0.488	0.575
141	0.182	0.214	0.237	0.279
142	0.188	0.222	0.238	0.280
143	0.228	0.268	0.270	0.317
144	2.337	2.754	2.801	3.295
145	0.158	0.185	0.183	0.215
146	0.153	0.180	0.179	0.211
147	0.229	0.270	0.268	0.315
148	0.267	0.315	0.312	0.368
149	1.354	1.595	1.566	1.844
150	0.381	0.449	0.466	0.549
151	0.498	0.587	0.583	0.687
152	1.164	1.372	1.246	1.468

A.3.3 Table of Statistical Outputs

Table A.7: This table displays the statistical outputs (mean, median and most probable value) related to the proton density, total magnetic field, acoustic Mach number fluctuations and the resistivity ratio inside the MC and in the background (see, Chapter 4 and [Bhattacharjee et al. \(2023a\)](#)). $\langle \delta M \rangle_{fB}$ and $\langle \delta M \rangle_{tB}$ represent the acoustic Mach number fluctuations in the MC front and trailing boundary layers respectively.

Parameter	t_{box} (minute)	Mean	Median	Most Probable Value
$\langle \delta n_p / n_p \rangle_{MC}$	40	0.24	0.20	0.13
$\langle \delta n_p / n_p \rangle_{MC}$	60	0.28	0.23	0.16
$\langle \delta n_p / n_p \rangle_{BG}$	40	0.11	0.10	0.08
$\langle \delta n_p / n_p \rangle_{BG}$	60	0.12	0.11	0.09
$\langle \delta B / B \rangle_{MC}$	40	0.044	0.042	0.038
$\langle \delta B / B \rangle_{MC}$	60	0.056	0.052	0.050
$\langle \delta B / B \rangle_{BG}$	40	0.067	0.060	0.059
$\langle \delta B / B \rangle_{BG}$	60	0.074	0.068	0.063
[using $\gamma = 5/3$]				
$\langle \delta M \rangle_{MC}$	40	0.15	0.12	0.09
$\langle \delta M \rangle_{MC}$	60	0.17	0.14	0.10
$\langle \delta M \rangle_{BG}$	40	0.84	0.46	0.12
$\langle \delta M \rangle_{BG}$	60	0.95	0.52	0.14
$\langle \delta M \rangle_{fB}$	10	0.14	0.07	0.05
$\langle \delta M \rangle_{tB}$	10	0.16	0.05	0.04
[using $\gamma = 1.2$]				
$\langle \delta M \rangle_{MC}$	40	0.17	0.14	0.11
$\langle \delta M \rangle_{MC}$	60	0.21	0.16	0.12
$\langle \delta M \rangle_{BG}$	40	0.98	0.54	0.14
$\langle \delta M \rangle_{BG}$	60	1.09	0.60	0.15
$\langle \delta M \rangle_{fB}$	10	0.17	0.08	0.05
$\langle \delta M \rangle_{tB}$	10	0.18	0.06	0.04

A.3. TABLES FOR CHAPTER 04:

Parameter	t_{box} (minute)	Mean	Median	Most Probable Value
[using $L_{max} = L_{MC}$]				
$R_{\eta_{MC}}$	40	7068.20	1258.70	387.10
$R_{\eta_{MC}}$	60	10157.41	1780	490.52
$R_{\eta_{BG}}$	40	1175	0.68	0.04
$R_{\eta_{BG}}$	60	1398.40	0.88	0.06
[using $L_{max} = 10^6 \text{km}$]				
$R_{\eta_{MC}}$	40	37344.12	7218.51	2025.50
$R_{\eta_{MC}}$	60	53545.63	10809.51	2770.22
$R_{\eta_{BG}}$	40	5777.11	4.05	0.32
$R_{\eta_{BG}}$	60	6898.70	4.75	0.52

Bibliography

- O. Alexandrova, C. H. K. Chen, L. Sorriso-Valvo, T. S. Horbury, and S. D. Bale. Solar Wind Turbulence and the Role of Ion Instabilities. *Space Sci. Rev.*, 178 (2-4):101–139, Oct. 2013. doi: 10.1007/s11214-013-0004-8.
- A. Ali and P. Zhu. Effects of plasmoid formation on sawtooth process in a tokamak. *Physics of Plasmas*, 26(5):052518, 2019.
- S. K. Antiochos, C. R. DeVore, and J. A. Klimchuk. A Model for Solar Coronal Mass Ejections. *ApJ*, 510(1):485–493, Jan. 1999. doi: 10.1086/306563.
- K. P. Arunbabu, H. M. Antia, S. R. Dugad, S. K. Gupta, Y. Hayashi, S. Kawakami, P. K. Mohanty, T. Nonaka, A. Oshima, and P. Subramanian. High-rigidity Forbush decreases: due to CMEs or shocks? *A&A*, 555:A139, July 2013. doi: 10.1051/0004-6361/201220830.
- K. P. Arunbabu, H. M. Antia, S. R. Dugad, S. K. Gupta, Y. Hayashi, S. Kawakami, P. K. Mohanty, A. Oshima, and P. Subramanian. How are Forbush decreases related to interplanetary magnetic field enhancements? *A&A*, 580:A41, Aug. 2015. doi: 10.1051/0004-6361/201425115.
- M. J. Aschwanden. *Physics of the Solar Corona. An Introduction with Problems and Solutions (2nd edition)*. 2005.
- W. I. Axford and C. O. Hines. A unifying theory of high-latitude geophysical phenomena and geomagnetic storms. *Canadian Journal of Physics*, 39:1433, Jan. 1961. doi: 10.1139/p61-172.
- B. Bavassano, R. Bruno, and L. W. Klein. Density-temperature correlation in solar wind magnetohydrodynamic fluctuations: A test for nearly incompressible models. *J. Geophys. Res.*, 100(A4):5871–5875, Apr. 1995. doi: 10.1029/94JA02571.
- D. Bhattacharjee, P. Subramanian, V. Bothmer, T. Nieves-Chinchilla, and A. Vourlidas. On Modeling ICME Cross-Sections as Static MHD Columns. *Sol. Phys.*, 297(4):45, Apr. 2022. doi: 10.1007/s11207-022-01982-x.

- D. Bhattacharjee, P. Subramanian, T. Nieves-Chinchilla, and A. Vourlidas. Turbulence and anomalous resistivity inside near-Earth magnetic clouds. *MNRAS*, 518(1):1185–1194, Jan. 2023a. doi: 10.1093/mnras/stac3186.
- D. Bhattacharjee, P. Subramanian, A. Vourlidas, T. Nieves-Chinchilla, N. Thejaswi, and N. Sachdeva. Characterizing the specific energy and pressure in near-Earth magnetic clouds. *A&A*, 669:A153, Jan. 2023b. doi: 10.1051/0004-6361/202243603.
- N. H. Bian, E. P. Kontar, and A. G. Emslie. Suppression of Parallel Transport in Turbulent Magnetized Plasmas and Its Impact on the Non-thermal and Thermal Aspects of Solar Flares. *ApJ*, 824(2):78, June 2016. doi: 10.3847/0004-637X/824/2/78.
- D. Biskamp. *Nonlinear magnetohydrodynamics*. 1993.
- A. Borgazzi, A. Lara, E. Echer, and M. V. Alves. Dynamics of coronal mass ejections in the interplanetary medium. *A&A*, 498(3):885–889, May 2009. doi: 10.1051/0004-6361/200811171.
- J. E. Borovsky. The velocity and magnetic field fluctuations of the solar wind at 1 AU: Statistical analysis of Fourier spectra and correlations with plasma properties. *Journal of Geophysical Research (Space Physics)*, 117(A5):A05104, May 2012. doi: 10.1029/2011JA017499.
- J. E. Borovsky. Perspective: Is Our Understanding of Solar-Wind/Magnetosphere Coupling Satisfactory? *Frontiers in Astronomy and Space Sciences*, 8:5, Feb. 2021. doi: 10.3389/fspas.2021.634073.
- J. E. Borovsky and M. H. Denton. Differences between CME-driven storms and CIR-driven storms. *Journal of Geophysical Research (Space Physics)*, 111(A7):A07S08, July 2006. doi: 10.1029/2005JA011447.
- V. Bothmer and I. A. Daglis. *Space weather: physics and effects*. Springer Science & Business Media, 2007.
- V. Bothmer and R. Schwenn. The structure and origin of magnetic clouds in the solar wind. *Annales Geophysicae*, 16(1):1–24, Jan. 1998. doi: 10.1007/s00585-997-0001-x.
- T. J. M. Boyd and J. J. Sanderson. *The Physics of Plasmas*. 2003a.
- T. J. M. Boyd and J. J. Sanderson. *The Physics of Plasmas*. 2003b.

- R. Bruno and V. Carbone. The Solar Wind as a Turbulence Laboratory. *Living Reviews in Solar Physics*, 10(1):2, May 2013. doi: 10.12942/lrsp-2013-2.
- L. Burlaga, E. Sittler, F. Mariani, and R. Schwenn. Magnetic loop behind an interplanetary shock: Voyager, Helios, and IMP 8 observations. *J. Geophys. Res.*, 86(A8):6673–6684, Aug. 1981. doi: 10.1029/JA086iA08p06673.
- L. F. Burlaga. Magnetic clouds and force-free fields with constant α . *J. Geophys. Res.*, 93(A7):7217–7224, July 1988. doi: 10.1029/JA093iA07p07217.
- J. Candia and E. Roulet. Diffusion and drift of cosmic rays in highly turbulent magnetic fields. *J. Cosmology Astropart. Phys.*, 2004(10):007, Oct. 2004. doi: 10.1088/1475-7516/2004/10/007.
- P. J. Cargill. On the Aerodynamic Drag Force Acting on Interplanetary Coronal Mass Ejections. *Sol. Phys.*, 221(1):135–149, May 2004. doi: 10.1023/B:SOLA.0000033366.10725.a2.
- F. Casse, M. Lemoine, and G. Pelletier. Transport of cosmic rays in chaotic magnetic fields. *Phys. Rev. D*, 65(2):023002, Dec. 2001. doi: 10.1103/PhysRevD.65.023002.
- J. Chen. Theory of prominence eruption and propagation: Interplanetary consequences. *J. Geophys. Res.*, 101(A12):27499–27520, Dec 1996. doi: 10.1029/96JA02644.
- J. Chen. Physics of erupting solar flux ropes: Coronal mass ejections (CMEs)—Recent advances in theory and observation. *Physics of Plasmas*, 24(9):090501, 08 2017. ISSN 1070-664X. doi: 10.1063/1.4993929. URL <https://doi.org/10.1063/1.4993929>.
- J. Chen and D. A. Garren. Interplanetary magnetic clouds: Topology and driving mechanism. *Geophys. Res. Lett.*, 20(21):2319–2322, Nov. 1993. doi: 10.1029/93GL02426.
- J. Chen, R. A. Howard, G. E. Brueckner, R. Santoro, J. Krall, S. E. Paswaters, O. C. St. Cyr, R. Schwenn, P. Lamy, and G. M. Simnett. Evidence of an Erupting Magnetic Flux Rope: LASCO Coronal Mass Ejection of 1997 April 13. *ApJ*, 490(2):L191–L194, Dec. 1997. doi: 10.1086/311029.
- P. F. Chen. Initiation and propagation of coronal mass ejections. *Journal of Astrophysics and Astronomy*, 29(1-2):179–186, Mar. 2008. doi: 10.1007/s12036-008-0023-0.
- P. F. Chen. Coronal Mass Ejections: Models and Their Observational Basis. *Living Reviews in Solar Physics*, 8(1):1, Apr. 2011. doi: 10.12942/lrsp-2011-1.

- A. R. Choudhuri et al. *The physics of fluids and plasmas: an introduction for astrophysicists*. Cambridge University Press, 1998.
- A. Ciaravella, J. C. Raymond, F. Reale, L. Strachan, and G. Peres. 1997 December 12 Helical Coronal Mass Ejection. II. Density, Energy Estimates, and Hydrodynamics. *ApJ*, 557(1):351–365, Aug. 2001. doi: 10.1086/321662.
- C. Cid, M. A. Hidalgo, T. Nieves-Chinchilla, J. Sequeiros, and A. F. Viñas. Plasma and Magnetic Field Inside Magnetic Clouds: a Global Study. *Sol. Phys.*, 207(1): 187–198, May 2002. doi: 10.1023/A:1015542108356.
- J. L. Close, J. M. Pittard, T. W. Hartquist, and S. A. E. G. Falle. Ram pressure stripping of the hot gaseous haloes of galaxies using the k-epsilon sub-grid turbulence model. *MNRAS*, 436(4):3021–3030, Dec. 2013. doi: 10.1093/mnras/stt1788.
- R. C. Colaninno. *Investigation of the Forces that Govern the Three-Dimensional Propagation and Expansion of Coronal Mass Ejections from Sun to Earth*. PhD thesis, George Mason University, Virginia, May 2012.
- F. K. Dagneu, N. Gopalswamy, S. B. Tessema, S. Akiyama, and S. Yashiro. Effect of the Heliospheric State on CME Evolution. *ApJ*, 936(2):122, Sept. 2022. doi: 10.3847/1538-4357/ac8744.
- Dakeyo, Maksimovic, Démoulin, Halekas, and Stevens. Statistical Analysis of the Radial Evolution of the Solar Winds between 0.1 and 1 au, and their Semi-empirical Iso-poly Fluid Modeling. *arXiv e-prints*, art. arXiv:2207.03898, July 2022.
- S. Dasso, M. S. Nakwacki, P. Démoulin, and C. H. Mandrini. Progressive Transformation of a Flux Rope to an ICME. Comparative Analysis Using the Direct and Fitted Expansion Methods. *Sol. Phys.*, 244(1-2):115–137, Aug. 2007. doi: 10.1007/s11207-007-9034-2.
- P. Démoulin and S. Dasso. Causes and consequences of magnetic cloud expansion. *A&A*, 498(2):551–566, May 2009. doi: 10.1051/0004-6361/200810971.
- S. Di Matteo, N. M. Viall, L. Kepko, S. Wallace, C. N. Arge, and P. MacNeice. Helios Observations of Quasiperiodic Density Structures in the Slow Solar Wind at 0.3, 0.4, and 0.6 AU. *Journal of Geophysical Research (Space Physics)*, 124(2): 837–860, Feb. 2019. doi: 10.1029/2018JA026182.
- M. Dryer, S. T. Wu, G. Gislason, S. M. Han, Z. K. Smith, J. F. Wang, D. F. Smart, and M. A. Shea. Magnetohydrodynamic Modelling of Interplanetary Disturbances

- Between the Sun and Earth. *Ap&SS*, 105(1):187–208, Oct. 1984. doi: 10.1007/BF00651218.
- D. Du, P. B. Zuo, and X. X. Zhang. Interplanetary Coronal Mass Ejections Observed by Ulysses Through Its Three Solar Orbits. *Sol. Phys.*, 262(1):171–190, Mar. 2010. doi: 10.1007/s11207-009-9505-8.
- L. Duan, I. Beekman, and M. P. Martín. Direct numerical simulation of hypersonic turbulent boundary layers. Part 3. Effect of Mach number. *Journal of Fluid Mechanics*, 672:245–267, Apr. 2011. doi: 10.1017/S0022112010005902.
- J. A. Eddy. A Nineteenth-century Coronal Transient. *A&A*, 34:235, Aug. 1974.
- C. J. Eyles, G. M. Simnett, M. P. Cooke, B. V. Jackson, A. Buffington, P. P. Hick, N. R. Waltham, J. M. King, P. A. Anderson, and P. E. Holladay. The Solar Mass Ejection Imager (Smei). *Sol. Phys.*, 217(2):319–347, Nov. 2003. doi: 10.1023/B:SOLA.0000006903.75671.49.
- T. V. Falkenberg, B. Vršnak, A. Taktakishvili, D. Odstrcil, P. MacNeice, and M. Hesse. Investigations of the sensitivity of a coronal mass ejection model (enlil) to solar input parameters. *Space Weather*, 8(6), 2010.
- C. J. Farrugia, F. T. Gratton, and R. B. Torbert. Viscous-type processes in the solar wind-magnetosphere interaction. *Space Sci. Rev.*, 95:443–456, Jan. 2001. doi: 10.1023/A:1005288703357.
- C. J. Farrugia, N. Lugaz, B. J. Vasquez, L. B. Wilson, W. Yu, K. Paulson, R. B. Torbert, and F. T. Gratton. A Study of a Magnetic Cloud Propagating Through Large-Amplitude Alfvén Waves. *Journal of Geophysical Research (Space Physics)*, 125(6):e27638, June 2020. doi: 10.1029/2019JA027638.
- H. Feng and J. Wang. Magnetic reconnection as a possible heating mechanism of the local high temperature protons within magnetic clouds. *Science China Earth Sciences*, 57(8):1979–1985, Aug. 2014. doi: 10.1007/s11430-013-4816-x.
- R. J. Forsyth, V. Bothmer, C. Cid, N. U. Crooker, T. S. Horbury, K. Kecskemety, B. Klecker, J. A. Linker, D. Odstrcil, M. J. Reiner, I. G. Richardson, J. Rodriguez-Pacheco, J. M. Schmidt, and R. F. Wimmer-Schweingruber. ICMEs in the Inner Heliosphere: Origin, Evolution and Propagation Effects. Report of Working Group G. *Space Sci. Rev.*, 123(1-3):383–416, Mar. 2006. doi: 10.1007/s11214-006-9022-0.
- J. Giacalone and J. R. Jokipii. The Transport of Cosmic Rays across a Turbulent Magnetic Field. *ApJ*, 520(1):204–214, July 1999. doi: 10.1086/307452.

- M. L. Goldstein, D. A. Roberts, and W. H. Matthaeus. Magnetohydrodynamic Turbulence In The Solar Wind. *ARA&A*, 33:283–326, Jan. 1995. doi: 10.1146/annurev.aa.33.090195.001435.
- S. Good, M. Ala-Lahti, E. Palmerio, E. Kilpua, and A. Osmane. Radial evolution of magnetic field fluctuations in an ICME sheath. In *EGU General Assembly Conference Abstracts*, EGU General Assembly Conference Abstracts, page 13664, May 2020. doi: 10.5194/egusphere-egu2020-13664.
- N. Gopalswamy. Coronal mass ejections and space weather. In *Climate and Weather of the Sun-Earth System (CAWSES): Selected Papers from the 2007 Kyoto Symposium*, pages 77–120, May 2009a.
- N. Gopalswamy. Halo coronal mass ejections and geomagnetic storms. *Earth, Planets and Space*, 61:595–597, May 2009b. doi: 10.1186/BF03352930.
- N. Gopalswamy, P. Mäkelä, S. Akiyama, H. Xie, S. Yashiro, and A. A. Reinard. The Solar Connection of Enhanced Heavy Ion Charge States in the Interplanetary Medium: Implications for the Flux-Rope Structure of CMEs. *Sol. Phys.*, 284(1): 17–46, May 2013. doi: 10.1007/s11207-012-0215-2.
- N. Gopalswamy, S. Akiyama, S. Yashiro, H. Xie, P. Mäkelä, and G. Michalek. Anomalous expansion of coronal mass ejections during solar cycle 24 and its space weather implications. *Geophys. Res. Lett.*, 41(8):2673–2680, Apr. 2014. doi: 10.1002/2014GL059858.
- N. Gopalswamy, S. Yashiro, H. Xie, S. Akiyama, and P. Mäkelä. Properties and geoeffectiveness of magnetic clouds during solar cycles 23 and 24. *Journal of Geophysical Research (Space Physics)*, 120(11):9221–9245, Nov. 2015. doi: 10.1002/2015JA021446.
- J. T. Gosling. Coronal mass ejections: The link between solar and geomagnetic activity. *Physics of Fluids B*, 5(7):2638–2645, July 1993. doi: 10.1063/1.860701.
- A. M. Gulisano, P. Démoulin, S. Dasso, M. E. Ruiz, and E. Marsch. Global and local expansion of magnetic clouds in the inner heliosphere. *A&A*, 509:A39, Jan. 2010. doi: 10.1051/0004-6361/200912375.
- S. Günter, Q. Yu, K. Lackner, A. Bhattacharjee, and Y. Huang. Fast sawtooth reconnection at realistic lundquist numbers. *Plasma Physics and Controlled Fusion*, 57(1):014017, 2014.
- A. Hewish, P. F. Scott, and D. Wills. Interplanetary Scintillation of Small Diameter Radio Sources. *Nature*, 203(4951):1214–1217, Sept. 1964. doi: 10.1038/2031214a0.

- M. A. Hidalgo, C. Cid, A. F. Vinas, and J. Sequeiros. A non-force-free approach to the topology of magnetic clouds in the solar wind. *Journal of Geophysical Research (Space Physics)*, 107(A1):1002, Jan. 2002. doi: 10.1029/2001JA900100.
- Z. Houminer and A. Hewish. Correlation of interplanetary scintillation and spacecraft plasma density measurements. *Planet. Space Sci.*, 22(6):1041–1042, June 1974. doi: 10.1016/0032-0633(74)90173-1.
- R. A. Howard. A Historical Perspective on Coronal Mass Ejections. *Geophysical Monograph Series*, 165:7, Oct. 2006. doi: 10.1029/165GM03.
- R. A. Howard, D. J. Michels, J. Sheeley, N. R., and M. J. Koomen. The observation of a coronal transient directed at Earth. *ApJ*, 263:L101–L104, Dec. 1982. doi: 10.1086/183932.
- R. A. Howard, J. Sheeley, N. R., D. J. Michels, and M. J. Koomen. Coronal mass ejections: 1979-1981. *J. Geophys. Res.*, 90(A9):8173–8192, Sept. 1985. doi: 10.1029/JA090iA09p08173.
- T. A. Howard, D. F. Webb, S. J. Tappin, D. R. Mizuno, and J. C. Johnston. Tracking halo coronal mass ejections from 0-1 AU and space weather forecasting using the Solar Mass Ejection Imager (SMEI). *Journal of Geophysical Research (Space Physics)*, 111(A4):A04105, Apr. 2006. doi: 10.1029/2005JA011349.
- Q. Hu and B. U. Ö. Sonnerup. Reconstruction of magnetic clouds in the solar wind: Orientations and configurations. *Journal of Geophysical Research (Space Physics)*, 107(A7):1142, July 2002. doi: 10.1029/2001JA000293.
- J. D. Huba. *NRL PLASMA FORMULARY Supported by The Office of Naval Research*. Naval Research Laboratory, Washington, DC, 2013. ISBN 9781234126070. URL <http://wwwppd.nrl.navy.mil/nrlformulary/>.
- H. S. Hudson, J. L. Bougeret, and J. Burkepile. Coronal Mass Ejections: Overview of Observations. *Space Sci. Rev.*, 123(1-3):13–30, Mar. 2006. doi: 10.1007/s11214-006-9009-x.
- A. Hundhausen. Coronal Mass Ejections. In K. T. Strong, J. L. R. Saba, B. M. Haisch, and J. T. Schmelz, editors, *The many faces of the sun: a summary of the results from NASA’s Solar Maximum Mission.*, page 143, Jan. 1999.
- A. J. Hundhausen, C. B. Sawyer, L. House, R. M. E. Illing, and W. J. Wagner. Coronal mass ejections observed during the solar maximum mission: Latitude distribution and rate of occurrence. *J. Geophys. Res.*, 89(A5):2639–2646, May 1984. doi: 10.1029/JA089iA05p02639.

- J. S. Hunter. The exponentially weighted moving average. *Journal of Quality Technology*, 18(4):203–210, 1986. doi: 10.1080/00224065.1986.11979014. URL <https://doi.org/10.1080/00224065.1986.11979014>.
- E. Husidic, M. Lazar, H. Fichtner, K. Scherer, and S. Poedts. Transport coefficients enhanced by suprathermal particles in nonequilibrium heliospheric plasmas. *A&A*, 654:A99, Oct. 2021. doi: 10.1051/0004-6361/202141760.
- A. Isavnin, E. K. J. Kilpua, and H. E. J. Koskinen. Grad-Shafranov Reconstruction of Magnetic Clouds: Overview and Improvements. *Sol. Phys.*, 273(1):205–219, Oct. 2011. doi: 10.1007/s11207-011-9845-z.
- C. H. Jackman, M. T. Deland, G. J. Labow, E. L. Fleming, D. K. Weisenstein, M. K. W. Ko, M. Sinnhuber, and J. M. Russell. Neutral atmospheric influences of the solar proton events in October-November 2003. *Journal of Geophysical Research (Space Physics)*, 110(A9):A09S27, Sept. 2005. doi: 10.1029/2004JA010888.
- H. Ji, M. Yamada, S. Hsu, and R. Kulsrud. Experimental Test of the Sweet-Parker Model of Magnetic Reconnection. *Phys. Rev. Lett.*, 80(15):3256–3259, Apr. 1998. doi: 10.1103/PhysRevLett.80.3256.
- L. Jian, C. T. Russell, J. T. Gosling, and J. G. Luhmann. Total Pressure Signature as a Qualitative Indicator of the Impact Parameter during ICME Encounters. In B. Fleck, T. H. Zurbuchen, and H. Lacoste, editors, *Solar Wind 11/SOHO 16, Connecting Sun and Heliosphere*, volume 592 of *ESA Special Publication*, page 731, Sept. 2005.
- M. Jin, W. B. Manchester, B. van der Holst, I. Sokolov, G. Tóth, R. E. Mullinix, A. Taktakishvili, A. Chulaki, and T. I. Gombosi. Data-constrained Coronal Mass Ejections in a Global Magnetohydrodynamics Model. *ApJ*, 834(2):173, Jan. 2017. doi: 10.3847/1538-4357/834/2/173.
- I. S. Kang and L. G. Leal. The drag coefficient for a spherical bubble in a uniform streaming flow. *Physics of Fluids*, 31(2):233–237, Feb. 1988. doi: 10.1063/1.866852.
- R. Keppens, J. Teunissen, C. Xia, and O. Porth. MPI-AMRVAC: a parallel, grid-adaptive PDE toolkit. *arXiv e-prints*, art. arXiv:2004.03275, Apr. 2020.
- E. K. J. Kilpua, S. W. Good, M. Ala-Lahti, A. Osmane, D. Fontaine, L. Hadid, M. Janvier, and E. Yordanova. Statistical analysis of magnetic field fluctuations in CME-driven sheath regions. *Frontiers in Astronomy and Space Sciences*, 7:109, Feb. 2021. doi: 10.3389/fspas.2020.610278.

- L. W. Klein and L. F. Burlaga. Interplanetary magnetic clouds at 1 AU. *J. Geophys. Res.*, 87(A2):613–624, Feb. 1982. doi: 10.1029/JA087iA02p00613.
- B. Kliem and T. Török. Torus Instability. *Phys. Rev. Lett.*, 96(25):255002, June 2006. doi: 10.1103/PhysRevLett.96.255002.
- R. H. Kraichnan. Inertial-Range Spectrum of Hydromagnetic Turbulence. *Physics of Fluids*, 8(7):1385–1387, July 1965. doi: 10.1063/1.1761412.
- R. M. Kulsrud. *Plasma Physics for Astrophysics*. 2005.
- A. Kumar and D. M. Rust. Interplanetary magnetic clouds, helicity conservation, and current-core flux-ropes. *J. Geophys. Res.*, 101(A7):15667–15684, July 1996a. doi: 10.1029/96JA00544.
- A. Kumar and D. M. Rust. Interplanetary magnetic clouds, helicity conservation, and current-core flux-ropes. *J. Geophys. Res.*, 101(A7):15667–15684, Jul 1996b. doi: 10.1029/96JA00544.
- P. K. Kundu and I. M. Cohen. *Fluid Mechanics: Fourth Edition*. 2008.
- L. D. Landau and E. M. Lifshitz. *Fluid Mechanics*. 1987.
- K. R. Lang. *The Cambridge Encyclopedia of the Sun*. 2001.
- R. P. Lepping, J. A. Jones, and L. F. Burlaga. Magnetic field structure of interplanetary magnetic clouds at 1 AU. *J. Geophys. Res.*, 95(A8):11957–11965, Aug. 1990. doi: 10.1029/JA095iA08p11957.
- R. P. Lepping, D. B. Berdichevsky, A. Szabo, C. Arqueros, and A. J. Lazarus. Profile of an Average Magnetic Cloud at 1 au for the Quiet Solar Phase: Wind Observations. *Sol. Phys.*, 212(2):425–444, Feb. 2003. doi: 10.1023/A:1022938903870.
- H. Li, C. Wang, J. D. Richardson, and C. Tu. Evolution of Alfvénic Fluctuations inside an Interplanetary Coronal Mass Ejection and Their Contribution to Local Plasma Heating: Joint Observations from 1.0 to 5.4 au. *ApJ*, 851(1):L2, Dec. 2017. doi: 10.3847/2041-8213/aa9c3f.
- H. Liang, C. Xiao, G. Zhou, Z. Pu, H. Wang, and X. Wang. Alfvénic Fluctuations in an Interplanetary Coronal Mass Ejection Observed Near 1 AU. *Plasma Science and Technology*, 14(2):102–106, Feb. 2012. doi: 10.1088/1009-0630/14/2/04.
- C.-H. Lin and J. Chen. Drag Force on Coronal Mass Ejections (CMEs). *Journal of Geophysical Research (Space Physics)*, 127(6):e28744, June 2022. doi: 10.1029/2020JA028744.

- J. A. Linker, Z. Mikić, D. A. Biesecker, R. J. Forsyth, S. E. Gibson, A. J. Lazarus, A. Lecinski, P. Riley, A. Szabo, and B. J. Thompson. Magnetohydrodynamic modeling of the solar corona during Whole Sun Month. *J. Geophys. Res.*, 104 (A5):9809–9830, May 1999. doi: 10.1029/1998JA900159.
- R. Lionello, C. Downs, J. A. Linker, T. Török, P. Riley, and Z. Mikić. Magnetohydrodynamic Simulations of Interplanetary Coronal Mass Ejections. *ApJ*, 777(1): 76, Nov. 2013. doi: 10.1088/0004-637X/777/1/76.
- Y. Liu, J. D. Richardson, J. W. Belcher, J. C. Kasper, and H. A. Elliott. Thermodynamic structure of collision-dominated expanding plasma: Heating of interplanetary coronal mass ejections. *Journal of Geophysical Research (Space Physics)*, 111(A1):A01102, Jan. 2006. doi: 10.1029/2005JA011329.
- B. C. Low. Solar Activity and the Corona. *Sol. Phys.*, 167(1-2):217–265, Aug. 1996. doi: 10.1007/BF00146338.
- J. M. Lucas and M. S. Saccucci. Exponentially weighted moving average control schemes: Properties and enhancements. *Technometrics*, 32(1):1–12, 1990. doi: 10.1080/00401706.1990.10484583. URL <https://www.tandfonline.com/doi/abs/10.1080/00401706.1990.10484583>.
- N. Lugaz, J. N. Hernandez-Charpak, I. I. Roussev, C. J. Davis, A. Vourlidas, and J. A. Davies. Determining the Azimuthal Properties of Coronal Mass Ejections from Multi-Spacecraft Remote-Sensing Observations with STEREO SECCHI. *ApJ*, 715(1):493–499, May 2010. doi: 10.1088/0004-637X/715/1/493.
- N. Lugaz, C. J. Farrugia, R. M. Winslow, N. Al-Haddad, E. K. J. Kilpua, and P. Riley. Factors affecting the geoeffectiveness of shocks and sheaths at 1 AU. *Journal of Geophysical Research (Space Physics)*, 121(11):10,861–10,879, Nov. 2016. doi: 10.1002/2016JA023100.
- N. Lugaz, C. J. Farrugia, R. M. Winslow, C. R. Small, T. Manion, and N. Savani. Importance of CME Radial Expansion on the Ability of Slow CMEs to Drive Shocks. In *AGU Fall Meeting Abstracts*, volume 2017, pages SH51E–02, Dec. 2017.
- N. Lugaz, T. M. Salman, R. M. Winslow, N. Al-Haddad, C. J. Farrugia, B. Zhuang, and A. B. Galvin. Inconsistencies Between Local and Global Measures of CME Radial Expansion as Revealed by Spacecraft Conjunctions. *ApJ*, 899(2):119, Aug. 2020. doi: 10.3847/1538-4357/aba26b.
- S. Lundquist. On the Stability of Magneto-Hydrostatic Fields. *Physical Review*, 83 (2):307–311, July 1951. doi: 10.1103/PhysRev.83.307.

- B. J. Lynch, W. A. Coles, and N. R. Sheeley. A comparison of mean density and microscale density fluctuations in a CME at $10 R_{\text{solar}}$. *Geophys. Res. Lett.*, 29(19):1913, Oct. 2002. doi: 10.1029/2001GL014152.
- B. J. Lynch, S. K. Antiochos, C. R. DeVore, J. G. Luhmann, and T. H. Zurbuchen. Topological Evolution of a Fast Magnetic Breakout CME in Three Dimensions. *ApJ*, 683(2):1192–1206, Aug. 2008. doi: 10.1086/589738.
- A. Lynnyk, J. Šafránková, Z. Němeček, and J. D. Richardson. Deformation of ICMEs/MCs along their path. *Planet. Space Sci.*, 59(9):840–847, July 2011. doi: 10.1016/j.pss.2011.03.016.
- R. M. MacQueen, J. A. Eddy, J. T. Gosling, E. Hildner, R. H. Munro, J. Newkirk, G. A., A. I. Poland, and C. L. Ross. The Outer Solar Corona as Observed from Skylab: Preliminary Results. *ApJ*, 187:L85, Jan. 1974. doi: 10.1086/181402.
- R. M. MacQueen, A. Csoeke-Poeckh, E. Hildner, L. House, R. Reynolds, A. Stanger, H. Tepoel, and W. Wagner. The High Altitude Observatory coronagraph/polarimeter on the Solar Maximum Mission. *Sol. Phys.*, 65(1):91–107, Feb. 1980. doi: 10.1007/BF00151386.
- S. A. Maloney and P. T. Gallagher. Solar Wind Drag and the Kinematics of Interplanetary Coronal Mass Ejections. *ApJ*, 724(2):L127–L132, Dec. 2010. doi: 10.1088/2041-8205/724/2/L127.
- I. Manchester, Ward B., A. Vourlidas, G. Tóth, N. Lugaz, I. I. Roussev, I. V. Sokolov, T. I. Gombosi, D. L. De Zeeuw, and M. Opher. Three-dimensional MHD Simulation of the 2003 October 28 Coronal Mass Ejection: Comparison with LASCO Coronagraph Observations. *ApJ*, 684(2):1448–1460, Sept. 2008. doi: 10.1086/590231.
- P. K. Manoharan. Evolution of Coronal Mass Ejections in the Inner Heliosphere: A Study Using White-Light and Scintillation Images. *Sol. Phys.*, 235(1-2):345–368, May 2006. doi: 10.1007/s11207-006-0100-y.
- P. K. Manoharan. Ooty Interplanetary Scintillation - Remote-Sensing Observations and Analysis of Coronal Mass Ejections in the Heliosphere. *Sol. Phys.*, 265(1-2):137–157, Aug. 2010. doi: 10.1007/s11207-010-9593-5.
- M. L. Maunder, C. Foullon, R. Forsyth, D. Barnes, and J. Davies. Multi-Spacecraft Observations of an Interplanetary Coronal Mass Ejection Interacting with Two Solar-Wind Regimes Observed by the Ulysses and Twin-STEREO Spacecraft. *Sol. Phys.*, 297(11):148, Nov. 2022. doi: 10.1007/s11207-022-02077-3.

- D. J. Michels, R. A. Howard, M. J. Koomen, and J. Sheeley, N. R. Satellite observations of the outer corona near sunspot maximum. In M. R. Kundu and T. E. Gergely, editors, *Radio Physics of the Sun*, volume 86, pages 439–442, Jan. 1980. doi: 10.1017/S0074180900037190.
- W. Mishra and Y. Wang. Modeling the Thermodynamic Evolution of Coronal Mass Ejections Using Their Kinematics. *ApJ*, 865(1):50, Sept. 2018. doi: 10.3847/1538-4357/aadb9b.
- W. Mishra, U. Doshi, and N. Srivastava. Radial sizes and expansion behavior of ICMEs in solar cycles 23 and 24. *Frontiers in Astronomy and Space Sciences*, 8: 142, Sept. 2021. doi: 10.3389/fspas.2021.713999.
- C. Moestl, A. Weiss, M. Reiss, R. Bailey, U. Amerstorfer, T. Amerstorfer, J. Hinterreiter, M. Bauer, S. W. McIntosh, N. Lugaz, and D. Stansby. Prediction of the In Situ Coronal Mass Ejection Rate for Solar Cycle 25: Implications for Parker Solar Probe In Situ Observations. In *AGU Fall Meeting Abstracts*, volume 2020, pages SH049–0001, Dec. 2020.
- M. B. Moldwin, S. Ford, R. Lepping, J. Slavin, and A. Szabo. Small-scale magnetic flux ropes in the solar wind. *Geophys. Res. Lett.*, 27(1):57–60, Jan. 2000. doi: 10.1029/1999GL010724.
- D. W. Moore. The rise of a gas bubble in a viscous liquid. *Journal of Fluid Mechanics*, 6:113–130, Jan. 1959. doi: 10.1017/S0022112059000520.
- D. W. Moore. The boundary layer on a spherical gas bubble. *Journal of Fluid Mechanics*, 16:161–176, Jan. 1963. doi: 10.1017/S0022112063000665.
- R. L. Moore, A. C. Sterling, H. S. Hudson, and J. R. Lemen. Onset of the Magnetic Explosion in Solar Flares and Coronal Mass Ejections. *ApJ*, 552(2):833–848, May 2001. doi: 10.1086/320559.
- C. Möstl, C. J. Farrugia, H. K. Biernat, M. Leitner, E. K. J. Kilpua, A. B. Galvin, and J. G. Luhmann. Optimized Grad - Shafranov Reconstruction of a Magnetic Cloud Using STEREO- Wind Observations. *Sol. Phys.*, 256(1-2):427–441, May 2009. doi: 10.1007/s11207-009-9360-7.
- C. Möstl, A. J. Weiss, M. A. Reiss, T. Amerstorfer, R. L. Bailey, J. Hinterreiter, M. Bauer, D. Barnes, J. A. Davies, R. A. Harrison, J. L. Freiherr von Forstner, E. E. Davies, D. Heyner, T. Horbury, and S. D. Bale. Multipoint Interplanetary Coronal Mass Ejections Observed with Solar Orbiter, BepiColombo, Parker Solar Probe, Wind, and STEREO-A. *ApJ*, 924(1):L6, Jan. 2022. doi: 10.3847/2041-8213/ac42d0.

- N. A. Murphy, J. C. Raymond, and K. E. Korreck. Plasma Heating During a Coronal Mass Ejection Observed By the Solar and Heliospheric Observatory. *ApJ*, 735(1):17, July 2011. doi: 10.1088/0004-637X/735/1/17.
- G. Nicolaou, G. Livadiotis, R. T. Wicks, D. Verscharen, and B. A. Maruca. Polytropic Behavior of Solar Wind Protons Observed by Parker Solar Probe. *ApJ*, 901(1):26, Sept. 2020. doi: 10.3847/1538-4357/abaaae.
- T. Nieves-Chinchilla and A. F. Viñas. Solar wind electron distribution functions inside magnetic clouds. *Journal of Geophysical Research (Space Physics)*, 113(A2):A02105, Feb. 2008. doi: 10.1029/2007JA012703.
- T. Nieves-Chinchilla, M. G. Linton, M. A. Hidalgo, A. Vourlidas, N. P. Savani, A. Szabo, C. Farrugia, and W. Yu. A Circular-cylindrical Flux-rope Analytical Model for Magnetic Clouds. *ApJ*, 823(1):27, May 2016. doi: 10.3847/0004-637X/823/1/27.
- T. Nieves-Chinchilla, M. G. Linton, M. A. Hidalgo, and A. Vourlidas. Elliptic-cylindrical Analytical Flux Rope Model for Magnetic Clouds. *ApJ*, 861(2):139, July 2018a. doi: 10.3847/1538-4357/aac951.
- T. Nieves-Chinchilla, A. Vourlidas, J. C. Raymond, M. G. Linton, N. Al-haddad, N. P. Savani, A. Szabo, and M. A. Hidalgo. Understanding the Internal Magnetic Field Configurations of ICMEs Using More than 20 Years of Wind Observations. *Sol. Phys.*, 293:25, Feb. 2018b. doi: 10.1007/s11207-018-1247-z.
- T. Nieves-Chinchilla, L. K. Jian, L. Balmaceda, A. Vourlidas, L. F. G. dos Santos, and A. Szabo. Unraveling the Internal Magnetic Field Structure of the Earth-directed Interplanetary Coronal Mass Ejections During 1995 - 2015. *Sol. Phys.*, 294(7):89, July 2019. doi: 10.1007/s11207-019-1477-8.
- T. Nieves-Chinchilla, N. Alzate, H. Cremades, L. Rodríguez-García, L. F. G. Dos Santos, A. Narock, H. Xie, A. Szabo, E. Palmerio, V. Krupar, M. Pulupa, D. Lario, M. L. Stevens, L. B. Wilson, R.-Y. Kwon, M. L. Mays, O. C. St. Cyr, P. Hess, K. K. Reeves, D. B. Seaton, T. Niembro, S. D. Bale, and J. C. Kasper. Direct First Parker Solar Probe Observation of the Interaction of Two Successive Interplanetary Coronal Mass Ejections in 2020 November. *ApJ*, 930(1):88, May 2022. doi: 10.3847/1538-4357/ac590b.
- D. Odstreil and V. J. Pizzo. Numerical Heliospheric Simulations as Assisting Tool for Interpretation of Observations by STEREO Heliospheric Imagers. *Sol. Phys.*, 259(1-2):297–309, Oct. 2009. doi: 10.1007/s11207-009-9449-z.

- V. A. Osherovich, C. J. Farrugia, L. F. Burlaga, R. P. Lepping, J. Fainberg, and R. G. Stone. Polytropic relationship in interplanetary magnetic clouds. *J. Geophys. Res.*, 98(A9):15331–15342, Sept. 1993. doi: 10.1029/93JA01012.
- A. A. Panferov. Jets of ss 433 on scales of dozens of parsecs. *Astronomy & Astrophysics*, 599:A77, 2017.
- E. N. Parker. Hydrodynamics, magnetohydrodynamics, and astrophysical plasmas. In *Climate and Weather of the Sun-Earth System (CAWSES): Selected Papers from the 2007 Kyoto Symposium*, pages 23–40, May 2009.
- J. J. Podesta and J. E. Borovsky. Scale invariance of normalized cross-helicity throughout the inertial range of solar wind turbulence. *Physics of Plasmas*, 17(11):112905, Nov. 2010. doi: 10.1063/1.3505092.
- J. J. Podesta, D. A. Roberts, and M. L. Goldstein. Spectral Exponents of Kinetic and Magnetic Energy Spectra in Solar Wind Turbulence. *ApJ*, 664(1):543–548, July 2007. doi: 10.1086/519211.
- T. Pulkkinen. Space Weather: Terrestrial Perspective. *Living Reviews in Solar Physics*, 4(1):1, May 2007. doi: 10.12942/lrsp-2007-1.
- C. E. Rakowski, J. M. Laming, and S. T. Lepri. Ion Charge States in Halo Coronal Mass Ejections: What Can We Learn about the Explosion? *ApJ*, 667(1):602–609, Sept. 2007. doi: 10.1086/520914.
- I. G. Richardson and H. V. Cane. Near-Earth Interplanetary Coronal Mass Ejections During Solar Cycle 23 (1996 - 2009): Catalog and Summary of Properties. *Sol. Phys.*, 264(1):189–237, June 2010. doi: 10.1007/s11207-010-9568-6.
- I. G. Richardson, C. J. Farrugia, and H. V. Cane. A statistical study of the behavior of the electron temperature in ejecta. *J. Geophys. Res.*, 102(A3):4691–4700, Mar. 1997. doi: 10.1029/96JA04001.
- P. Riley, R. Lionello, Z. Mikić, and J. Linker. Using Global Simulations to Relate the Three-Part Structure of Coronal Mass Ejections to In Situ Signatures. *ApJ*, 672(2):1221–1227, Jan. 2008. doi: 10.1086/523893.
- D. A. Roberts. Evolution of the spectrum of solar wind velocity fluctuations from 0.3 to 5 AU. *Journal of Geophysical Research (Space Physics)*, 115(A12):A12101, Dec. 2010. doi: 10.1029/2009JA015120.
- G. Rohen, C. von Savigny, M. Sinnhuber, E. J. Llewellyn, J. W. Kaiser, C. H. Jackman, M. B. Kallenrode, J. SchröTer, K. U. Eichmann, H. Bovensmann, and J. P.

- Burrows. Ozone depletion during the solar proton events of October/November 2003 as seen by SCIAMACHY. *Journal of Geophysical Research (Space Physics)*, 110(A9):A09S39, Sept. 2005. doi: 10.1029/2004JA010984.
- A. Ruzmaikin, J. Feynman, and E. J. Smith. Turbulence in coronal mass ejections. *J. Geophys. Res.*, 102(A9):19753–19760, Sept. 1997. doi: 10.1029/97JA01558.
- N. Sachdeva, P. Subramanian, R. Colaninno, and A. Vourlidas. CME Propagation: Where does Aerodynamic Drag 'Take Over'? *ApJ*, 809:158, Aug. 2015. doi: 10.1088/0004-637X/809/2/158.
- N. Sachdeva, P. Subramanian, A. Vourlidas, and V. Bothmer. CME Dynamics Using STEREO and LASCO Observations: The Relative Importance of Lorentz Forces and Solar Wind Drag. *Sol. Phys.*, 292:118, Sept. 2017. doi: 10.1007/s11207-017-1137-9.
- C. Salem, A. Mangeney, S. D. Bale, and P. Veltri. Solar Wind Magnetohydrodynamics Turbulence: Anomalous Scaling and Role of Intermittency. *ApJ*, 702(1): 537–553, Sept. 2009. doi: 10.1088/0004-637X/702/1/537.
- R. Schwenn. An Essay on Terminology, Myths and Known Facts: Solar Transient - Flare - CME - Driver Gas - Piston - BDE - Magnetic Cloud - Shock Wave - Geomagnetic Storm. *Ap&SS*, 243(1):187, Mar. 1996. doi: 10.1007/BF00644053.
- C. Scolini, L. Rodriguez, M. Mierla, J. Pomoell, and S. Poedts. Observation-based modelling of magnetised coronal mass ejections with EUHFORIA. *A&A*, 626: A122, June 2019a. doi: 10.1051/0004-6361/201935053.
- C. Scolini, L. Rodriguez, M. Mierla, J. Pomoell, and S. Poedts. Observation-based modelling of magnetised coronal mass ejections with EUHFORIA. *A&A*, 626: A122, June 2019b. doi: 10.1051/0004-6361/201935053.
- C. D. Scott-Pomerantz. The k-epsilon model in the theory of turbulence. 2004.
- M. Sheikholeslami and D. D. Ganji. Chapter 1 - magnetohydrodynamic and ferrohydrodynamic. In M. Sheikholeslami and D. D. Ganji, editors, *External Magnetic Field Effects on Hydrothermal Treatment of Nanofluid*, pages 1–47. William Andrew Publishing, 2016. ISBN 978-0-323-43138-5. doi: <https://doi.org/10.1016/B978-0-323-43138-5.00001-X>. URL <https://www.sciencedirect.com/science/article/pii/B978032343138500001X>.
- A. Smits and J. Dussauge. *Turbulent shear layers in supersonic flow: Second edition*. Springer New York, United States, 2006. ISBN 0387261400. doi: 10.1007/b137383. Copyright: Copyright 2013 Elsevier B.V., All rights reserved.

- H. Song, L. Li, and Y. Chen. Toward a Unified Explanation for the Three-part Structure of Solar Coronal Mass Ejections. *ApJ*, 933(1):68, July 2022. doi: 10.3847/1538-4357/ac7239.
- S. R. Spangler and L. G. Spitler. An empirical investigation of compressibility in magnetohydrodynamic turbulence. *Physics of Plasmas*, 11(5):1969–1977, May 2004. doi: 10.1063/1.1687688.
- O. C. St. Cyr, S. P. Plunkett, D. J. Michels, S. E. Paswaters, M. J. Koomen, G. M. Simnett, B. J. Thompson, J. B. Gurman, R. Schwenn, D. F. Webb, E. Hildner, and P. L. Lamy. Properties of coronal mass ejections: SOHO LASCO observations from January 1996 to June 1998. *J. Geophys. Res.*, 105(A8):18169–18186, Jan. 2000. doi: 10.1029/1999JA000381.
- P. A. Sturrock. The Role of Eruption in Solar Flares. *Sol. Phys.*, 121(1-2):387–397, Mar. 1989. doi: 10.1007/BF00161708.
- P. A. Sturrock. *Plasma Physics, An Introduction to the Theory of Astrophysical, Geophysical and Laboratory Plasmas*. 1994.
- P. Subramanian and A. Vourlidas. Driving Currents for Flux Rope Coronal Mass Ejections. *ApJ*, 693(2):1219–1222, Mar. 2009. doi: 10.1088/0004-637X/693/2/1219.
- P. Subramanian, H. M. Antia, S. R. Dugad, U. D. Goswami, S. K. Gupta, Y. Hayashi, N. Ito, S. Kawakami, H. Kojima, P. K. Mohanty, P. K. Nayak, T. Nonaka, A. Oshima, K. Sivaprasad, H. Tanaka, S. C. Tonwar, and Grapes-3 Collaboration. Forbush decreases and turbulence levels at coronal mass ejection fronts. *A&A*, 494(3):1107–1118, Feb. 2009. doi: 10.1051/0004-6361:200809551.
- P. Subramanian, A. Lara, and A. Borgazzi. Can solar wind viscous drag account for coronal mass ejection deceleration? *GRL*, 39(19):L19107, Oct. 2012. doi: 10.1029/2012GL053625.
- A. Taktakishvili, M. Kuznetsova, P. MacNeice, M. Hesse, L. Rastätter, A. Pulkkinen, A. Chulaki, and D. Odstrcil. Validation of the coronal mass ejection predictions at the earth orbit estimated by enlil heliosphere cone model. *Space Weather*, 7(3), 2009.
- M. Temmer. Space weather: the solar perspective. *Living Reviews in Solar Physics*, 18(1):4, Dec. 2021. doi: 10.1007/s41116-021-00030-3.
- T. Török and B. Kliem. The evolution of twisting coronal magnetic flux tubes. *A&A*, 406:1043–1059, Aug. 2003. doi: 10.1051/0004-6361:20030692.

- G. Tóth, B. van der Holst, I. V. Sokolov, D. L. De Zeeuw, T. I. Gombosi, F. Fang, W. B. Manchester, X. Meng, D. Najib, K. G. Powell, Q. F. Stout, A. Gloer, Y.-J. Ma, and M. Opher. Adaptive numerical algorithms in space weather modeling. *Journal of Computational Physics*, 231(3):870–903, Feb. 2012. doi: 10.1016/j.jcp.2011.02.006.
- R. Tousey. The solar corona. In *Space Research Conference*, volume 2, pages 713–730, Jan. 1973.
- M. Vandas, A. Geranios, and E. Romashets. On expansion of magnetic clouds in the solar wind. *Astrophysics and Space Sciences Transactions*, 5(1):35–38, Aug. 2009. doi: 10.5194/astra-5-35-2009.
- B. J. Vasquez, C. W. Smith, K. Hamilton, B. T. MacBride, and R. J. Leamon. Evaluation of the turbulent energy cascade rates from the upper inertial range in the solar wind at 1 AU. *Journal of Geophysical Research (Space Physics)*, 112(A7):A07101, July 2007. doi: 10.1029/2007JA012305.
- C. Verbeke, B. Schmieder, P. Démoulin, S. Dasso, B. Grison, E. Samara, C. Scolini, and S. Poedts. Over-expansion of coronal mass ejections modelled using 3D MHD EUHFORIA simulations. *Advances in Space Research*, 70(6):1663–1683, Sept. 2022. doi: 10.1016/j.asr.2022.06.013.
- M. K. Verma. Nonclassical viscosity and resistivity of the solar wind plasma. *J. Geophys. Res.*, 101(A12):27543–27548, Dec. 1996. doi: 10.1029/96JA02324.
- M. K. Verma, D. A. Roberts, and M. L. Goldstein. Turbulent heating and temperature evolution in the solar wind plasma. *J. Geophys. Res.*, 100(A10):19839–19850, Oct. 1995. doi: 10.1029/95JA01216.
- R. von Steiger and J. D. Richardson. ICMEs in the Outer Heliosphere and at High Latitudes: An Introduction. *Space Sci. Rev.*, 123(1-3):111–126, Mar. 2006. doi: 10.1007/s11214-006-9015-z.
- B. Vršnak and N. Gopalswamy. Influence of the aerodynamic drag on the motion of interplanetary ejecta. *Journal of Geophysical Research (Space Physics)*, 107(A2):1019, Feb. 2002a. doi: 10.1029/2001JA000120.
- B. Vršnak and N. Gopalswamy. Influence of the aerodynamic drag on the motion of interplanetary ejecta. *Journal of Geophysical Research (Space Physics)*, 107(A2):1019, Feb. 2002b. doi: 10.1029/2001JA000120.
- B. Vršnak, D. Vrbanec, J. Čalogović, and T. Žic. The role of aerodynamic drag in dynamics of coronal mass ejections. In N. Gopalswamy and D. F. Webb, editors,

- Universal Heliophysical Processes*, volume 257 of *IAU Symposium*, pages 271–277, Mar. 2009a. doi: 10.1017/S1743921309029391.
- B. Vršnak, D. Vrbanec, J. Čalogović, and T. Žic. The role of aerodynamic drag in dynamics of coronal mass ejections. In N. Gopalswamy and D. F. Webb, editors, *Universal Heliophysical Processes*, volume 257 of *IAU Symposium*, pages 271–277, Mar. 2009b. doi: 10.1017/S1743921309029391.
- B. Vršnak, T. Žic, T. V. Falkenberg, C. Möstl, S. Vennerstrom, and D. Vrbanec. The role of aerodynamic drag in propagation of interplanetary coronal mass ejections. *A&A*, 512:A43, Mar 2010. doi: 10.1051/0004-6361/200913482.
- B. Vršnak, T. Žic, D. Vrbanec, M. Temmer, T. Rollett, C. Möstl, A. Veronig, J. Čalogović, M. Dumbović, S. Lulić, Y. J. Moon, and A. Shanmugaraju. Propagation of Interplanetary Coronal Mass Ejections: The Drag-Based Model. *Sol. Phys.*, 285(1-2):295–315, Jul 2013a. doi: 10.1007/s11207-012-0035-4.
- B. Vršnak, T. Žic, D. Vrbanec, M. Temmer, T. Rollett, C. Möstl, A. Veronig, J. Čalogović, M. Dumbović, S. Lulić, Y. J. Moon, and A. Shanmugaraju. Propagation of Interplanetary Coronal Mass Ejections: The Drag-Based Model. *Sol. Phys.*, 285(1-2):295–315, Jul 2013b. doi: 10.1007/s11207-012-0035-4.
- B. Vršnak, T. Amerstorfer, M. Dumbović, M. Leitner, A. M. Veronig, M. Temmer, C. Möstl, U. V. Amerstorfer, C. J. Farrugia, and A. B. Galvin. Heliospheric Evolution of Magnetic Clouds. *ApJ*, 877(2):77, June 2019. doi: 10.3847/1538-4357/ab190a.
- C. Wang and J. D. Richardson. Interplanetary coronal mass ejections observed by Voyager 2 between 1 and 30 AU. *Journal of Geophysical Research (Space Physics)*, 109(A6):A06104, June 2004. doi: 10.1029/2004JA010379.
- Y. Wang, F. S. Wei, X. S. Feng, S. H. Zhang, P. B. Zuo, and T. R. Sun. Energetic Electrons Associated with Magnetic Reconnection in the Magnetic Cloud Boundary Layer. *Phys. Rev. Lett.*, 105(19):195007, Nov. 2010. doi: 10.1103/PhysRevLett.105.195007.
- D. F. Webb, D. R. Mizuno, A. Buffington, M. P. Cooke, C. J. Eyles, C. D. Fry, L. C. Gentile, P. P. Hick, P. E. Holladay, T. A. Howard, J. G. Hewitt, B. V. Jackson, J. C. Johnston, T. A. Kuchar, J. B. Mozer, S. Price, R. R. Radick, G. M. Simnett, and S. J. Tappin. Solar Mass Ejection Imager (SMEI) observations of coronal mass ejections (CMEs) in the heliosphere. *Journal of Geophysical Research (Space Physics)*, 111(A12):A12101, Dec. 2006. doi: 10.1029/2006JA011655.

- D. F. Webb, T. A. Howard, C. D. Fry, T. A. Kuchar, D. Odstrcil, B. V. Jackson, M. M. Bisi, R. A. Harrison, J. S. Morrill, R. A. Howard, and J. C. Johnston. Study of CME Propagation in the Inner Heliosphere: SOHO LASCO, SMEI and STEREO HI Observations of the January 2007 Events. *Sol. Phys.*, 256(1-2): 239–267, May 2009. doi: 10.1007/s11207-009-9351-8.
- F. Wei, R. Liu, Q. Fan, and X. Feng. Identification of the magnetic cloud boundary layers. *Journal of Geophysical Research (Space Physics)*, 108(A6):1263, June 2003a. doi: 10.1029/2002JA009511.
- F. Wei, R. Liu, X. Feng, D. Zhong, and F. Yang. Magnetic structures inside boundary layers of magnetic clouds. *Geophys. Res. Lett.*, 30(24):2283, Dec. 2003b. doi: 10.1029/2003GL018116.
- A. Weiss, C. Möstl, T. Nieves-Chinchilla, T. Amerstorfer, E. Palmerio, M. Reiss, R. Bailey, J. Hinterreiter, U. Amerstorfer, and M. Bauer. Modelling coronal mass ejection flux ropes signatures using Approximate Bayesian Computation: applications to Parker Solar Probe. In *EGU General Assembly Conference Abstracts*, EGU General Assembly Conference Abstracts, page 8398, May 2020a. doi: 10.5194/egusphere-egu2020-8398.
- A. Weiss, C. Möstl, T. Nieves-Chinchilla, T. Amerstorfer, E. Palmerio, M. Reiss, R. Bailey, J. Hinterreiter, U. Amerstorfer, and M. Bauer. Modelling coronal mass ejection flux ropes signatures using Approximate Bayesian Computation: applications to Parker Solar Probe. In *EGU General Assembly Conference Abstracts*, EGU General Assembly Conference Abstracts, page 8398, May 2020b. doi: 10.5194/egusphere-egu2020-8398.
- A. J. Weiss, C. Möstl, E. E. Davies, T. Amerstorfer, M. Bauer, J. Hinterreiter, M. A. Reiss, R. L. Bailey, T. S. Horbury, H. O’Brien, V. Evans, V. Angelini, D. Heyner, I. Richter, H. U. Auster, W. Magnes, D. Fischer, and W. Baumjohann. Multi-point analysis of coronal mass ejection flux ropes using combined data from Solar Orbiter, BepiColombo, and Wind. *A&A*, 656:A13, Dec. 2021. doi: 10.1051/0004-6361/202140919.
- M. L. Wilson, J. C. Raymond, S. T. Lepri, R. Lionello, N. A. Murphy, K. K. Reeves, and C. Shen. Constraining the CME Core Heating and Energy Budget with SOHO/UVCS. *arXiv e-prints*, art. arXiv:2111.03178, Nov. 2021.
- R. M. Winslow, N. Lugaz, C. Scolini, and A. B. Galvin. First Simultaneous In Situ Measurements of a Coronal Mass Ejection by Parker Solar Probe and STEREO-A. *ApJ*, 916(2):94, Aug. 2021. doi: 10.3847/1538-4357/ac0821.

- S. Yashiro, N. Gopalswamy, G. Michalek, O. C. St. Cyr, S. P. Plunkett, N. B. Rich, and R. A. Howard. A catalog of white light coronal mass ejections observed by the SOHO spacecraft. *Journal of Geophysical Research (Space Physics)*, 109(A7): A07105, July 2004. doi: 10.1029/2003JA010282.
- J. Zhang, K. P. Dere, R. A. Howard, M. R. Kundu, and S. M. White. On the Temporal Relationship between Coronal Mass Ejections and Flares. *ApJ*, 559(1): 452–462, Sept. 2001. doi: 10.1086/322405.
- L. L. Zhao, G. P. Zank, J. S. He, D. Telloni, Q. Hu, G. Li, M. Nakanotani, L. Adhikari, E. K. J. Kilpua, T. S. Horbury, H. O’Brien, V. Evans, and V. Angelini. Turbulence and wave transmission at an ICME-driven shock observed by the Solar Orbiter and Wind. *A&A*, 656:A3, Dec. 2021. doi: 10.1051/0004-6361/202140450.
- Z. Zhong, Y. Guo, and M. D. Ding. The role of non-axisymmetry of magnetic flux rope in constraining solar eruptions. *Nature Communications*, 12:2734, Jan. 2021. doi: 10.1038/s41467-021-23037-8.
- X. Zhou and B. T. Tsurutani. Interplanetary shock triggering of nightside geomagnetic activity: Substorms, pseudobreakups, and quiescent events. *J. Geophys. Res.*, 106(A9):18957–18968, Sept. 2001. doi: 10.1029/2000JA003028.
- T. H. Zurbuchen and I. G. Richardson. In-Situ Solar Wind and Magnetic Field Signatures of Interplanetary Coronal Mass Ejections. *Space Sci. Rev.*, 123(1-3): 31–43, Mar. 2006. doi: 10.1007/s11214-006-9010-4.