

**Imperial College
London**

The Evolution of Interplanetary Coronal Mass Ejections in the Heliosphere

Emma Elizabeth Davies

Submitted in partial fulfilment of the requirements for the degree of
Doctor of Philosophy

May 2021

Space and Atmospheric Physics Group
Department of Physics
The Blackett Laboratory
Imperial College London
SW7 2AZ

Declarations

The work presented in this thesis is original and solely the work of the author. All else has been appropriately referenced.

The copyright of this thesis rests with the author and is made available under a Creative Commons Attribution Non-Commercial No Derivatives licence. Researchers are free to copy, distribute or transmit the thesis on the condition that they attribute it, that they do not use it for commercial purposes and that they do not alter, transform or build upon it. For any reuse or redistribution, researchers must make clear to others the licence terms of this work.

The work presented in this thesis has contributed to two peer-reviewed published papers:

- Davies *et al.* (2020), “On the Radial and Longitudinal Variation of a Magnetic Cloud: ACE, Wind, ARTEMIS and Juno Observations.” *Solar Physics* 295(11), pp. 157. DOI: 10.1007/s11207-020-01714-z
- Davies *et al.* (2021), “In situ multi-spacecraft and remote imaging observations of the first CME detected by Solar Orbiter and BepiColombo.” *Astronomy & Astrophysics*, DOI: 10.1051/0004-6361/202040113

Abstract

Interplanetary coronal mass ejections (ICMEs) are large scale structures of plasma and magnetic field that are driven from the solar atmosphere and propagate through the heliosphere. ICMEs are the main drivers of strong geomagnetic activity at Earth, thus understanding their evolution is important in space weather forecasting.

Our best knowledge of ICME evolution beyond 1 AU comes from the Ulysses mission, launched in 1990 and decommissioned in 2009. The cruise phase of the Juno mission to Jupiter provides the most recent opportunity to study ICMEs between 1 and 5.4 AU. In this thesis, ICMEs identified in the Juno magnetic field dataset have been catalogued and analysed. The inclination of magnetic flux ropes was found to decrease with increasing heliocentric distance, perhaps a suggestion of ICME deflection and rotation towards the ecliptic plane continuing beyond 1 AU. The mean magnetic field strength of the flux ropes was found to decrease with heliocentric distance as $r^{-1.17 \pm 0.31}$, in agreement with previous studies conducted using Ulysses data.

11 of the catalogued events were also observed by other spacecraft situated at a heliocentric distance of 1 AU or below, allowing for a wider multi-spacecraft study to be conducted and forming the basis for more detailed case studies. In one such case study, significant differences were found between observations and event properties at different spacecraft despite the small longitudinal separation, demonstrating that caution should be exercised in radial alignment studies and the importance of taking the solar wind background into consideration when analysing ICMEs.

A comparison of two separate isolated ICMEs was conducted, one occurring during solar maximum and the other at solar minimum. A clear deformation of the ICME observed at solar minimum is observed, likely due to the highly structured solar wind environment through which it propagated. Neither ICME was found to expand self-similarly as one would expect if we consider the magnetic flux ropes to be cylindrical and force-free, which may have important implications for space weather modelling.

Acknowledgements

First and foremost, I would like to thank my supervisor, Bob. Thank you for your guidance and support throughout these past three and a half years. Your wealth of knowledge and keen eye for detail has been invaluable in my development as a scientist - in fact, I already hear your voice inside my head, correcting my wording as I write, and I hope this long continues. I must also extend thanks to everyone who gave me opportunities throughout my PhD, including Jonathan, Tim, Matt, Christian, Lucie, Emilia and Simon. Thank you for your help, advice and time - it has been a pleasure to learn from you all.

I am grateful to have been part of the Space and Atmospheric Physics Group and to have got to know such lovely people. Thank you to Ralf and Chris, the constructive comments on my work throughout my PhD have been much appreciated. And of course, special thanks goes out to my office mates, Joe, Maks, Ned and Arthur. You've all been wonderful distractions - here's to us finishing our PhDs together.

I have visited some wonderful places during my PhD, and for that, I am indebted to STFC for funding my PhD project and to the Royal Astronomical Society, the Institute of Physics and the Imperial College Trust for supporting these trips, without which I would not have made the friends and connections I have.

Finally, thank you to my family and friends. Serena and Akash, Helly and Rhiannon - you are brilliant. Dan and Pete - thank you for being brave enough to help proofread this thesis. Aunty Pam - your enthusiasm for my work inspires me. Granny Vonny and Roger - thank you for all the support you have given me. Harry - you're the best big little brother out. Ed - thank you for making me laugh every day, I feel like the luckiest person in the heliosphere.

And most of all, Mum and Dad, thank you for your love and encouragement since day one; this thesis is dedicated to you.

Contents

List of Abbreviations	11
List of Figures	15
List of Tables	16
1 Introduction	17
1.1 Thesis Motivation	17
1.2 The Sun	19
1.3 The Solar Wind and the Heliosphere	24
1.4 The Heliospheric Magnetic Field	30
1.5 Coronal Mass Ejections	34
1.5.1 Solar origin of CMEs	35
1.5.2 Coronagraphs and Heliospheric Imaging	38
1.5.3 In situ Observations of ICMEs and Magnetic Clouds	40
1.5.4 ICME Evolution and Current Understanding	42
2 Multi-Spacecraft Observations of ICMEs and Analysis Methods	48
2.1 Spacecraft and Instrumentation	48
2.1.1 Instrumentation	49
2.1.2 Coordinate Systems	52
2.1.3 The Juno Mission	53
2.1.4 Solar Orbiter	55
2.1.5 Near-Earth Spacecraft	58
2.1.6 The STEREO Mission	59
2.1.7 Venus Express	60
2.2 Methods of ICME Analysis	61
2.2.1 Timing Considerations	61
2.2.2 Minimum Variance Analysis	62

2.2.3	Force-Free Flux Rope Fitting	62
2.2.4	Dimensionless Expansion Parameter	65
2.2.5	Distortion Parameter	65
2.2.6	ICME Scaling	66
3	A Catalogue of ICMEs Observed by Juno	68
3.1	Overview of Juno Cruise Data	70
3.2	ICME Identification Criteria	71
3.3	ICME Catalogue	72
3.3.1	Summary of Catalogue Events	76
3.3.2	Variation of Event Properties with Heliocentric Distance	78
3.4	ICMEs Observed by Juno and Other Spacecraft	78
3.5	Summary	88
4	The Radial Evolution and Longitudinal Variation of an ICME	91
4.1	Spacecraft Observations	92
4.2	Solar Source of the In Situ Structures	101
4.3	Analysis	102
4.3.1	Timing Considerations	103
4.3.2	Minimum Variance Analysis	103
4.3.3	Force-Free Flux Rope Fitting	106
4.4	Summary and Discussion	113
5	A Comparison of Isolated ICMEs in the Heliosphere	117
5.1	In Situ Spacecraft Observations	119
5.1.1	April 2013 ICME	120
5.1.2	April 2020 ICME	123
5.2	The Solar Wind Environment	125
5.3	Radial Evolution of the ICMEs	128
5.4	Summary and Discussion	135
6	Conclusions and Outlook	138
	Bibliography	145
	Appendix	171

List of Abbreviations

ACE	Advanced Composition Explorer
AR	Active region
ARTEMIS	Acceleration, Reconnection, Turbulence, and Electro-dynamics of the Moon's Interaction with the Sun
AU	Astronomical unit, 1.496×10^8 km
CDAWeb	Coordinated Data Analysis Web
CME	Coronal mass ejection
CIR	Corotating interaction region
DC	Direct current
DiP	Distortion parameter
DSM	Deep Space Manoeuvre
EFB	Earth flyby
EIT	Extreme Ultraviolet Imaging Telescope
EPD	Energetic Particle Detector
ESA	Electrostatic Analyser
ESA	European Space Agency
EUI	Extreme Ultraviolet Imager
EUV	Extreme Ultraviolet
FGM	Fluxgate magnetometer
GAM	Gravity assist manoeuvre
HAE	Heliocentric Aries Ecliptic
HCS	Heliospheric current sheet
HEEQ	Heliocentric Earth Equatorial
HELCATS	Heliospheric Cataloguing, Analysis and Techniques Service
HI	Heliospheric imager
HMF	Heliospheric magnetic field

ICME	Interplanetary coronal mass ejection
IMF	Interplanetary magnetic field
IMP	Interplanetary Monitoring Platform
ISEE	International Sun-Earth Explorer
JADE	Jovian Auroral Distributions Experiment
JEDI	Jupiter Energetic-particle Detector Instrument
JIRAM	Jovian Infrared Auroral Mapper
JOI	Jupiter orbit insertion
JUICE	Jupiter Icy Moons Explorer
L1	First Lagrangian point
LASCO	Large Angle and Spectrometric Coronagraph
MAG	Magnetometer
MESSENGER	Mercury Surface, Space Environment, Geochemistry, and Ranging
MFR	Magnetic flux rope
MHD	Magnetohydrodynamics
MSFC	Marshall Space Flight Center
MVA	Minimum variance analysis
MWR	Microwave radiometer
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
PC	Planetocentric
PDS	Planetary Data System
PIL	Polarity inversion line
PL	Payload
PMS	Planar magnetic structure
PPI	Planetary Plasma Interactions
PSA	Planetary Science Archive
R_s	Solar radius, 6.955×10^5 km
RMSE	Root mean square error
RPW	Radio and Plasma Wave analyser
RTN	Radial-tangential-normal
SE	Solar equatorial

SEP	Solar energetic particle
SIR	Stream interaction region
SOHO	Solar and Heliospheric Observatory
SO/PHI	Polarimetric and Helioseismic Imager
SPDF	Space Physics Data Facility
SRF	Spacecraft reference frame
SS	Sun-state
STEREO	Solar TERrestrial RELations Observatory
STIX	X-ray Spectrometer/Telescope
SWA	Solar Wind Analyser
SWE	Solar Wind Experiment
SWEPAM	Solar Wind Electron Proton Alpha Monitor
SWOOPS	Solar Wind Observations Over the Poles of the Sun
SWPC	Space Weather Prediction Center
THEMIS	Time History of Events and Macroscale Interactions during Substorms
UMFR	Unperturbed magnetic flux rope
UVS	Ultraviolet Spectrograph

List of Figures

1.1	Structure of the Sun	20
1.2	The Babcock model of the solar dynamo	21
1.3	Recorded sunspot area	23
1.4	SOHO EIT Images of the solar disk	24
1.5	Parker solar wind equation solutions	26
1.6	Variance of solar wind speed with latitude, Ulysses observations	27
1.7	The outer structure of the heliosphere	29
1.8	Coronal field model	31
1.9	The Parker spiral	32
1.10	The heliospheric current sheet at solar minimum	33
1.11	Flux cancellation of a sheared magnetic field	35
1.12	Solar flare model	37
1.13	Coronal signatures of CME eruption	38
1.14	Example CMEs captured by coronagraphs/ a total solar eclipse	39
1.15	Flux rope classifications	42
1.16	Structure of an ICME	43
2.1	How a fluxgate magnetometer works.	51
2.2	Scientific payload onboard Juno	54
2.3	Juno's cruise phase trajectory	55
2.4	Science payload onboard Solar Orbiter	57
2.5	Range of heliocentric distances and latitudes during Solar Orbiter mission phases	58
3.1	Overview of the Juno cruise phase	70
3.2	Spacecraft position at which catalogued events were observed at Juno	76
3.3	Variation of magnetic field strength with heliocentric distance	79

3.4	Magnetic field data of events observed by Wind	81
3.5	Magnetic field data of events observed by STEREO B	82
3.6	Magnetic field data of events observed by Venus Express and STEREO A	83
3.7	Latitudinal, longitudinal and radial separation between events observed by multi-spacecraft	85
3.8	Variation of magnetic field strengths of individual events observed by spacecraft at different heliocentric distances	87
3.9	Variation with heliocentric distance of the magnetic field strengths in- cluding multi-spacecraft observations	88
4.1	Spacecraft locations on 25 October 2011	93
4.2	In situ magnetic field and plasma data of Oct 2011 ICME observed at Wind	95
4.3	In situ magnetic field data of Oct 2011 ICME observed at Juno	96
4.4	Force-free flux rope model fitting to Wind observations	107
4.5	Force-free flux rope model fitting to Juno observations	108
4.6	Orientations of ICME shock/sheath and magnetic flux rope axis	109
5.1	Spacecraft configurations during ICME observation	119
5.2	In situ observations of the April 2013 ICME	121
5.3	In situ observations of the April 2020 ICME	124
5.4	Solar wind backgrounds during the propagation of the April 2013 and April 2020 ICMEs	127
5.5	HI images of the April 2013 and April 2020 ICMEs	128
5.6	Scaled magnetic field observations of the April 2013 ICME	130
5.7	Scaled magnetic field observations of the April 2020 ICME	133
6.1	In situ magnetic field data of Oct 2011 ICME observed at ACE	171
6.2	In situ magnetic field data of Oct 2011 ICME observed at THEMIS B	172
6.3	In situ magnetic field data of Oct 2011 ICME observed at THEMIS C	173
6.4	Force-free flux rope model fitting to ACE observations	174
6.5	Force-free flux rope model fitting to THEMIS B observations	175
6.6	Force-free flux rope model fitting to THEMIS C observations	176

List of Tables

1.1	In situ signatures of ICMEs at 1 AU	41
3.1	Catalogue of events observed by Juno	75
3.2	Summary of the Juno ICME catalogue	77
3.3	List of Juno events observed by multi-spacecraft	84
3.4	The differences in ICME parameters between observing spacecraft . . .	86
4.1	Observed Oct 2011 ICME parameters at near-Earth spacecraft and Juno	100
4.2	Timing and flux rope fitting results of Oct 2011 ICME	105
5.1	April 2013 and April 2020 ICME parameters	120

Chapter 1

Introduction

1.1 Thesis Motivation

Interplanetary coronal mass ejections (ICMEs) are large-scale structures of plasma and magnetic field that are driven from the solar atmosphere and propagate through the heliosphere. These transient structures are distinguished from the ambient solar wind in situ by distinct magnetic field and plasma signatures amongst many other features. ICMEs are the main drivers of strong geomagnetic activity at Earth which can have severe effects on systems both in space and on the ground, and therefore their evolution and interaction with the solar wind and other structures is of great interest in space weather forecasting.

In this thesis, analysis of the kinematic and structural magnetic properties of ICMEs as they evolve is presented. Observations are used from a wide range of spacecraft in the solar wind, including dedicated solar wind missions, planetary mission spacecraft when outside of their planetary environments, and those spacecraft in their cruise phase to another planet. Magnetic field data of the Juno spacecraft is primarily used throughout this thesis, in combination with other spacecraft, especially those located at 1 AU. The Juno mission spent a total of 5 years in the solar wind during its cruise phase to Jupiter and is therefore an ideal resource to study ICME evolution beyond 1 AU. The motivation for using Juno cruise data to study ICMEs is clear:

- i) The Juno mission during its cruise phase (2011–2016) provided observations of the magnetic field at heliocentric distances between 1 and 5.4 AU, the most recent and comprehensive opportunity to study ICMEs beyond 1 AU since the Ulysses

mission (1990–2009).

- ii) Juno is located mostly at low heliocentric latitudes (apart from later on in its cruise phase) giving an opportunity for multi-spacecraft studies of ICMEs in the solar ecliptic plane, at wider separations with spacecraft located at and below 1 AU.
- iii) The dataset has not been analysed for ICME signatures previously and could be a valuable addition to future statistical studies of ICMEs.

Chapter 2 provides a detailed description of the Juno mission and instrumentation used throughout this thesis. Other spacecraft used in combination with Juno observations are described: the ACE, Wind, and ARTEMIS missions located near the Earth; STEREO-A and B at 1 AU; and Venus Express at ~ 0.7 AU. The mission objectives and instrumentation of Solar Orbiter are also outlined, as the in situ observations of the first ICME observed by Solar Orbiter are presented in Chapter 5. Methods commonly used in multi-spacecraft studies of ICMEs are also presented.

In Chapter 3, a catalogue and statistical analysis of ICMEs identified at Juno is presented. The Juno cruise dataset only comprises magnetic field data, and therefore ICMEs, or rather magnetic ejecta, are identified by increases in magnetic field magnitude which are coincident with a rotating magnetic field structure, comparable with the structure of a flux rope. ICME properties and their dependence on the heliocentric distance at which they were measured have been used to provide a statistical picture of ICME evolution beyond 1 AU and have been compared with previous analyses and catalogues of ICMEs identified by Ulysses.

Observations at spacecraft within small longitudinal separations of events identified at Juno are also noted in the catalogue and analysed in Chapter 3. Observations of the same ICME from the multiple spacecraft are especially useful in providing not only a global picture of the ICME but also an indication of the variability of the magnetic field within the ICME. Chapter 4 provides an in-depth analysis of an ICME observed by both Juno and four spacecraft near the Earth. The small separation between the four near-Earth spacecraft gives the variability of observations along different trajectories through the ICME and allows for estimates of the uncertainty of force-free fitting models used to analyse the event. The near-Earth spacecraft also observe significantly different ICME signatures and event properties in comparison with Juno despite the small longitudinal and radial separation, due to the interaction of the ICME with another solar wind

transient. Chapter 4 is based on the journal article published by the author in *Solar Physics*, Davies *et al.* (2020).

Chapter 5 provides a comparison of two separate isolated ICMEs. The first ICME was observed in April 2013 by both the Wind spacecraft and Juno, and the second was observed in April 2020 by both Solar Orbiter and Wind. The in situ observations of each ICME between observing spacecraft are remarkably similar in both cases. This has provided an opportunity to match smaller-scale features observed in the magnetic data which are clearly identified at both observing spacecraft. Both the global and local expansion of these ICMEs as they evolve have been investigated.

The expansion of ICMEs is a key question throughout this thesis. Do ICMEs expand self-similarly? Do ICME properties such as the magnetic field strength follow the same trends as they evolve beyond 1 AU as in the inner heliosphere, or what might be the reason they differ? The extent to which the solar wind background affects the propagation and evolution of ICMEs is also a key motivator in the work of this thesis. Are ICMEs coherent structures with features or properties observed by spacecraft that apply globally over the whole ICME, or just locally to the in situ measurement site?

An introduction to heliospheric physics is presented in the remainder of this chapter. The physical processes of the Sun and its solar cycle, and its physical extension into the heliosphere provide context to the environment through which ICMEs propagate, and the current understanding of ICME evolution is described.

1.2 The Sun

The Sun is the primary source of energy and most plasmas within the solar system. It is a typical star which occupies the main sequence of the Hertzsprung-Russell diagram where the majority of stars lie, and it is of intermediate temperature (G-type classification) and luminosity (class V). The full spectral class for the Sun is G2V, indicating a main sequence star with a surface temperature around 5,800 K (e.g. Tayler, 1997).

The structure of the Sun can be split into the interior and the atmosphere, separated by the photosphere, considered the surface of the Sun (see Figure 1.1). At the centre of the Sun is its core, and between the core and photosphere are two zones: radiative and convective, the depth of which are determined by the most efficient form of heat transport. The convective zone of the Sun comprises the outer 30% of its interior, the depth of which is determined by helioseismology observations (see Thompson, 2004).

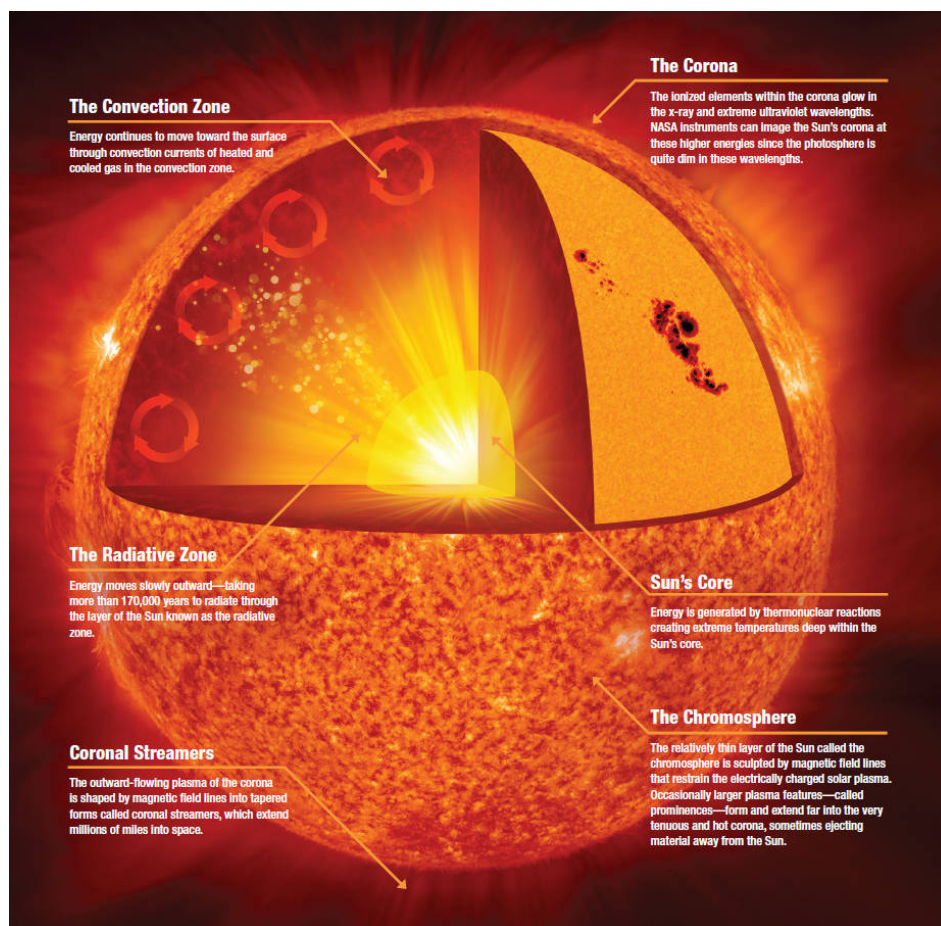


Figure 1.1: The structure of Sun. The interior of the Sun comprises the core, radiative zone and convective zone. The solar atmosphere can be divided into two regions: the chromosphere and the corona. The photosphere separates the interior and atmosphere. Credit: NASA/Jenny Mottar, https://www.nasa.gov/mission_pages/sunearth/science/solar-anatomy.html.

The rotation rate of the convective zone varies with solar latitude (e.g. Schou *et al.*, 1998; Thompson *et al.*, 2003), rotating fastest at low latitudes with a period of ~ 25 days and slowest at high latitudes with a rotation rate > 30 days. The layer of radial shear around the base of the convection zone which separates the radiative and convective zones is known as the tachocline (Spiegel and Zahn, 1992), and is of great interest in dynamo theory (the generation of the solar magnetic field) as it appears to be the site of the strongest differential rotation within the Sun.

A popular model of the solar dynamo, which explains many observable features and the cyclical nature of the Sun, is known as the Babcock–Leighton dynamo model

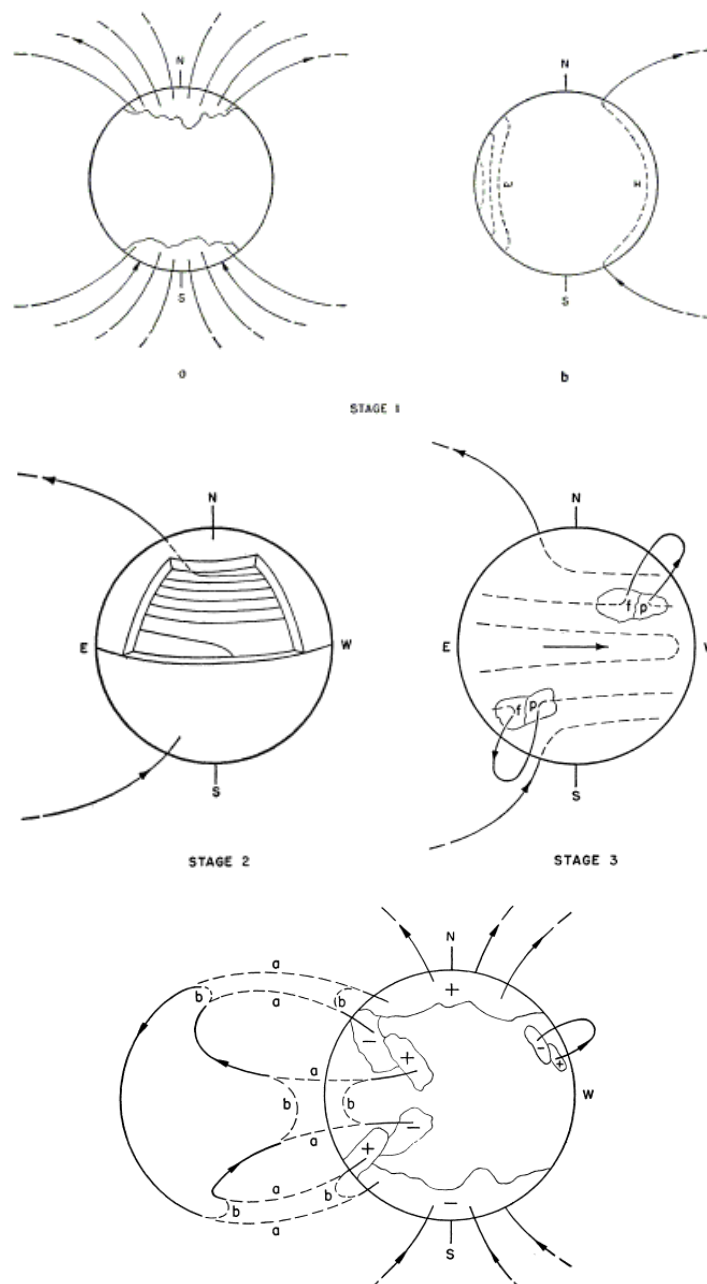


Figure 1.2: The Babcock model of the solar dynamo. The solar magnetic field begins as an axisymmetric dipole magnetic field (stage 1) which becomes sheared due to the different rotation rates between the equator and poles (stage 2). Sunspots emerge and the toroidal magnetic field becomes buoyant (stage 3) and transported to the poles where it is cancelled (final stage). Figures 1, 2, 3 and 8 of Babcock (1961).

(Babcock, 1961; Leighton, 1969). The Babcock model as a basis, has four main stages (Figure 1.2). The first stage shows an axisymmetric dipole magnetic field, where magnetic field lines emerge from the poles and connect to the opposite pole through the convection zone. In stage 2, due to the radial shear created by the difference in rotation rates at the equator and the poles, the magnetic field is stretched in the toroidal direction. Stage 3 shows the emergence of sunspots, as the toroidal magnetic field becomes buoyant and rises through the convection zone, emerging at the photosphere where the leading sunspot matches the polarity of the polar magnetic field in that hemisphere. The Coriolis force causes loops of magnetic flux to twist, creating an oppositely directed poloidal component of the magnetic field. The final stage shows the cancellation of the leading polarity fields as the magnetic flux of the sunspots is shed. The polarity is then transported towards the poles, cancelling with the initial polar field to create a new poloidal field with opposite polarity, and thus, beginning a new solar cycle.

If we assume that the toroidal field that forms sunspots rises radially from where the magnetic field is strongest, sunspots can be interpreted as a map of the toroidal magnetic field that evolves over time. Figure 1.3 presents a ‘butterfly diagram’ which shows how the positions of sunspots evolve with time. This diagram provides important observational constraints to the solar dynamo model, showing the emergence of sunspots at latitudes closer to the equator as the solar cycle progresses, covering a latitudinal band approximately 30° wide, symmetric about the solar equator.

The lower panel of Figure 1.3 shows the average daily area covered by sunspots on the visible side of the Sun. It clearly shows the periodicity of the solar cycle which is ~ 11 years. This measure, along with the daily/monthly mean sunspot numbers gives a sense of the magnitude of each solar cycle and when the solar activity was at its lowest/highest. The point in the solar cycle at which the number of sunspots and therefore activity is lowest is known as solar minimum, and its peak is known as solar maximum. The new solar cycle, Solar Cycle 25, recently began in December 2019, following a deep solar minimum and the weak Solar Cycle 24.

The solar atmosphere can be divided into two regions: the chromosphere and the corona (Figure 1.1). The chromosphere is nearest the photosphere where it is partially ionised and radiates heat effectively, thus it is relatively low in temperature. The ratio between plasma pressure and magnetic pressure (the plasma beta) is relatively balanced in the chromosphere, and therefore dense clouds of plasma can be suspended by loops of the magnetic field. These features are known as filaments, or prominences when

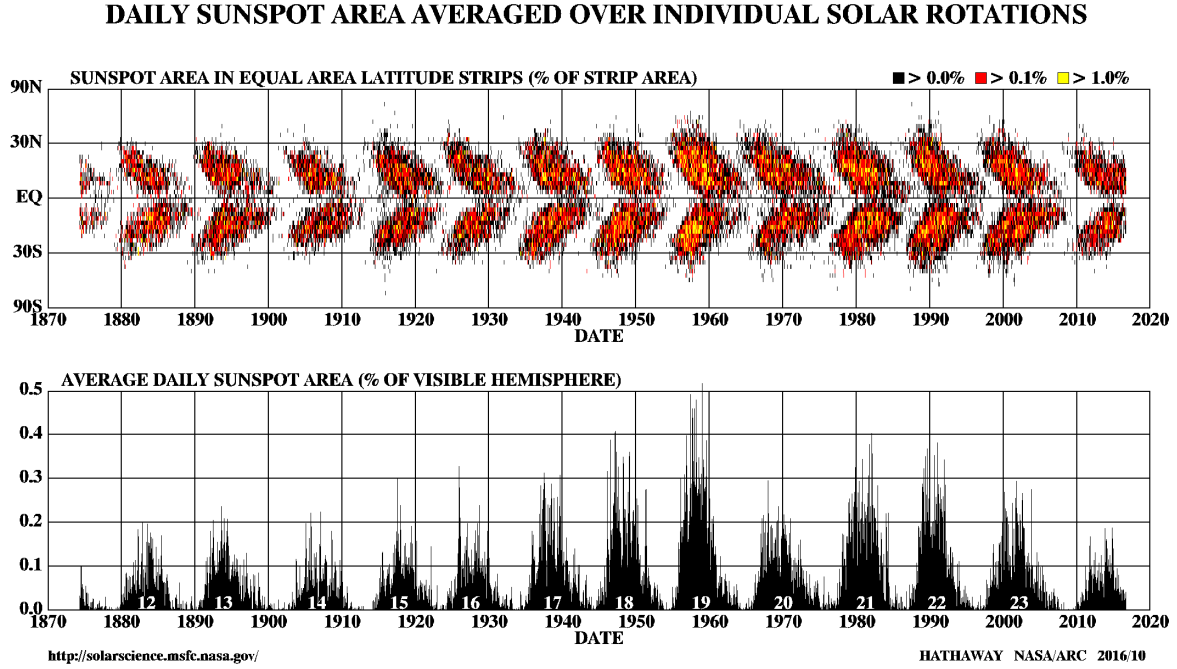


Figure 1.3: Upper panel: the sunspot ‘butterfly diagram’, demonstrating the coverage of sunspots as a function of solar latitude and time, from 1874 to 2016. Lower panel: the average daily sunspot area as a percentage of the visible side of the Sun. Figure courtesy of D. Hathaway, NASA/MSFC; <http://solarscience.msfc.nasa.gov/images/bfly.gif>.

observed on the solar limb. The role of filaments in CME initiation is described in Section 1.5.1.

The corona, however, is fully ionised with temperatures greater than 1 million K. Many features exist in the corona, such as active regions over sunspots that contain magnetic field loops, or coronal loops, that are the source of solar flares and other bursts of activity. The corona is also the source of the solar wind, whether that be from streamer belt regions (slow solar wind, Crooker *et al.*, 2012), or from coronal holes (fast solar wind, Krieger, Timothy, and Roelof, 1973) which are vast structures of open magnetic field, less dense and therefore cooler, and thus appear as dark regions in remote imaging of the Sun.

Figure 1.4 shows images of the Sun taken by the Extreme Ultraviolet Imaging Telescope (EIT; Delaboudinière *et al.*, 1995) onboard the Solar and Heliospheric Observatory (SOHO; Domingo, Fleck, and Poland, 1995), showing plasma at temperatures of around two million degrees K (spectral emission lines from Fe XV, 284 Å). These images

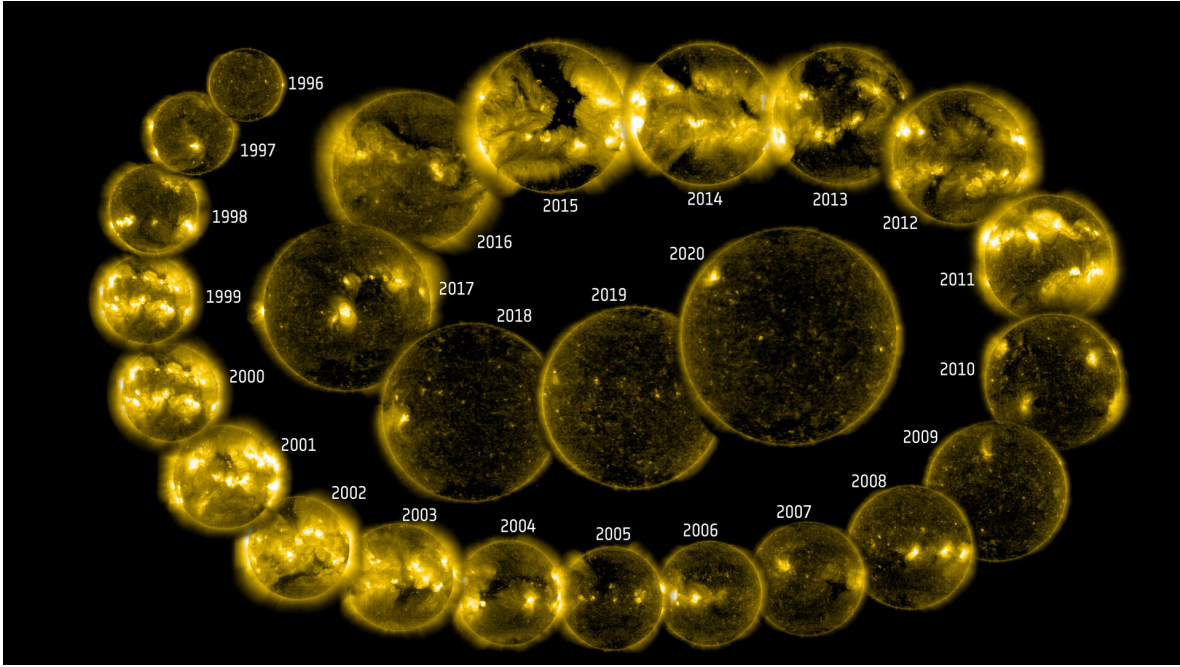


Figure 1.4: Solar and Heliospheric Observatory (SOHO) observations across two solar cycles, from 1996 to 2020. The images are captured by the Extreme Ultraviolet Imaging Telescope (EIT) which reads spectral emission lines from Fe XV (284 Å) and shows the changing face of the Sun over the solar activity cycle. Credit: SOHO (ESA & NASA), https://www.esa.int/ESA_Multimedia/Images/2020/11/SOHO_25_years_of_solar_imaging.

show how the structure of the corona varies with the progressing solar cycles, where at solar minimum, active regions are shown near the equator and coronal holes towards the poles, whereas at solar maximum, active regions and coronal holes are much more disordered.

The features described so far are not the only consequences of the Sun's magnetic field. A far-reaching consequence of the solar magnetic field is the solar wind, and as a further consequence, the large region in space in which it flows, known as the heliosphere. These are discussed below in Section 1.3.

1.3 The Solar Wind and the Heliosphere

The solar wind is a magnetised plasma that continuously emanates from the solar corona, from where it propagates through interplanetary space. An early indicator of

the solar wind's existence were observations of comet tails that pointed away from the Sun despite their direction of travel (Eddington, 1910; Hoffmeister, 1943; Biermann, 1951). Eugene Parker was the first to propose a hydrodynamic model of the solar wind, demonstrating that the corona cannot maintain a hydrostatic equilibrium due to its high temperature (Parker, 1958). The large pressure gradient overcomes the gravitational force of the Sun and leads to a radial acceleration of plasma. Assuming a steady flow of solar wind from a non-rotating Sun, with spherical symmetry, the conservation of mass and conservation of momentum equations are given by Equations 1.1 and 1.2

$$\frac{1}{r^2} \frac{d}{dr}(r^2 \rho u) = 0, \quad (1.1)$$

$$\rho u \frac{du}{dr} = -\frac{dP}{dr} - \rho \frac{GM_s}{r^2}, \quad (1.2)$$

respectively, where u represents the velocity of the solar wind in the radial direction, ρ is the density, G is the gravitational constant, P is the pressure, and M_s is the mass of the Sun. Assuming the solar wind is isothermal (and that electron and ion temperatures are equal), the ideal gas law can be used, where the mass of ions, m_i , dominates over the mass of electrons. It can therefore be shown that

$$\frac{1}{u} \frac{du}{dr} \left(u^2 - \frac{2k_B T}{m} \right) = \frac{4k_B T}{mr} - \frac{GM_s}{r^2} \quad (1.3)$$

where k_B is the Boltzmann constant, and T is the temperature of the solar wind. Equation 1.3 is known as the Parker solar wind equation. There are 6 possible solutions to the Parker solar wind equation, illustrated by Figure 1.5. However, only 2 solutions, A and F are physical. Solution F corresponds to the ‘solar breeze’ (Chamberlain, 1961) where the solar wind speed remains subsonic, and is an unstable solution (Velli, 1994).

Solution A is the only solution to meet known boundary conditions describing the solar wind as a subsonic flow that transitions to supersonic at a critical radius, r_c . The speed profile of the solar wind is only dependent on the temperature of the corona and can be shown to be approximately constant after a small distance from the Sun ($\sim 10 R_S$). A constant solar wind speed means that density decreases as $1/r^2$ with increasing heliocentric distance.

Shortly after Parker’s prediction, the solar wind was measured in situ by plasma instruments onboard Luna 1, Luna 2, and Luna 3 (the Cosmic Rockets), which reported

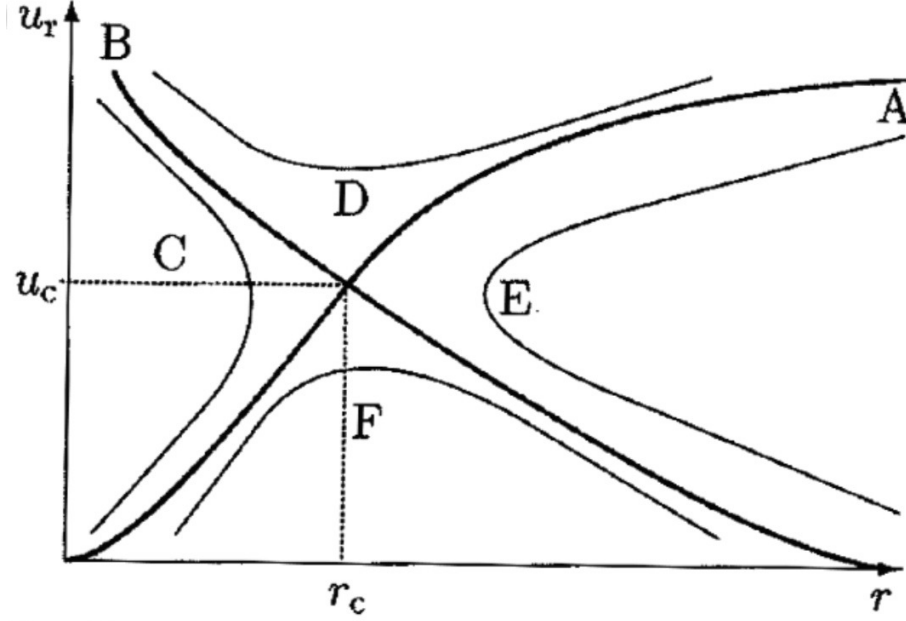


Figure 1.5: The 6 possible solutions to the Parker solar wind equation. Solution A most accurately describes the solar wind as a subsonic wind that transitions to supersonic at a critical radius, r_c . Figure from Kallenrode (2004).

the detection of supersonic solar wind ions as predicted (Gringauz *et al.*, 1960). Observations of a supersonic solar wind were further confirmed by Mariner 2 as it travelled to Venus (Neugebauer and Snyder, 1962). In situ measurements of the solar wind have been gathered almost continuously since, by missions such as IMP-8 launched in 1973 to investigate the magnetosphere of Earth, and the two Helios spacecraft launched in 1974 and 1976 to investigate solar wind processes. The first spacecraft to orbit the first Earth-Sun Lagrangian point (L1) was the International Sun-Earth Explorer-3 (ISEE-3), launched in 1978, where it stayed for ~ 5 years before commencing a heliocentric orbit.

The solar wind comprises charged particles of both electrons and ions, allowing for overall quasi-neutrality. 95% of the ions by mass are H^+ and 4% are He^{2+} , with many others (up to iron) in smaller quantities (Bame, 1972; Ogilvie and Coplan, 1995). The properties of the solar wind at 1 AU are well observed by upstream monitors such as ACE and Wind, positioned at L1 during the period of interest covered in this thesis, with an average density of 8 cm^{-3} and an average speed of 450 km s^{-1} (Hundhausen, 1995). However, averages do not show the full picture. As noted previously, we can

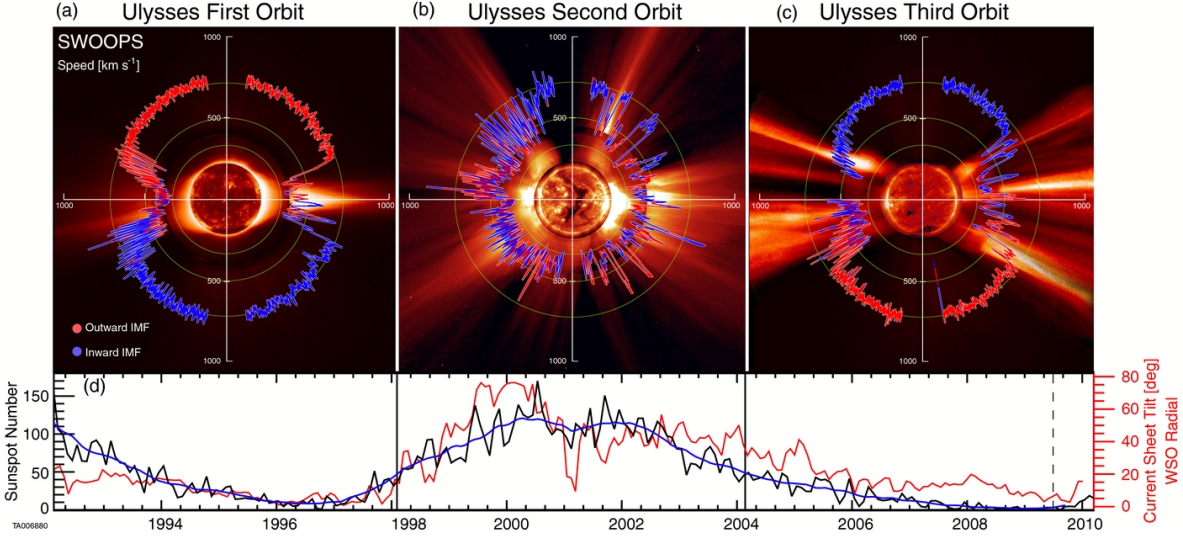


Figure 1.6: The solar wind speed measured by the Solar Wind Observations Over the Poles of the Sun (SWOOPS; Bame *et al.*, 1992) instrument onboard Ulysses as a function of latitude. The bottom panel gives the average monthly sunspot number (black) over the course of the three Ulysses orbits. The sunspot number demonstrates that the first Ulysses orbit occurred during solar minimum, the second during solar maximum, and the third during solar minimum of the following solar cycle. The polarity of the solar magnetic field is represented by red (outward) or blue (inward) lines in these panels. Figure from McComas *et al.* (2013).

categorise the solar wind into two types: fast solar wind and slow solar wind. Schwenn (1990) summarised the properties of the solar wind around solar minimum: the fast solar wind has velocities between 400 and 800 km s⁻¹ and an average density of 3.0 cm⁻³, whereas the slow solar wind has velocities between 250 and 400 km s⁻¹ and an average density of 10.7 cm⁻³.

Measurements of the solar wind speed taken by the Ulysses spacecraft are presented in Figure 1.6. The Ulysses spacecraft was launched in 1990, arriving at Jupiter in 1992 where a manoeuvre was performed to raise its inclination to the ecliptic plane by $\sim 80^\circ$ and into a polar orbit around the Sun, where aphelion was at approximately 5.4 AU and perihelion at 1.35 AU. The left hand panel of the figure shows measurements over the course of one orbit (~ 6 years) during the solar minimum following Solar Cycle 22, demonstrating the highly structured nature of the solar wind, and the origins of the slow and fast solar wind, with remarkable clarity (Phillips *et al.*, 1995; McComas *et al.*, 1998b, 2000). The middle panel presents measurements taken during Ulysses second

orbit at solar maximum of Solar Cycle 23, showing a much more disordered solar wind structure (McComas *et al.*, 2003). The right hand panel shows the final orbit of Ulysses which took place during the following solar minimum, where the magnetic field is again highly structured but opposite in polarity to the previous solar minimum (McComas *et al.*, 2013).

The outflow of the solar wind pushes against the interstellar plasma, thus carving out a volume embedded within interstellar space in which it dominates. This region is known as the heliosphere, the term first introduced by Dessler (1967). Figure 1.7 presents the structure of the outer heliosphere. The first boundary shown is the termination shock, caused by the supersonic solar wind transitioning to subsonic as it meets the plasma of the interstellar medium. Ahead of the termination shock is a compressed region of solar wind known as the heliosheath. The boundary between the heliosphere and interstellar space is known as the heliopause and a simple estimate of its distance can be calculated theoretically by considering the pressure balance between the solar wind and the interstellar medium, P_{ISM} .

$$\frac{B^2}{2\mu_0} + \rho u^2 + 2nk_B T = P_{ISM} \quad (1.4)$$

Equation 1.4 shows the balance between the magnetic pressure, dynamic pressure and thermal pressure of the solar wind, respectively, with the pressure of the interstellar medium. The dynamic pressure term dominates due to the supersonic nature of the solar wind, and the magnetic pressure can be assumed approximately equal to the thermal pressure (the plasma beta of the solar wind $\simeq 1$). Using Equation 1.4, reasonable estimates of the distance to the heliopause range between 120 and 200 AU.

Figure 1.7 also presents the asymmetric shape of the heliosphere (Schwadron and Bzowski, 2018). As the Sun travels through the interstellar medium, the front of the heliosphere with respect to direction of travel (the ‘nose’) is compressed and a ‘tail’ is created behind. The only spacecraft to have started exploring the outer boundaries of the heliosphere are Voyager 1 and 2. The Voyager spacecraft were launched in 1977 with the mission to study the outer solar system. Both spacecraft were launched towards the ‘nose’ of the heliosphere, with Voyager 1 travelling northwards above the ecliptic plane and Voyager 2 travelling southwards. Voyager 1 crossed the termination shock on 16 December 2004 at a distance of 94.01 AU (Stone *et al.*, 2005) and Voyager 2 on 30 August 2007 at a distance of 83.7 AU (Stone *et al.*, 2008). These measurements are

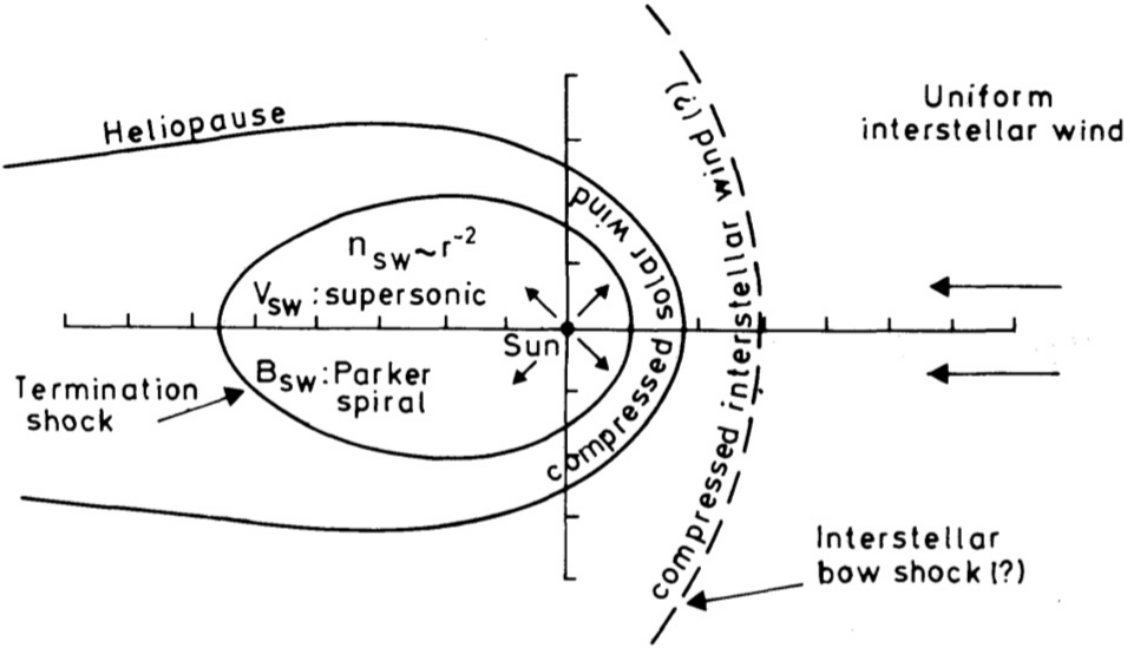


Figure 1.7: The outer structure of the heliosphere. A termination shock is formed in response to the supersonic solar wind meeting the interstellar wind, transitioning to subsonic. The compressed region of solar wind ahead of the termination shock is known as the heliosheath and is bounded by the heliopause. The interstellar wind is due to the motion of the solar system through the galaxy and it is possible that an interstellar bow shock could be formed. Figure from Ratkiewicz (1992).

in agreement with previous estimations of the termination shock distance (Stone and Cummings, 2001). Voyager 1 crossed the heliopause in August 2012 at a distance of 122 AU when it observed a sudden change of intensity of both anomalous cosmic rays and galactic cosmic rays (Webber and McDonald, 2013). Other evidence of crossing includes observations of plasma oscillations which were used to calculate the plasma electron density. The calculated densities were comparable to densities expected in the local interstellar medium (Gurnett *et al.*, 2013). In November 2018, Voyager 2 also crossed the heliopause at a distance of 119 AU, marked by an increase in galactic cosmic ray intensity (Stone *et al.*, 2019). Measurements of the plasma indicated a crossing into a denser, cooler plasma, although the measured temperature was higher than expected (Richardson *et al.*, 2019). A heliopause crossing at ~ 120 AU is in line with the estimate given by solving Equation 1.4, although towards the lower bound. In

reality the calculation of the distance to the heliopause is more complex, affected by factors such as mass loading, where the solar wind is slowed down by increased density as it picks up ions that have entered the heliosphere from the interstellar medium (e.g. Richardson *et al.*, 2008a,b; Lee *et al.*, 2009).

1.4 The Heliospheric Magnetic Field

The solar corona is a low beta plasma where the magnetic pressure dominates over the thermal pressure, therefore dynamics in the corona are controlled by its magnetic field. Figure 1.8 shows a simple model of the open magnetic field lines of the polar regions, and the closed field lines located around the heliomagnetic equator. This is the quasi-dipolar form of the coronal field typical of solar minimum, where the field strength is greater at the poles than at the equator. Moving outwards from the Sun, open field lines expand and the magnetic pressure starts to equalise. The magnetic field becomes radial at the distance at which magnetic field pressure equalises (the source surface). With increasing distance from the Sun, the plasma beta increases and thus the magnetic field becomes carried along by the solar wind plasma. The heliospheric magnetic field (HMF), also referred to as the interplanetary magnetic field (IMF), is therefore formed by the solar magnetic field carried into the heliosphere by the solar wind plasma.

As the Sun rotates, the footpoint of the magnetic field line remains fixed in the photosphere as the solar wind flows radially outwards, resulting in the characteristic spiral shape of the heliospheric magnetic field predicted by Parker (1958). The Archimedian spiral traced out by the HMF is therefore known as the Parker spiral, illustrated by Figure 1.9. In Parker’s model, the HMF varies only in the radial direction and as a consequence of the conservation of magnetic flux, it can be shown that the radial component decreases with radial distance, r , as

$$B_r = B_0 \left(\frac{r_0}{r} \right)^2, \quad (1.5)$$

where r_0 is the distance of the source surface of the solar wind. This distance is $\approx 10 R_S$, although it is often adjusted to values such as $2.5 R_S$ in coronal and interplanetary magnetic field models such as the potential-field source-surface model (PFSS; e.g. Schatten, Wilcox, and Ness, 1969; Altschuler and Newkirk, 1969).

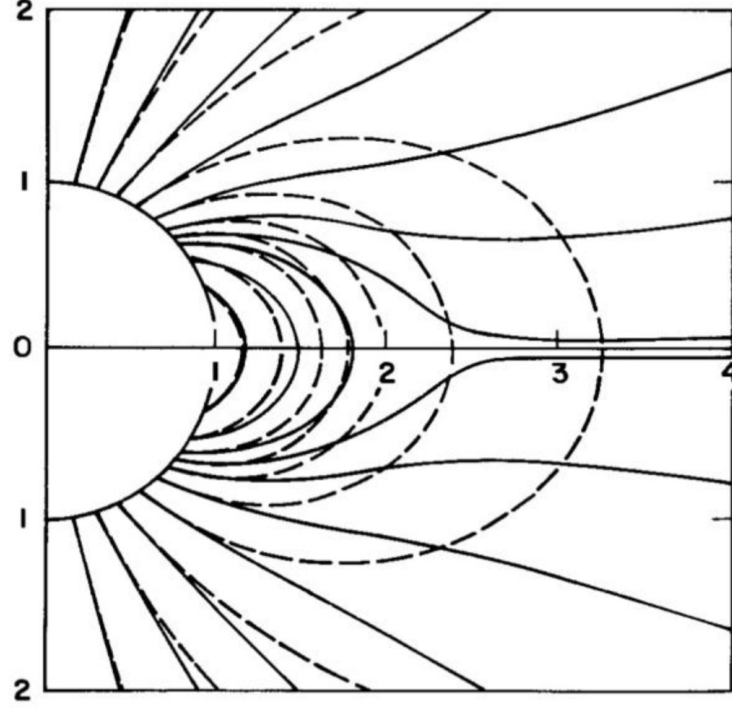


Figure 1.8: A model of the coronal field. The magnetic field of the corona (solid lines) is compared to a dipolar potential field model (dashed lines), demonstrating the effect of the solar wind on the coronal field. Figure from Pneuman and Kopp (1971).

In the frame of reference of the Sun, assuming that the Sun rotates with an angular speed Ω , the azimuthal solar wind speed, V_ϕ , is given by $-\Omega r \sin \theta$, where θ is the colatitude and thus $\sin \theta$ accounts for the change in speed between the solar equator and the poles. In the same frame, the frozen-in magnetic field line follows the same path as the solar wind plasma, thus $B_\phi/B_r = V_\phi/V_r$. We can therefore write

$$\frac{B_\phi}{B_r} = \frac{V_\phi}{V_r} = \frac{-\Omega r \sin \theta}{V_r}. \quad (1.6)$$

By substituting Equation 1.5 into Equation 1.6, it can be shown that

$$B_\phi = -B_r \frac{\Omega r_0^2 \sin \theta}{V_r r}, \quad (1.7)$$

demonstrating that the azimuthal component of the magnetic field decreases as $1/r$ with distance from the Sun. The rotation period of the Sun is approximately 27 days when viewed from the Earth, and therefore considering a typical solar wind speed

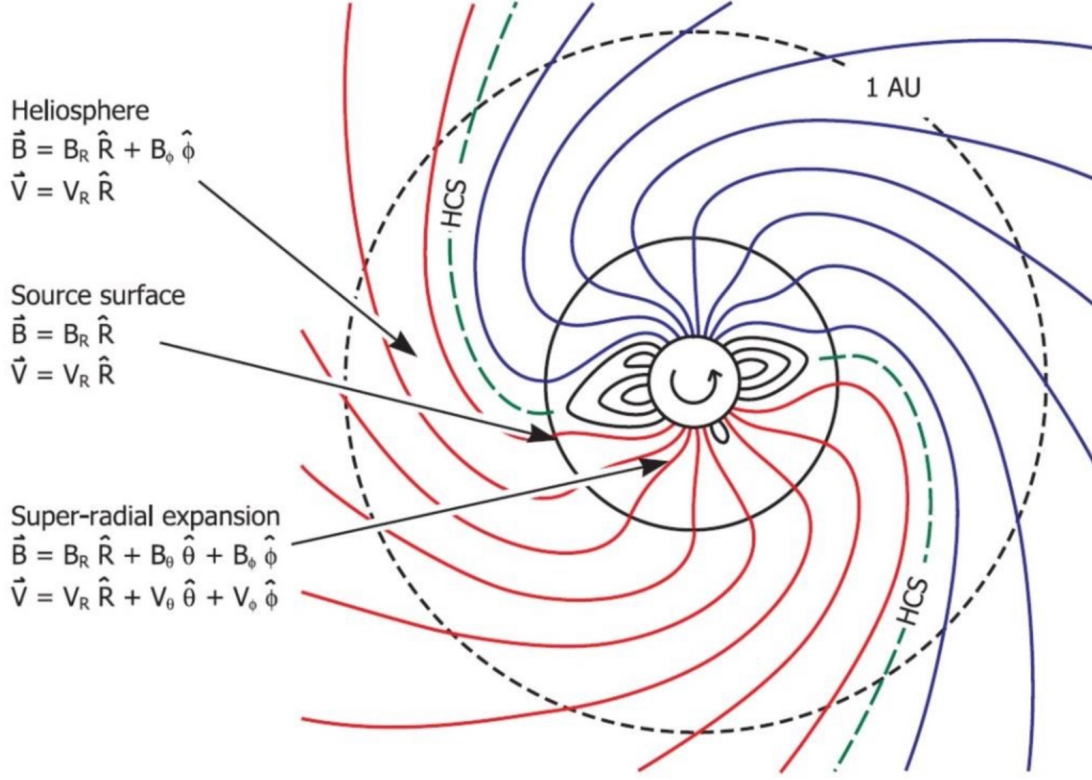


Figure 1.9: The Parker spiral in the solar equatorial plane. The red and blue lines forming the spiral represent opposite field polarities, with the green dashed line separating the two polarities depicting the heliospheric current sheet. The sector structure is due to the tilt between the heliomagnetic equatorial and the solar equatorial planes. Figure from Owens and Forsyth (2013).

of 450 km s^{-1} at 1 AU, the angle that the HMF makes with the radial direction is approximately 45° near the Earth.

Due to the quasi-dipolar nature of the Sun, the HMF anchored in (approximately) each solar hemisphere extends throughout the heliosphere with opposing magnetic polarities, represented by the red and blue lines in Figure 1.9. A neutral current sheet is formed between opposing polarities, known as the heliospheric current sheet (HCS; see review by Smith, 2001), represented by the dashed green line in Figure 1.9. The magnetic dipole axis of the Sun is tilted with respect to its rotation axis, thus the HCS is not simply flat and rather appears to be wavy, taking the form of a rippled ‘ballerina skirt’ (Alfven, 1977). Figure 1.10 presents the results of an MHD simulation of the HCS, demonstrating its warped shape. The existence of the HCS was first observed in situ by

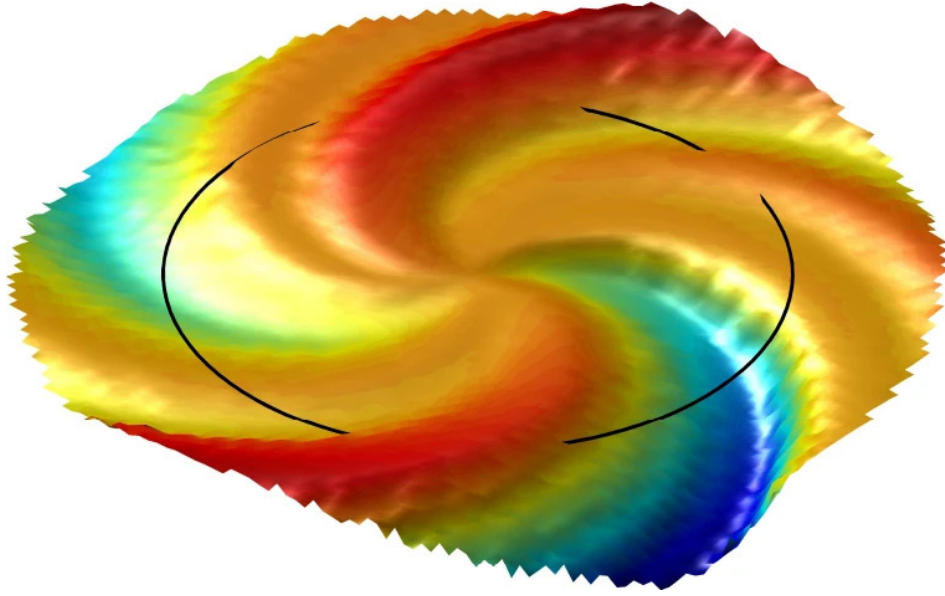


Figure 1.10: MHD simulation demonstrating the shape of the heliospheric current sheet (HCS) during solar minimum. The colour scale gives an indication of the heliographic latitude at which the HCS surface lies, where red and blue represent the extremes of the scale, where the HCS lies approximately 10 degrees above/below the equator. The Earth (black line) crosses the warped surface multiple times during its orbit. Figure from Owens and Forsyth (2013).

the Interplanetary Monitoring Platform (IMP)-1 spacecraft where measurements of the magnetic field alternated between polarities, showing that the solar wind was organised into magnetic sectors separated by a ‘sector boundary’, indicating a crossing of the HCS (Wilcox and Ness, 1965).

Whilst the Parker model provides a good description of the HMF, it does not quite capture the full dynamics and time-variability of the system. Even around solar minimum where the coronal structure is more ordered (slow solar wind ordered around the magnetic equator and faster solar wind emanating from the poles), there are significant deviations to the Parker spiral. The inclination of the solar magnetic dipole axis to the solar rotation axis causes successive streams of fast and slow wind to extend into the heliosphere. This results in stream interaction regions (SIRs), where streams of fast wind catch up with the preceding stream of slow solar wind, distorting the Parker spiral. SIRs corotate with the Sun, and are therefore often referred to as corotating interaction regions (CIRs). In situ observations of CIRs often include a forward shock moving into the slow wind ahead indicated by sudden increases of the solar wind speed,

density, and magnetic field strength, and a reverse shock moving backwards into the fast stream indicated by an increase of the solar wind velocity and decrease of magnetic field strength (Heber, Sanderson, and Zhang, 1999). A stream interface between the original slow solar wind and fast solar wind plasma is identified within the CIR by a sharp decrease in density, increase in temperature and a flow shear within the solar wind (Forsyth and Marsch, 1999).

CIRs can be geoeffective, most commonly causing weak to moderate geomagnetic storm conditions at Earth (Zhang *et al.*, 2008). The severity of geomagnetic storms can be assessed using physical measures of the geomagnetic disturbances monitored by ground-based magnetic observatories and converted to indices such as the Kp (<https://www.gfz-potsdam.de/en/kp-index/>) and Dst index (<http://wdc.kugi.kyoto-u.ac.jp/dst/dir/>). These indices are related to more general storm descriptors by the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) at <https://www.swpc.noaa.gov/noaa-scales-explanation>. CIRs, however, are not the only solar transient events that propagate through the solar wind. The most extreme deviations from the Parker model are known as coronal mass ejections (CMEs) which are often the cause of more severe space weather at Earth, described in Section 1.5 below.

1.5 Coronal Mass Ejections

Coronal mass ejections (CMEs) are large-scale expulsions of plasma and magnetic fields that are driven from the solar atmosphere and propagate through the heliosphere. These transient structures are distinguished from the ambient solar wind in both remote and in situ observations and have long been causally linked with geomagnetic activity at Earth (Gosling *et al.*, 1991; Kahler, 1992). Although CIRs can also be geoeffective, CMEs are the main drivers of severe space weather at Earth (e.g. Eastwood, 2008; Kilpua *et al.*, 2017). Adverse space weather effects include damage to communication, navigation, and power systems, and can pose a risk to the health of humans both in space and on polar-transiting flights (Baker, 1996). A recent study by Hapgood *et al.* (2021) presents the reasonable worst case scenarios caused by space weather disrupting particular sectors of national infrastructure. Understanding CMEs and their evolution is therefore of great interest in space weather modelling and the future mitigation of associated risks.

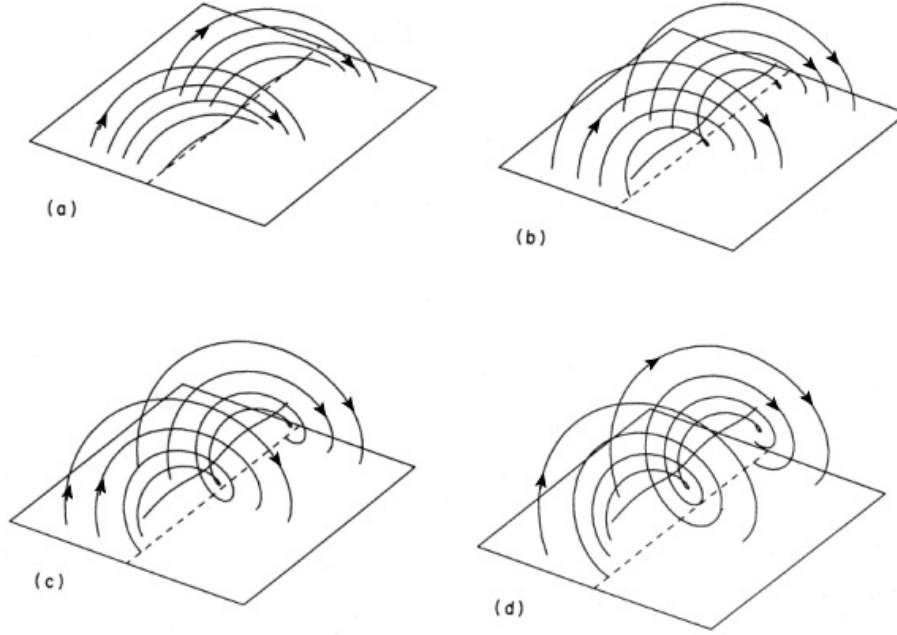


Figure 1.11: Flux cancellation of a sheared magnetic field. The initial magnetic field lines are sheared by opposing flows on either side of the PIL (a). Magnetic reconnection between opposing magnetic field lines creates a magnetic flux rope (b, c, d). The magnetic flux rope can be released by further flux cancellation. Figure from Chen (2011), originally adapted from van Ballegooijen and Martens (1989).

1.5.1 Solar origin of CMEs

The formation and magnetic configuration of CME source regions prior to eruption are still open questions, however, it is clear that CMEs are a mechanism of releasing built-up energy in the solar corona. CMEs often develop from loops of closed field near active regions, hence their occurrence is strongly related to the solar cycle and evolving solar magnetic fields.

Literature suggests two forms of pre-eruptive magnetic structure: a sheared magnetic arcade (e.g. Moore and Roumeliotis, 1992; Antiochos, DeVore, and Klimchuk, 1999) or a magnetic flux rope (e.g. Chen, 1989; Amari *et al.*, 2000; Török and Kliem, 2005), or perhaps some combination of both. Magnetic flux ropes are structures of twisted helical magnetic field lines wound around a central axis. A mathematical description of magnetic flux ropes is given in Chapter 2. In contrast, sheared magnetic arcades are a set of magnetic field lines that do not have a central axis about which the magnetic field lines twist, however, they can still contain a small amount of twisted

flux. Both structures can exist over polarity inversion lines (PILs) which separate regions of positive and negative polarity on the Sun. Filament channels are the atmospheric counterparts of the photospheric PILs, and are remotely observed as filaments (or prominences when viewed on the solar limb) when filled with plasma (e.g. Vourlidas *et al.*, 2010). The formation of filament channels is thought to be key in understanding the pre-eruptive structure of (some) CMEs. There are many different proposed physical mechanisms responsible for their formation (see review by Patsourakos *et al.*, 2020). One such mechanism is flux cancellation, shown in Figure 1.11. The orientation of the axis of an erupting magnetic flux rope can be considered to be approximately parallel to the orientation of the PIL (Marubashi, 1986).

There are many mechanisms that can trigger the release of a CME, including the tether-cutting or flux cancellation mechanism, shearing motions, the magnetic breakout model, and those involving instabilities or sudden causes of instability (for review of mechanisms, see Chen, 2011; Green *et al.*, 2018). It is important to note that most mechanisms involve magnetic reconnection in some capacity, and the formation of a magnetic flux rope if not already present. Figure 1.11 shows the formation of a magnetic flux rope via the magnetic reconnection of opposing polarity field lines in a sheared arcade, where further flux cancellation could be the mechanism by which the magnetic flux rope is released.

Magnetic flux ropes are often observed remotely in EUV images (e.g. Dere *et al.*, 1997; Zhang, Cheng, and Ding, 2012; Vourlidas, 2014). Signatures of CME eruption include solar flares, coronal ‘waves’, coronal dimming, and post-eruption arcades (see review by Harra, 2009). Figure 1.12 presents a mechanism by which the eruption of CMEs and some of these signatures may be related: magnetic reconnection between opposing magnetic field lines releases the CME flux rope as well as large amounts of magnetic energy, converted into strong bursts of electromagnetic radiation - a solar flare. Whilst solar flares and CMEs are often associated with each other, flares do not trigger CMEs, and are more likely to be symptoms of the same eruptive processes in the corona (Harrison, 1995).

Figure 1.13 presents some of these coronal signatures. The right hand panel shows a sigmoid structure, with a characteristic ‘S’ shape. Only two orientations of sigmoid are possible, forward or reverse, dependent on the chirality of the magnetic field in the region where it forms (e.g. Pevtsov, Canfield, and McClymont, 1997; Green *et al.*, 2007). A sigmoid (if present) is therefore a good indicator of the helicity of the magnetic

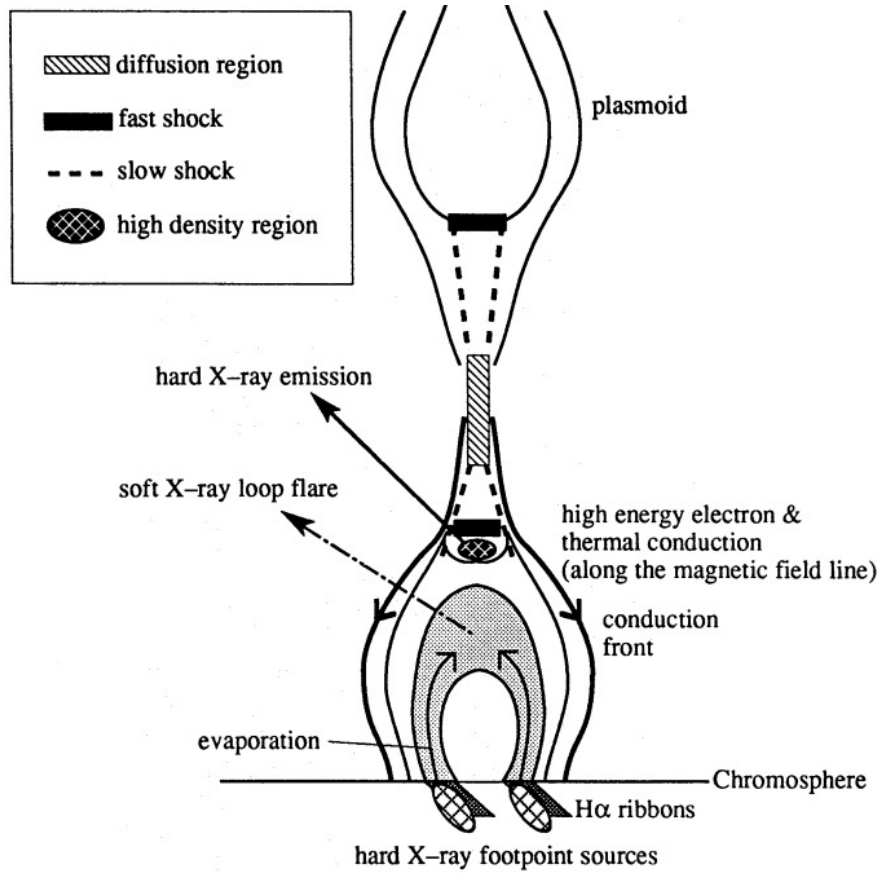


Figure 1.12: Solar flare model. Reconnection between opposing magnetic field lines releases the plasmoid (or CME flux rope) and directs jets of particles towards the magnetic field loop, causing the emission of X-rays (solar flares). Figure adapted from Magara *et al.* (1996).

flux rope. The configuration of the magnetic flux rope, based on solar indicators of its magnetic helicity and axis orientation, can be used to estimate the structure and type of CME measured in situ (see Palmerio *et al.*, 2017, 2018, and references therein).

Not all CMEs exhibit these features: CMEs which lack the classic low coronal signatures typically associated with CME eruption are known as stealth CMEs. Previous studies suggest that stealth CMEs may originate from higher in the corona (Robbrecht, Patsourakos, and Vourlidas, 2009; O’Kane *et al.*, 2021b), where plasma density and magnetic field strengths are lower leading to low energy releases at slower speeds (D’Huys *et al.*, 2014). Despite these weaker characteristics, stealth CMEs can be geoeffective and therefore present a challenge for space weather forecasters (Kilpua *et al.*, 2014; Nitta and Mulligan, 2017).

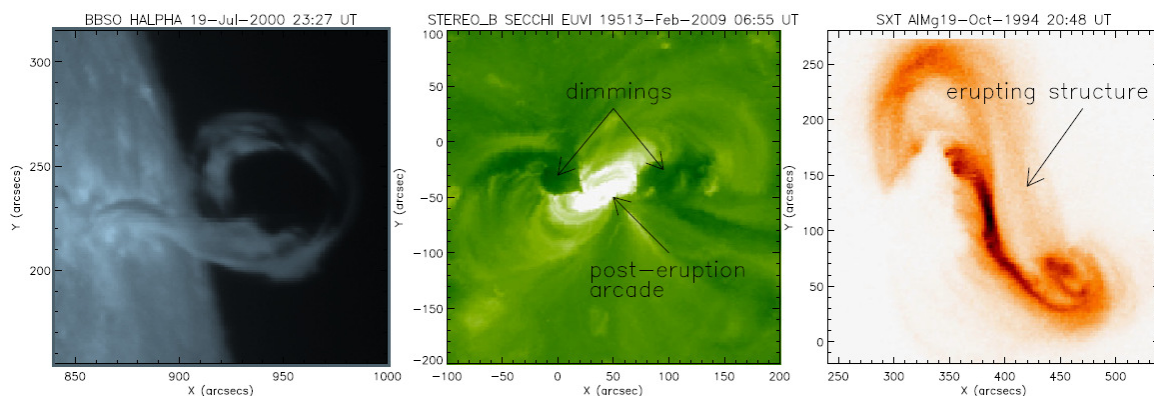


Figure 1.13: Coronal signatures of CME eruption. Left panel: a filament eruption. Middle panel: post-eruption arcades and coronal dimming regions. Right panel: rising EUV/soft X-ray structures over a sigmoid shaped feature. Figure from Green *et al.* (2018).

1.5.2 Coronagraphs and Heliospheric Imaging

After release, CMEs are accelerated through the corona before entering the heliosphere, where fast CMEs are decelerated and slow CMEs are accelerated toward the speed of the ambient solar wind (e.g. Gopalswamy *et al.*, 2000). Coronagraphs are telescopes in which the solar disk of the Sun is occulted. As CMEs exit the corona, they become visible in coronagraph fields of view. CMEs were first observed by coronagraphs in 1971 (Tousey, 1973) as bright structures in Thompson scattered white light, where brightness correlates with electron density (Billings, 1966). Prior to coronagraphs, the solar corona could only be observed remotely during a total solar eclipse. The only depiction of a CME observed during a total solar eclipse was observed by Guglielmo Temple in 1860, until the total solar eclipse of December 2020. Figure 1.14 (left) presents a composite image of the total solar eclipse in 2020 during which a CME was captured leaving the corona.

Figure 1.14 (right) shows an image of a CME taken by the C2 telescope of the Large Angle and Spectrometric Coronagraph (LASCO) onboard the Solar and Heliospheric Observatory (SOHO). The simplest configuration of a CME observed in visible-light images has a three-part structure: a bright high-density leading loop enclosing a dark low-density cavity and a bright core (e.g. Illing and Hundhausen, 1985; Hundhausen, 1993; Howard *et al.*, 1997; Vourlidis *et al.*, 2013), where the cavity is thought to be a magnetic flux rope structure (Dere *et al.*, 1999; Wood *et al.*, 1999).

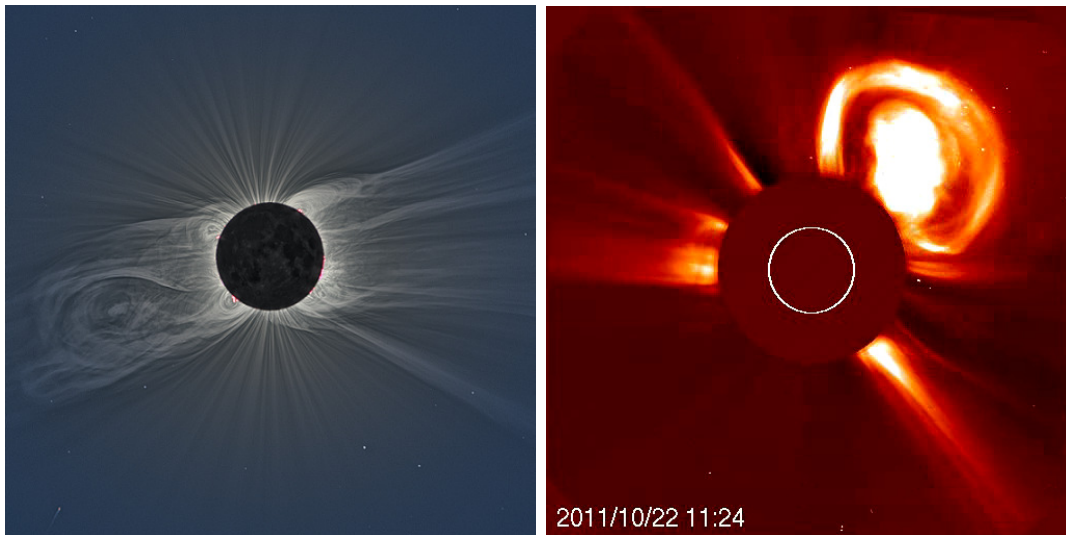


Figure 1.14: Left: A CME leaving the corona during the total solar eclipse of 14th December 2020. The image is a processed composite of 55 calibrated exposures taken during the event. Image credit: Miloslav Druckmuller and Andreas Moller, Brno University of Technology (<http://www.zam.fme.vutbr.cz/~druck/Eclipse/index.htm>). **Right:** A coronagraph image taken from the C2 telescope of the Large Angle and Spectrometric Coronagraph (LASCO) onboard the Solar and Heliospheric Observatory (SOHO) on 22nd October 2011 showing an expulsion of a CME. The CME exhibits a 3-part structure: a bright leading edge, a dark cavity, and a bright core.

LASCO, launched onboard SOHO in 1995, has now observed the corona of the Sun for two complete solar cycles. The SOHO LASCO CME catalogue lists all CMEs manually identified since 1996 (https://cdaw.gsfc.nasa.gov/CME_list/). This list has been used to assess occurrence rates of CMEs, found to vary from approximately 1 per day at solar minimum, to approximately 5 per day at solar maximum (see Webb and Howard, 2012, and references therein).

As CMEs move further away from the corona, they enter the field of view of heliospheric imagers. Similarly to coronagraphs, heliospheric imagers also observe Thompson scattered white light. The Heliospheric Imagers (HIs) onboard STEREO (Eyles *et al.*, 2009) can be used to track the evolution of CMEs between the Sun and the Earth (e.g. Davis *et al.*, 2009). The Heliospheric Imager CME catalogue keeps an up to date record of CMEs identified by the HIs as part of the Heliospheric Cataloguing, Analysis and Techniques Service (HELCATS) project (https://www.helcats-fp7.eu/catalogues/wp2_cat.html).

1.5.3 In situ Observations of ICMEs and Magnetic Clouds

Interplanetary CMEs (ICMEs) measured in situ are the heliospheric counterparts of CMEs as they propagate out within the ambient solar wind. ICMEs can be distinguished from the ambient solar wind in situ by many features including plasma, magnetic field, compositional and charge-state signatures (e.g. Zurbuchen and Richardson, 2006). Table 1.1 lists a number of possible identifying features. In this work, we identify ICMEs based primarily on the magnetic features measured in situ, complemented where possible by signatures in the plasma data. An initial in situ indicator of a possible ICME is an enhancement of the magnetic field strength. A decline in plasma velocity can also be measured as the ICME passes over the spacecraft, indicating that the ICME is expanding. A strong ICME identifier is often a particularly low proton temperature. Richardson and Cane (1995) calculated an expected proton temperature, T_{exp} , based on the empirical relationship between the observed solar wind speed and proton temperature, and found that ICMEs typically have proton temperatures $< 0.5T_{exp}$. It is important to note that not all features listed in Table 1.1 are observed in every ICME identified or are necessarily unique to ICMEs, and features present in the ICME are not always coincident.

In situ measurements of ICMEs often display signatures of magnetic flux rope structures (Cane and Richardson, 2003), likely the interplanetary manifestations of the magnetic flux rope associated with the dark cavity observed remotely (Burlaga *et al.*, 1982). Such ICMEs are known as magnetic clouds, defined as having features that include an enhanced magnetic field, smooth rotation of the magnetic field vector, low plasma β and a low proton temperature (Burlaga *et al.*, 1981). Magnetic clouds exhibit well structured magnetic fields consistent with force-free flux ropes (Goldstein, 1983). Figure 1.15 presents the different flux rope types based on the categorisations of Bothmer and Schwenn (1998) and Mulligan, Russell, and Luhmann (1998). By observing the rotation of the magnetic field components in situ, a sense of the inclination and handedness of the flux rope can be estimated. In practice, this involves identifying the direction of the dominant magnetic field component (either north, east, south, or west) at the start, middle, and end of the flux rope to produce the three letter combination of the flux rope type. A mathematical description of force-free magnetic flux ropes and possible solutions are presented in Section 2.2.3.

Figure 1.16 presents a schematic of the structure of an ICME (or magnetic cloud)

Signature	Description
B1: B rotation	$> 30^\circ$, smooth
B2: B enhancement	$> 10 \sim \text{nT}$
B3: B variance decrease	
B4: B discontinuity at ICME boundaries	
B5: HMF draping around ICME	
B6: Low plasma β	$\beta = \frac{\sum nkT}{B^2/2\mu_0} \ll 1$
P1: Declining velocity profile	
P2: Proton density (n_p) decrease	$\leq 1 \sim \text{cm}^{-3}$
P3: Proton temperature (T_p) decrease	$T_p < 0.5 T_{exp}; T_p \ll T_e$
P4: Electron temperature (T_e) decrease	$T_e < 6 \times 10^4 \text{ K}$
P5: Upstream forward shock	
C1: Enhanced $\text{He}^{2+}/\text{H}^+$	$\text{He}^{2+}/\text{H}^+ > 8\%$
C2: Elevated $\text{O}^{7+}/\text{O}^{6+}$	$\text{O}^{7+}/\text{O}^{6+} > 1$
C3: High Fe charge states	
C4: Occurrence of He^+	$\text{H}^+/\text{He}^{2+} > 0.01$
C5: Enhancements of Fe/O	
C6: Unusually high $^3\text{He}/^4\text{He}$	
W1: Ion acoustic waves	
S1: Bidirectional electron strahl	
S2: Bidirectional $\sim \text{MeV}$ ions	
S3: Cosmic ray depletions (Forbush decreases)	
S4: Bidirectional cosmic rays	

Table 1.1: In situ signatures of ICMEs observed at $\sim 1 \text{ AU}$. Magnetic field (B), plasma dynamics (P), plasma composition (C), plasma waves (W), and suprathermal particle (S) signatures are listed. Adapted from Table 1 of Zurbuchen and Richardson (2006).

as it expands through the heliosphere. It mirrors the three-part structure observed remotely, where a central magnetic flux rope attached to the solar corona has compressed the solar wind material ahead, driving a shock. It is important to note that not all ICMEs propagate at speeds fast enough relative to the solar wind speed to drive a shock. The compressed solar wind material ahead of the flux rope is known as the sheath region (see Kilpua, Koskinen, and Pulkkinen, 2017, for a review on the structure of CMEs and their sheath regions).

It is often useful to fit magnetic flux rope models to in situ observations (Burlaga,

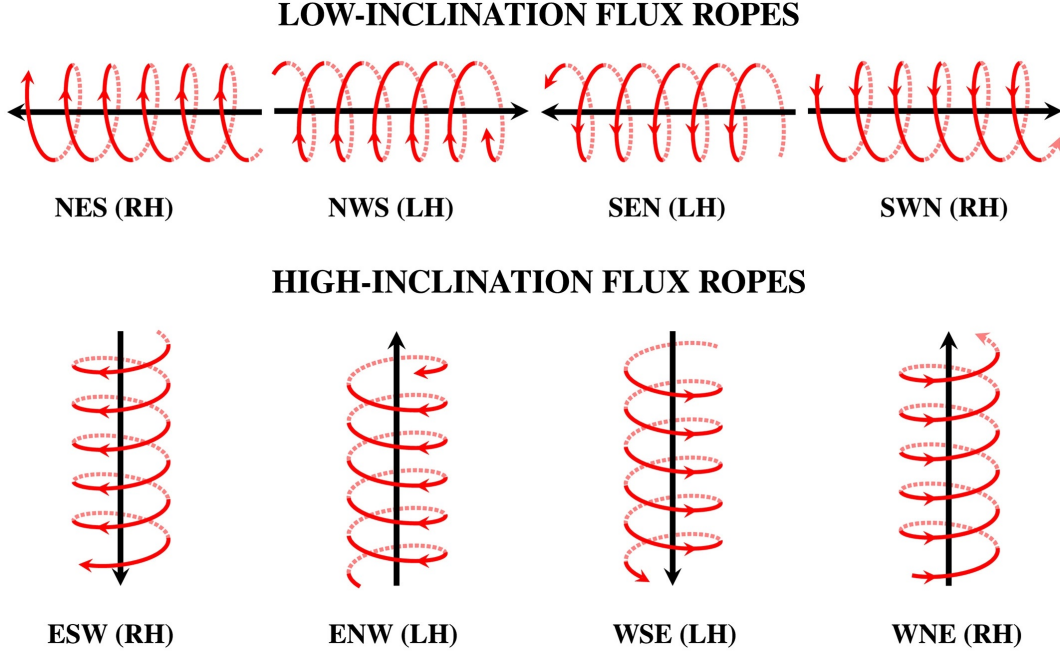


Figure 1.15: Flux rope types based on the categorisations of Bothmer and Schwenn (1998) and Mulligan, Russell, and Luhmann (1998). Each flux rope type comprises three letters, where each letter is one of the four cardinal directions: north (N), east (E), south (S), and west (W). Each flux rope type gives a sense of its inclination (low or high inclination) and its handedness (left- or right-handed). Figure from Palmerio *et al.* (2018).

1988; Lepping, Jones, and Burlaga, 1990). Two such models are described in Section 2.2.3. The proportion of ICMEs identified as magnetic clouds at 1 AU is on average $\sim 30\%$ (Gosling, 1990), however this rate varies with the solar cycle; at solar minimum, 60% of ICMEs can be identified as magnetic clouds, whereas at solar maximum, this reduces to 15% (Cane and Richardson, 2003). There is some debate as to whether all ICMEs include magnetic flux ropes (e.g. Russell, Shinde, and Jian, 2005). It is possible that observing spacecraft simply may not traverse the region in which the magnetic flux rope is present (Owens, 2016), or that distortion of the flux rope as the ICME propagates may affect observations (Jacobs *et al.*, 2009).

1.5.4 ICME Evolution and Current Understanding

The geoeffectiveness of an ICME depends strongly on the magnitude and the orientation of the magnetic field (flux rope type, axis orientation, and rotation of the magnetic field)

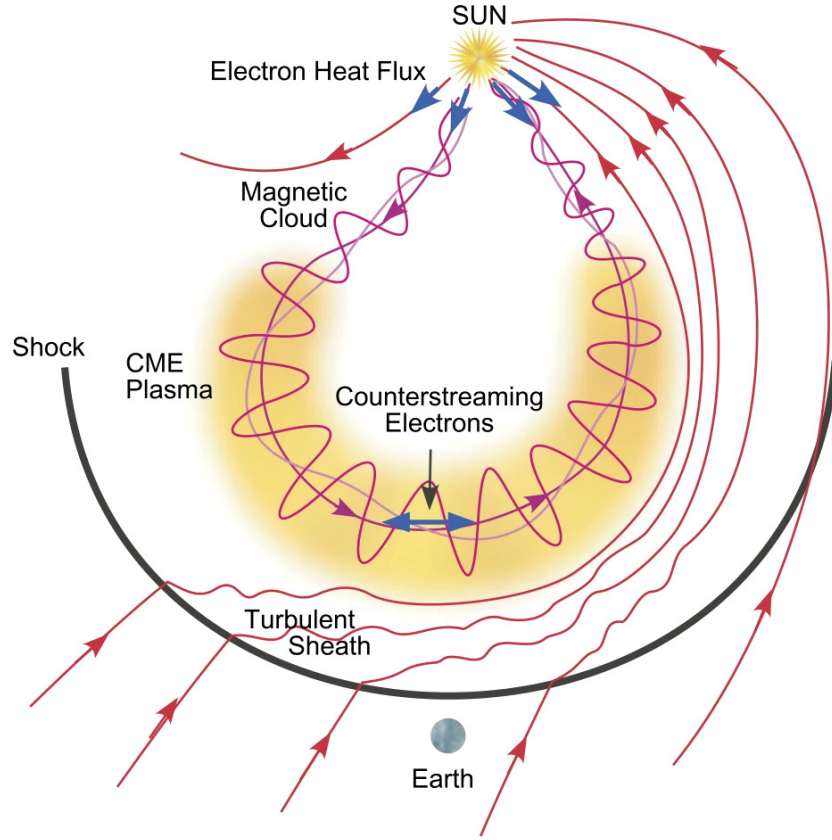


Figure 1.16: Diagram of an ICME showing the features commonly observed in situ. These include the leading shock and the compressed solar wind region forming a turbulent sheath, both driven by the ejected magnetic flux rope. Figure from Zurbuchen and Richardson (2006).

within the flux rope (e.g. Bothmer and Schwenn, 1998; Huttunen *et al.*, 2005; Kilpua *et al.*, 2017).

To understand the evolution of ICMEs as they move out in the solar wind, it is useful to track signatures of specific events over a range of heliocentric distances. The link between CMEs and ICMEs and their global structure and kinematics has previously been studied by using remote observations in combination with in situ observations (e.g. Davis *et al.*, 2009; Möstl *et al.*, 2009a; Wood and Howard, 2009; Liu *et al.*, 2010; Rouillard *et al.*, 2010; Nieves-Chinchilla *et al.*, 2012, 2013). The global structure of a CME is a complex issue affected by the interaction of the CME with the solar wind, and also possibly other CMEs, as it propagates (see Lugaz *et al.*, 2017b, for a review of CME-CME interaction). The kinematic distortion of the large-scale structure of

the ICME in a latitudinally structured solar wind leads to a flattening or ‘pancaking’ of the ICME flux rope cross-section (Odstreil and Pizzo, 1999; Riley and Crooker, 2004; Owens, 2006; Owens, Lockwood, and Barnard, 2017). This has previously been identified in remote observations by Savani *et al.* (2010) and is also investigated in Chapter 5, partially based on the recent study of the first ICME observed by Solar Orbiter (Davies *et al.*, 2021).

Alignments between spacecraft observing the same ICME in situ can also be exploited to study the radial evolution of ICMEs as they propagate (e.g. Burlaga *et al.*, 1981; Mulligan *et al.*, 1999; Möstl *et al.*, 2009b; Nakwacki *et al.*, 2011; Good *et al.*, 2015, 2018, 2019; Winslow *et al.*, 2016; Kilpua *et al.*, 2019; Lugaz, Winslow, and Farrugia, 2020; Vršnak *et al.*, 2019; Salman, Winslow, and Lugaz, 2020). As ICMEs propagate through the heliosphere, processes affecting their evolution include radial deflections which can change the course of an ICME significantly (Gosling *et al.*, 1987), rotation or changes to the inclination of the flux rope (e.g. Nieves-Chinchilla *et al.*, 2013), and erosion of the magnetic flux rope via magnetic reconnection between the ICME and the magnetic field of the solar wind (McComas *et al.*, 1998a; Dasso *et al.*, 2006; Ruffenach *et al.*, 2012, 2015). Manchester *et al.* (2017) provides a detailed review of the physical processes of CME/ICME evolution.

ICMEs have been studied in situ at varying heliocentric distances, using both dedicated solar wind spacecraft such as Helios (0.3–1 AU, e.g. Cane, Richardson, and Wibberenz, 1997; Bothmer and Schwenn, 1998), ACE/Wind (at 1 AU, e.g. Cane and Richardson, 2003; Richardson and Cane, 2010) and Ulysses (1–5.4 AU, e.g. Liu, Richardson, and Belcher, 2005; Wang, Du, and Richardson, 2005; Ebert *et al.*, 2009; Du, Zuo, and Zhang, 2010; Richardson, 2014), and planetary mission spacecraft such as MESSENGER and Venus Express (Winslow *et al.*, 2015; Good and Forsyth, 2016).

For heliocentric distances between 0.3–1 AU, Cane, Richardson, and Wibberenz (1997) used Helios data to investigate the association between decreases in cosmic ray intensity and ICME ejecta, and found that 88% of decreases in intensity were associated with ejecta. Bothmer and Schwenn (1998) identified 46 magnetic clouds in the Helios data and found that magnetic clouds could be described as large-scale quasi-cylindrical magnetic flux ropes. Most of the magnetic cloud axes were found to be of low inclination to the ecliptic plane and closely aligned to the east-west direction. Using multi-spacecraft observations, the magnetic clouds investigated were observed to have the same magnetic configuration at longitudinal separations of up to 60°. Good

and Forsyth (2016) identified 35 ICMEs using magnetic field data of MESSENGER (in orbit around Mercury) from March 2007 to April 2012, and 84 ICMEs using Venus Express data from May 2006 to December 2013. The study found that ICME magnetic flux ropes with low inclinations to the solar equatorial plane were approximately four times more common than those with high inclinations, in agreement with Bothmer and Schwenn (1998), but noted that this could be an observational effect. Good and Forsyth (2016) also used multi-spacecraft observations to investigate the longitudinal extent of magnetic flux ropes and found that, for spacecraft separations below 15° , both spacecraft observed the flux rope in 88% of cases, whereas only 12% of flux ropes were observed by both spacecraft for separations between 45° and 60° . It was also found that the wider the separation between spacecraft, the more likely that only the ICME sheath region would be observed, and not the magnetic flux rope.

At 1 AU, Richardson and Cane (2010) catalogued more than 300 ICMEs observed in situ by ACE between 1996 and 2009 (an extension of the Cane and Richardson (2003) catalogue between 1996 and 2002). Occurrence rates of ICMEs were found to follow solar activity levels, increasing by approximately an order of magnitude between solar minimum (4 ICMEs per year in 1996) and solar maximum (51 per year in 2000). Richardson and Cane (2010) also found that magnetic flux ropes were only occasionally observed as substructures of larger regions of ICME-like plasma. This observation is in line with that of Good and Forsyth (2016), suggesting that the longitudinal extent of ICME flux ropes is smaller than that of the compressed plasma and shocks or discontinuities that they drive.

The longitudinal structure and extent of ICME flux ropes has previously been studied by using multi-spacecraft at 1 AU with large longitudinal separations (e.g. Liu *et al.*, 2008; Kilpua *et al.*, 2011). Kilpua *et al.* (2011) found that for weak ICMEs at solar minimum, there were clear differences in flux rope observations over longitudinal separations of only a few degrees. Lugaz *et al.* (2018) reported clear differences in the observations of ICME flux rope magnetic field components separated by less 0.01 AU, adding to evidence that ICME flux ropes may not be coherent structures (Owens, Lockwood, and Barnard, 2017).

Winslow *et al.* (2015) identified 61 ICMEs in the MESSENGER data, observed over a wider time period than Good and Forsyth (2016), between March 2011 and September 2014. A statistical analysis of ICME properties and their evolution was conducted by combining the catalogued events with those identified at 1 AU by Richardson and

Cane (2010). The mean magnetic field strength was found to decrease with increasing heliocentric distance, r , as $r^{-1.95 \pm 0.19}$. This relationship is in agreement with that found by Gulisano *et al.* (2010) using Helios 1 and 2 observations ($r^{-1.85 \pm 0.07}$).

Janvier *et al.* (2019) compared the average properties of ICMEs at Mercury, Venus, and Earth, using the catalogues of Winslow *et al.* (2015), Good and Forsyth (2016) and Richardson and Cane (2010), respectively. ICME properties such as the magnetic field strength, were found to follow trends in agreement with previous multi-spacecraft studies. Janvier *et al.* (2019) also investigated how ICME magnetic field profiles change with heliocentric distance for different velocity categories of ICME (see Section 2.2.5 for discussion of technique). The magnetic field profiles at Mercury were found to have a slightly higher asymmetry than those observed at Venus and Earth. More generally, the magnetic field profiles were found to be more symmetric for slower ICMEs, in contrast to faster ICMEs with more asymmetric profiles, where the magnetic field magnitude was larger at the front of the magnetic flux rope than towards the trailing edge.

ICME evolution beyond 1 AU has previously been investigated using data from the Ulysses mission. Du, Zuo, and Zhang (2010) identified 181 ICMEs at Ulysses between 1991 and 2007, 43% of which could be classified as magnetic clouds. The study found that the occurrence rate of ICMEs approximately follows the solar activity level, further confirming the finding of Wang, Du, and Richardson (2005), and in agreement with the Richardson and Cane (2010) study of ICMEs at 1 AU. Ebert *et al.* (2009) identified 178 ICMEs in the Ulysses data between 1992 and 2007. Most ICMEs were identified at latitudes less than 40° and only small latitudinal variations of ICME properties were observed. Richardson (2014) identified 279 ICMEs over the Ulysses mission duration (1990–2008), and found that the latitudinal distribution of ICMEs related to the level of solar activity; around solar minimum, most ICMEs were identified at latitudes below 50° , whereas around solar maximum, ICMEs were observed by Ulysses at latitudes up to the 80° reached by the spacecraft.

The relationship between mean magnetic field strength and heliocentric distance was also investigated by the different Ulysses studies. Between 1 and 5.4 AU, Richardson (2014) found $B \propto r^{-1.21 \pm 0.09}$ and Ebert *et al.* (2009) found $B \propto r^{-1.29 \pm 0.12}$. These relationships are very different to those found in the inner heliosphere (<1 AU). Including 103 ICMEs observed by the Helios 1 and 2 spacecraft and those identified in the Richardson and Cane (2010) catalogue, Richardson (2014) calculated a relationship of $B \propto r^{-1.38 \pm 0.03}$ between 0.3 and 5.4 AU. Similarly, Liu, Richardson, and Belcher (2005)

found that $B \propto r^{-1.40 \pm 0.08}$ by including ICMEs identified at Helios, Wind, and ACE, and Wang, Du, and Richardson (2005) found that $B \propto r^{-1.52}$ by including ICMEs identified at Helios, the Pioneer Venus Orbiter and ACE. The magnetic field strength relationships calculated over heliocentric distances between 0.3 and 5.4 AU are mostly in agreement with power dependencies somewhere between those calculated over heliocentric distances below 1 AU and those beyond 1 AU.

In this thesis, we primarily use the magnetic field dataset of the Juno mission to investigate the evolution of ICMEs beyond 1 AU. A statistical analysis of the magnetic properties of the catalogued ICMEs (Chapter 3) is directly comparable with the studies of ICMEs identified by Ulysses, as both missions cover the same heliocentric distance range (1–5.4 AU). Events identified within the Juno catalogue also observed by other radially aligned spacecraft allow for a wider multi-spacecraft study of ICME evolution. One such event is the focus of Chapter 4, where significant differences were identified in observations and event properties between aligned spacecraft despite the small longitudinal separation, likely due to the solar wind environment. The influence of the solar wind background is further investigated by comparing the propagation of two very different ICMEs in Chapter 5. The distortion of one ICME by the structured solar wind is clearly observed in remote images and related to properties measured in situ. The relationship between local and global expansion measures is also assessed.

Chapter 2

Multi-Spacecraft Observations of ICMEs and Analysis Methods

Much of our knowledge of ICMEs has been gained using in situ measurements from single spacecraft, as alignments between multiple spacecraft are rare. In the last few years, there has been an increase of missions to the inner heliosphere (<1 AU), including Parker Solar Probe, Solar Orbiter and BepiColombo. Conjunctions between such missions has led to increased interest in multi-spacecraft studies of ICMEs. Multi-spacecraft studies are vital towards improving our understanding of the global structure and evolution of ICMEs. In this chapter, the spacecraft and their instrument suites used throughout this thesis, and the coordinate systems used to present data and spacecraft positions are presented, as well as common methods used to analyse the observed ICMEs.

2.1 Spacecraft and Instrumentation

ICMEs can be observed by a wide range of spacecraft in the solar wind, including dedicated solar wind missions, planetary mission spacecraft when outside of their planetary environments, and those spacecraft in their cruise phase to another planet. Whilst most recent multi-spacecraft studies have focused on the inner heliosphere within 1 AU, Juno cruise phase data provides a new opportunity to study ICME evolution over greater distances.

This section provides a description of each spacecraft used in this thesis and a gen-

eral description of how magnetic field and plasma measurements are obtained (Section 2.1.1). The magnetic field measurements made by Juno (Section 2.1.3) are primarily used in this work, in conjunction with those made by other spacecraft located at heliocentric distances of 1 AU and below. Chapter 3 utilises magnetic field measurements taken by Wind (Section 2.1.5), STEREO-A and STEREO-B (Section 2.1.6), and Venus Express (Section 2.1.7). Chapter 4 uses both magnetic field and plasma measurements taken by Wind, ACE, and the ARTEMIS mission (Section 2.1.5) to investigate the propagation of an ICME in the near-Earth environment. Chapter 5 compares two ICMEs, one of which was identified using the magnetic field data taken by Solar Orbiter (Section 2.1.4), and both were observed remotely by heliospheric imagers onboard STEREO (Section 2.1.6).

2.1.1 Instrumentation

The magnetic field measurements in this study have been measured using fluxgate magnetometers (FGMs) onboard the spacecraft described. Typically, FGMs comprise a permeable alloy core and two coils of wire (see Balogh, 2010, for a review of instrumentation). The two coils of wire are known as the ‘drive winding’ which is wrapped around the core, and the ‘sense winding’ which is wrapped around the disc of the core (Figure 2.1a). An alternating current is applied to the drive winding (a drive waveform, Figure 2.1b), magnetising and demagnetising the core in a continuous alternating cycle of magnetic saturation. As the current flows through the drive winding, the two halves of the core generate magnetic fields equal but opposite in direction. In the absence of an external magnetic field, the two half cores magnetise and demagnetise at the same time (Figure 2.1c) and thus the generated magnetic fields cancel each other out, and no current is induced in the sense winding. However, when in the presence of an external magnetic field, the half core which generates a magnetic field with an anti-parallel component to the external field demagnetises sooner than the half core with a parallel component to the external field (Figure 2.1d). During the time period of magnetisation, the magnetic fields no longer cancel each other out and a time-varying magnetic field is produced by the core, inducing a current in the sense winding. This net change in magnetic flux also induces a voltage measured by the sense coil at twice the frequency of the applied voltage (Figure 2.1e). This voltage can be converted into a DC voltage and fed back into the sense winding to counteract the core field, improving the linearity

between the external field and induced voltage. Triaxial fluxgate magnetometers comprise three orthogonal cores, able to precisely measure the orientation of the external magnetic field vector in three dimensions.

It is important to note the difference between the digital resolution and the calibrated accuracy of the magnetometer data. The digital resolution of the data depends on the physical limitations of the instrument: the reading has to be stored in binary form, and data packets have a set number of bits available to store and send these values. Magnetometers can measure over different magnetic field strength ranges, and therefore the wider the range, the larger the resolution of the data able to be recorded. The raw data returned from the spacecraft must still be calibrated. This is done by removing interference caused by solar arrays, neighbouring instruments, heaters and movement of mechanical parts onboard the spacecraft. Offsets, rotation matrices and scale factors are also applied. The calibration accuracy therefore reflects how close the final measurement is to the real value of the magnetic field after these processes have been applied.

In this work, plasma measurements have been used (where available) in combination with magnetic field measurements. The plasma measurements have been made by electrostatic analysers, which generally work by separating particles according to their direction of arrival and different values of energy per unit charge, E/q (Fazakerley, Schwartz, and Paschmann, 1998). The discretisation method by which particle measurements are obtained is primarily dependent on the spacecraft stabilisation method: whether the spacecraft is spin-stabilised or three-axis stabilised. For a spin-stabilised spacecraft, angular elevation (θ) channels are orientated perpendicular to the spin plane, and measurements are taken throughout each spacecraft rotation to increase the resolution in the azimuthal direction (ϕ) of the discrete channels or ‘bins’. The number of particles entering each discrete angular ‘bin’ is measured for a fixed E/q , and incremented per rotation to permit sampling across the range of desired E/q channels (e.g. the THEMIS ESA plasma instrument; McFadden *et al.*, 2008). Three-axis stabilised spacecraft require alternative methods to sample particle numbers. These include the use of an entrance deflection system, where a specific potential is applied to deflector plates to steer the incident particles towards the entrance of the electrostatic analyser. Particle counts can be accumulated in all azimuthal bins simultaneously, but elevation sweeping and energy stepping is necessary to cover all elevation and energy bins (e.g. the Solar Orbiter SWA instrument; Owen *et al.*, 2020). The three-dimensional velocity

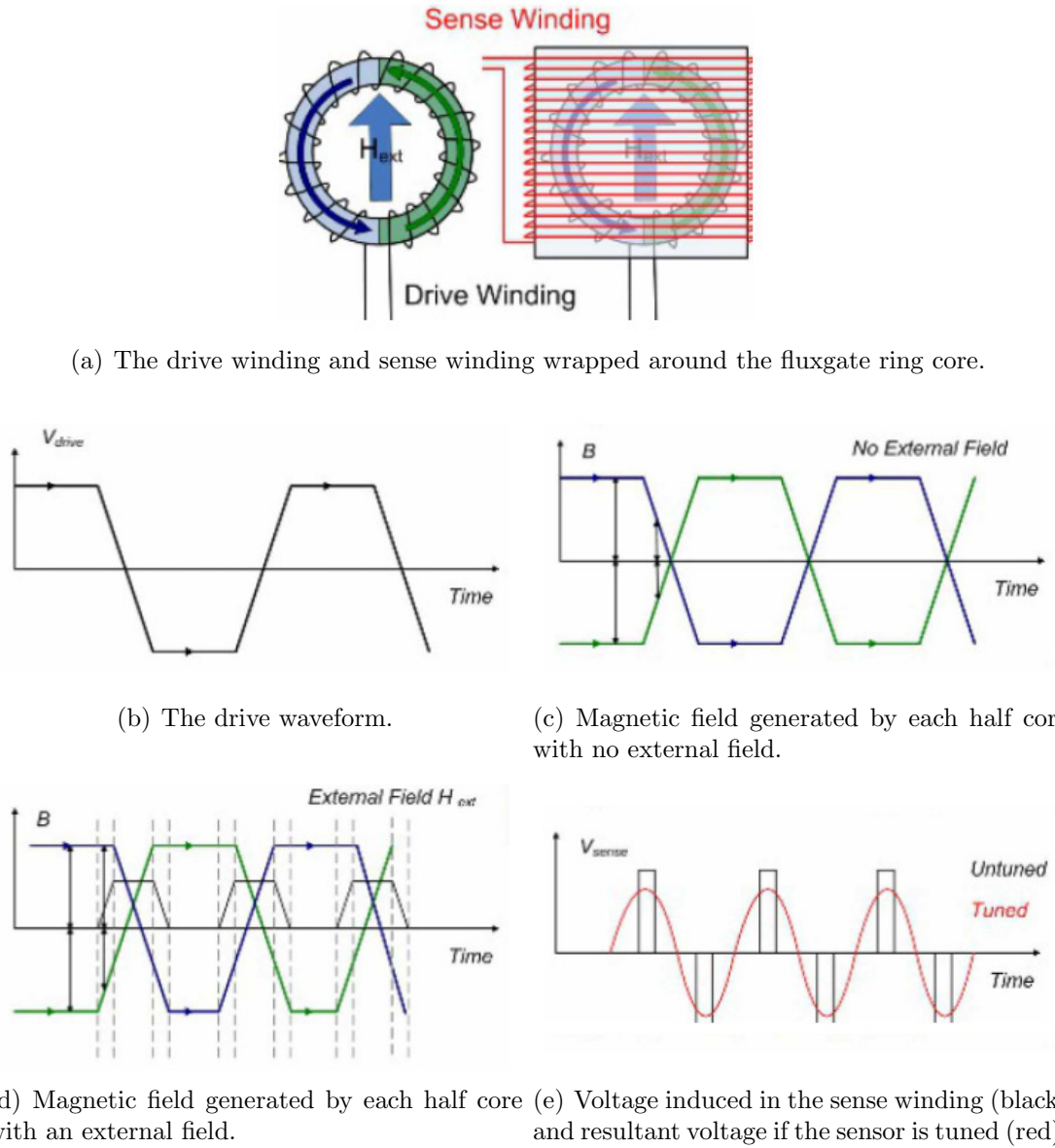


Figure 2.1: How a fluxgate magnetometer works. Figure adapted from <https://www.imperial.ac.uk/space-and-atmospheric-physics/research/areas/space-magnetometer-laboratory/space-instrumentation-research/magnetometers/fluxgate-magnetometers/how-a-fluxgate-works/>.

distributions obtained can be used to calculate the zero-, first-, second-, and third-order moments of number density, the number flux density vector, the momentum flux density tensor, and the energy flux density vector, respectively (Paschmann, Fazakerley, and Schwartz, 1998). These moments are used in combination to calculate parameters

such as the plasma bulk velocity and temperature. These parameters, in addition to the number density, are useful measurements of the solar wind plasma used throughout this thesis.

2.1.2 Coordinate Systems

Throughout this thesis, heliocentric coordinate systems have been used to present data and spacecraft positions. The heliocentric systems described below are defined as having their origin at the centre of the Sun. The systems can be divided into two categories: those based on the Sun's rotation axis, and those on the ecliptic plane.

Co-ordinate systems based on the Sun's rotation axis include:

- Heliocentric Earth Equatorial (HEEQ): the Z axis is parallel to the solar rotation axis (positive North), and the X axis points towards the intersection of the solar equator and the solar central meridian as seen from the Earth.
- Radial-Tangential-Normal (RTN): the X axis (R) points along the Sun-spacecraft line, and the Y axis (T) is the cross product of the solar rotational axis and X, and therefore lies in the solar equatorial plane.

Co-ordinate systems based on the ecliptic plane include:

- Heliocentric Earth Ecliptic (HEE): the X axis points along the Sun-Earth line and the Z axis perpendicular to the ecliptic plane of the Earth (positive North). This system is fixed with respect to the Sun-Earth line.
- Heliocentric Aries Ecliptic (HAE): similarly to HEE, the Z axis is perpendicular to the ecliptic plane of the Earth (positive North). The X axis points towards the First Point of Aries (the Vernal Equinox). This system is therefore (approximately) fixed with respect to distant stars.

To convert between different coordinate systems, transformation matrices are used which comprise one or more simple rotation matrices (see Hapgood, 1992, for detailed discussion of coordinate transforms). When converting between HAE and HEE, the transformation matrix includes the rotation between the First Point of Aries to the Sun-Earth line. Converting between HAE/HEE systems and HEEQ requires a more complex series of rotation matrices, including a rotation from the ecliptic plane to the solar equatorial plane (the solar equator is tilted by 7.25° to the ecliptic plane).

Magnetic data (and solar wind velocity data where available) is presented in RTN coordinates throughout this thesis. Spacecraft positions are presented in HAE coordinates in Chapters 3 and 4, and HEEQ coordinates in Chapter 5.

2.1.3 The Juno Mission

The Juno mission (Bolton *et al.*, 2010; Bolton *et al.*, 2017) was launched on 5 August 2011, made a flyby of Earth on 9 October 2013, and was inserted into orbit around Jupiter on 5 July 2016. It is the first solar powered mission to Jupiter and the second mission to be part of NASA’s New Frontiers Program. Juno is currently in a polar orbit around Jupiter, originally planned to last for 37 orbits, but recently extended for an additional 42 orbits until September 2025.

The primary scientific objectives of the Juno mission include the investigation of:

- i) the formation of the giant planets
- ii) the importance of the internal magnetic field of Jupiter
- iii) the importance of water and heavy element enrichment of the planet
- iv) dynamical processes in the atmosphere
- v) dynamical processes in the magnetosphere.

The Juno spacecraft carries instruments for nine science investigations which include the Jovian Auroral Distributions Experiment (JADE), the Jupiter Energetic-particle Detector Instrument (JEDI), the Ultraviolet Spectrograph (UVS), the JunoCam, the Jovian Infrared Auroral Mapper (JIRAM), the Plasma Waves Instrument (Waves), the Microwave radiometer (MWR), the Magnetometer (MAG), and the Gravity Science experiment. These instruments are shown in Figure 2.2.

The Juno Magnetic Field investigation (MAG; Connerney *et al.*, 2017) is used to investigate the interior of Jupiter and the magnetic structure of Jupiter’s magnetosphere. It comprises two independent magnetometer sensor suites, each consisting of a triaxial fluxgate magnetometer and a pair of co-located star cameras that provide accurate attitude information. The two FGMs are fixed to a 4 m magnetometer boom attached to the end of one of the solar array assemblies, placing the magnetometers 10 and 12 m away from the body of the spacecraft for magnetic cleanliness. The FGMs are capable of measuring magnetic field strengths over a large dynamic range: from 1 nT to 1,600,000 nT with a resolution of ~ 0.05 nT, and can sample the magnetic field at a rate of 64 vectors per second.



Figure 2.2: The scientific payload onboard Juno including the Jovian Auroral Distributions Experiment (JADE), the Jupiter Energetic-particle Detector Instrument (JEDI), the Ultraviolet Spectrograph (UVS), the JunoCam, the Jovian Infrared Auroral Mapper (JIRAM), the Plasma Waves Instrument (Waves), the Microwave radiometer (MWR), the Magnetometer (MAG), and the Gravity Science experiment. Figure from Bolton *et al.* (2017).

Juno was launched on 5 August 2011 on the trajectory shown by Figure 2.3. The figure shows that two deep space manoeuvres (DSMs) were made on 30 August and 14 September 2012, 13 months after launch. The final orbital manoeuvre was an Earth flyby on 9 October 2013 (26 months after launch) before Jovian orbital insertion on 5 July 2016, 33 months after the Earth flyby. The cruise phase of Juno therefore lasted a total of 59 months, or approximately 5 years between 2011 and 2016. The heliocentric distance and latitudes covered during the course of Juno’s cruise phase are presented in Chapter 3.

MAG data taken throughout the cruise phase is publicly available via the Planetary Plasma Interactions (PPI) node of the Planetary Data System (PDS) archive at <https://pds-ppi.igpp.ucla.edu/>. Data is available at both 1 minute and 1 second cadence, in 4 coordinate systems: planetocentric (PC), payload (PL), solar-equatorial (SE), and sun-state (SS). For this study, we use data at a 1 minute time resolution and in SE coordinates, equivalent to radial-tangential-normal (RTN) coordinates where the R axis

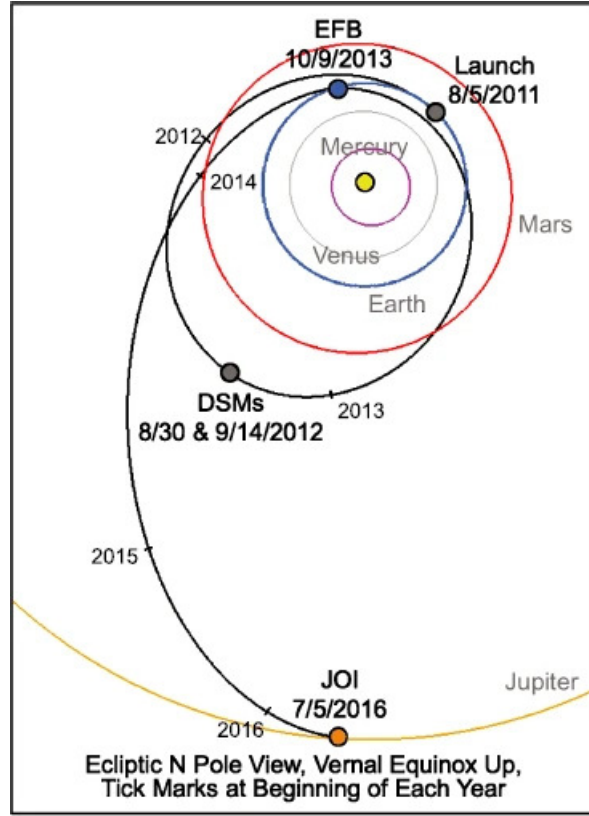


Figure 2.3: The trajectory of Juno’s cruise phase, from launch in August 2011 to Jupiter Orbit Insertion (JOI) in July 2016. The cruise phase included two Deep Space Manoeuvres (DSMs) during 2012 and an Earth flyby (EFB) during October 2013.

points from Sun centre to the spacecraft, the T axis is the cross product of the solar rotational axis and R (and thus lies in the solar equatorial plane), and N completes the right handed system. Data taken by other instruments onboard Juno is unavailable during the cruise phase, with the exception of plasma data measured by the JADE instrument during the final month of approach to Jupiter.

2.1.4 Solar Orbiter

Solar Orbiter (Müller *et al.*, 2020) is the first mission of ESA’s Cosmic Vision 2015–2025 programme, and a collaborative mission between ESA and NASA. It was launched on 10 February 2020 with a planned nominal mission duration of 7 years (including the cruise phase) and an extended mission duration of 3 years. Over the full mission duration, a total of seven gravity assists at Venus and one at Earth will be used to decrease the

perihelion distance to a minimum of 0.28 AU.

The main scientific objectives (Müller *et al.*, 2013) of Solar Orbiter aim to answer:

- i) What drives the solar wind and where does the coronal magnetic field originate?
- ii) How do solar transients drive heliospheric variability?
- iii) How do solar eruptions produce energetic particle radiation that fills the heliosphere?
- iv) How does the solar dynamo work and drive connections between the Sun and the heliosphere?

Two of the four science objectives relate directly to CMEs. Objective *iii* aims to advance our understanding of the source of energetic particles and how they are released, in which solar energetic particle (SEP) acceleration by CME-driven shocks plays a key role. Objective *ii* is the most directly related to CMEs and can be broken down into questions of CME evolution through the corona and inner heliosphere, and their contribution to the solar magnetic flux and helicity balance. The work of this thesis aims to address the evolution of CMEs throughout the heliosphere.

To achieve these science objectives, the mission carries six remote-sensing instruments (the Extreme Ultraviolet Imager (EUI), Visible light and UV Coronagraph (Metis), Polarimetric and Helioseismic Imager (SO/PHI), Heliospheric Imager (SoloHI), EUV Imaging Spectrograph (SPICE), and the X-ray Spectrometer/Telescope (STIX)) to observe the Sun and the solar corona at different wavelengths, and four in situ instruments (the Energetic Particle Detector (EPD), Magnetometer (MAG), Radio and Plasma Wave analyser (RPW), and the Solar Wind Analyser (SWA)) to measure the solar wind, energetic particles, and electromagnetic fields. These instruments are shown onboard the spacecraft in Figure 2.4.

The Solar Orbiter magnetometer (MAG; Horbury *et al.*, 2020) comprises two flux-gate magnetometers: an inboard and outboard magnetometer fixed to the spacecraft boom, 1 m and 3 m away from the spacecraft body, respectively. The magnetometer can operate at different modes, with a sample rate of up to 16 vectors per second in ‘normal’ mode and capable of both 64 or 128 vectors per second in ‘burst’ mode. Low latency (1 sample per 8 seconds) and engineering (1920 samples per second, for use during commissioning) modes are also available. The magnetometer has a nominal resolution of 4 pT when operating in the range ± 128 nT, but is capable of measuring magnetic field magnitudes of up to $\pm 58,000$ nT (at a resolution of 1800 pT).

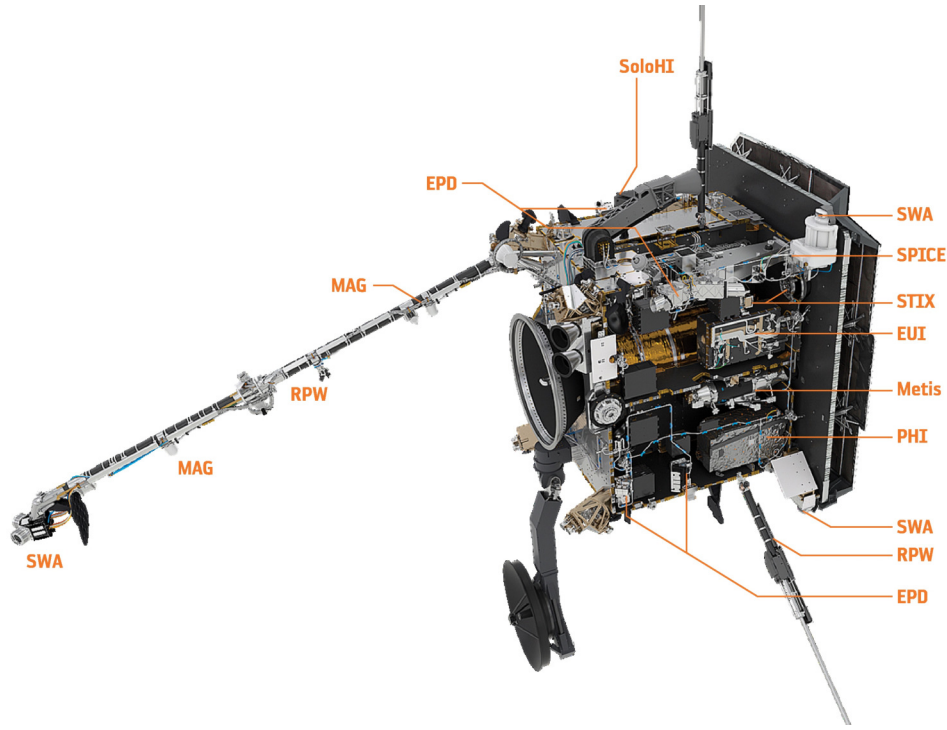


Figure 2.4: In situ and remote instruments onboard Solar Orbiter. The side panel has been removed to display the instruments mounted internally. Figure from Müller *et al.* (2020).

The nominal mission duration (which includes the cruise phase) is planned to last 7 years, with an extended mission duration of 3 years. Multiple gravity assist manoeuvres (GAMs) using both Earth and Venus are planned over the duration of the mission to increase the inclination of the spacecraft with respect to the solar ecliptic plane and decrease the perihelion distance. Figure 2.5 displays the variation in spacecraft latitude and heliocentric distance as the mission progresses. During Solar Orbiter’s cruise phase, it will reach a maximum latitude of 7° , rising to 18° in March 2025 during the nominal mission and peaking at 33° first reached in July 2029 during the extended mission phase. Figure 2.5 also shows that Solar Orbiter will reach its closest perihelion distance of 0.28 AU after the 5 Venus GAM on 24 December 2026 (end of nominal mission phase).

Data throughout the mission is publicly available via the Solar Orbiter Archive (<http://soar.esac.esa.int/soar/>). MAG files are available in normal mode, burst mode, and low latency in both RTN and spacecraft reference frame (SRF) coordinates. Daily 1 minute resolution RTN coordinate files are also available for those more inter-

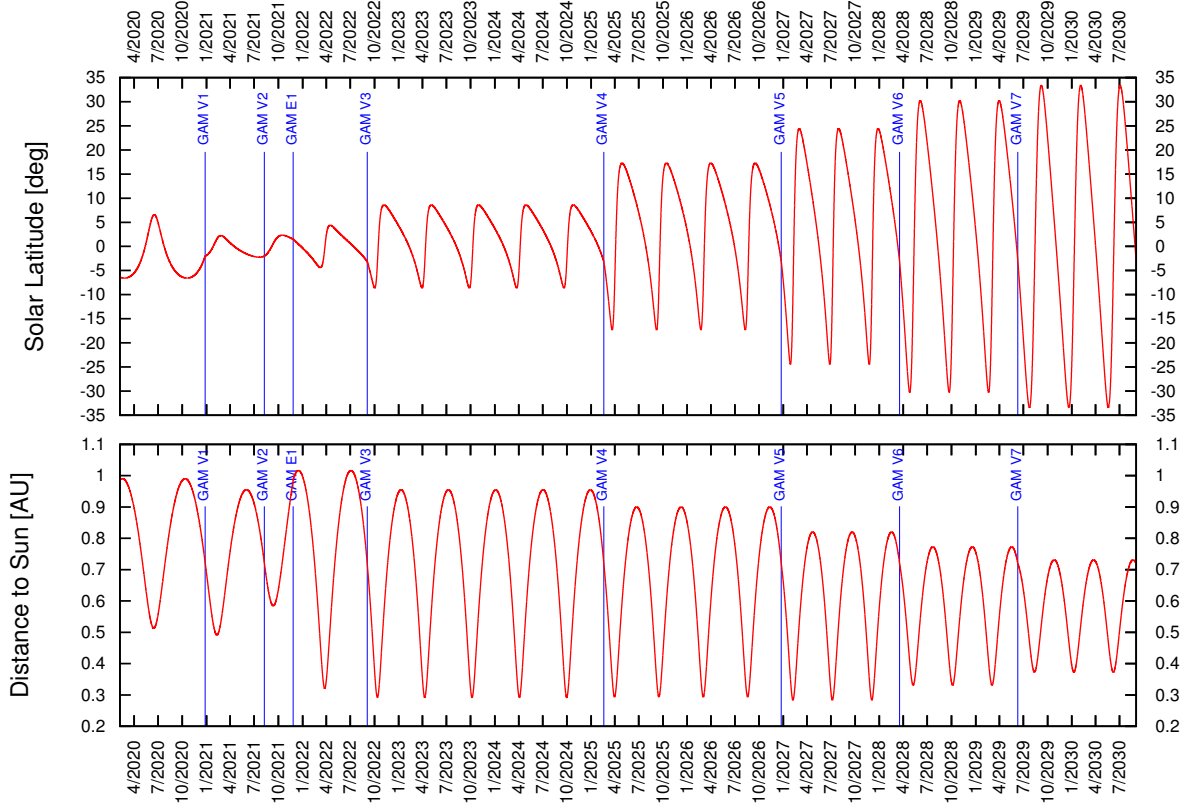


Figure 2.5: The heliocentric latitude (top panel) and distance (bottom panel) of Solar Orbiter’s trajectory over the course of the mission. The blue vertical lines indicate the times at which the Earth and Venus gravity assist manoeuvres occur. Figure from Müller *et al.* (2020).

ested in large-scale solar wind structures.

2.1.5 Near-Earth Spacecraft

This thesis makes use of multi-spacecraft data when ICMEs are observed by more than one spacecraft. In situ data taken by the Advanced Composition Explorer (ACE; Stone *et al.*, 1998), Wind (Ogilvie and Desch, 1997), and the Acceleration, Reconnection, Turbulence, and Electrodynamics of the Moon’s Interaction with the Sun (ARTEMIS; Angelopoulos, 2011) mission has been used to identify ICMEs near the Earth.

Both ACE and Wind are NASA spacecraft that orbit the L1 Lagrangian point, upstream of the Earth. Wind was launched in November 1994, three years prior to ACE in August 1997. The ACE Magnetic Field Experiment (MAG; Smith *et al.*,

1998) comprises two ring-core triaxial fluxgate magnetometers, each fixed 4.2 m away from the centre of the spacecraft on separate booms. The ACE MAG samples data at rates between 3 and 6 vectors per second, with an accuracy of ± 0.1 nT. The ACE MAG is the reconditioned flight spare of the Wind Magnetic Field Investigation (MFI; Lepping *et al.*, 1995). The Wind MFI comprises a dual triaxial fluxgate magnetometer system, with the inboard FGM mounted ~ 8 m away from the spacecraft body and the outboard FGM mounted at 12 m along the same boom. Each magnetometer is capable of measuring over 8 dynamic ranges, from ± 4 nT (at a resolution of ± 0.001 nT) to $\pm 65,536$ nT (at a resolution of ± 16.0 nT) with sample rate of 44 vectors per second in snapshot memory and 10.87 vectors per second as standard.

The NASA ARTEMIS mission comprises two of the Time History of Events and Macroscale Interactions during Substorms (THEMIS; Angelopoulos, 2008) spacecraft, THEMIS B and C. THEMIS B and C were two of the five THEMIS spacecraft launched in February 2007, and were moved to a lunar orbit in 2010. The THEMIS Fluxgate Magnetometer (FGM; Auster *et al.*, 2008) comprises a single triaxial fluxgate magnetometer on a 2 m boom. It is capable of measuring magnetic field strengths in the range $\pm 25,000$ nT, with an accuracy of 0.01 nT.

The magnetic field measurements taken by the ACE, Wind, and THEMIS magnetometers (as well as those taken by Juno) are used in Chapter 4 of this thesis, in combination with measurements of the solar wind plasma taken by the Solar Wind Electron Proton Alpha Monitor (SWEPAM; McComas *et al.*, 1998a) onboard ACE, the Solar Wind Experiment (SWE; Ogilvie *et al.*, 1995) onboard Wind, and the THEMIS Electrostatic Analyzer (ESA) plasma instrument (McFadden *et al.*, 2008). All data from the ACE, Wind, and THEMIS missions is available via NASA’s Space Physics Data Facility (SPDF) Coordinated Data Analysis Web (CDAWeb) archives (<https://cdaweb.gsfc.nasa.gov/index.html/>).

2.1.6 The STEREO Mission

The NASA Solar TERrestrial RELations Observatory (STEREO; Kaiser *et al.*, 2008) mission is formed of two twin spacecraft, launched on 26 October 2006. The spacecraft are both in heliocentric orbits at a distance of 1 AU, where one spacecraft orbits ahead of the Earth (STEREO-A) and the other spacecraft trails behind the Earth’s orbit (STEREO-B). The longitude separation between each spacecraft increases by approx-

imately 44–45° per year, contributing to a wider coverage of heliocentric longitudes and viewpoints in space. Each STEREO spacecraft carries a single triaxial fluxgate magnetometer as part of its IMPACT instrument suite (Acuña *et al.*, 2008). Each magnetometer is fixed to the spacecraft boom ~ 3 m away from the spacecraft body. They cover a wide variation of magnetic field strengths in two ranges: $\pm 65,536$ nT (with a resolution of 2 nT) and ± 512 nT (with a resolution of 0.015 nT), and provide continuous measurements at a sample rate of 32 vectors per second. Communications with STEREO-B were lost in October 2014 and despite re-establishing contact in August 2016, the attempt to recover the spacecraft was unsuccessful. STEREO-A remains fully operational. IMPACT data is publicly available via the CDAWeb archive.

The STEREO spacecraft also carries a wide range of remote imaging instruments. One instrument of particular interest in this work is the Heliospheric Imager (HI; Eyles *et al.*, 2009). Each HI instrument comprises two cameras, HI-1 and HI-2, which have fields of view of 20° and 70°, respectively, with their optical axes aligned with the solar ecliptic plane. The arrangement of the two cameras provides coverage over solar elongation angles from 4.0° to 88.7° and therefore allows observation of CMEs along the Sun-Earth line from the vicinity of the Sun to beyond the Earth. HI observations are presented in the work of Chapter 5, providing context to the in situ observations taken by Solar Orbiter, Wind, and Juno, and can be obtained via the STEREO Science Center (<https://stereo-ssc.nascom.nasa.gov/>).

2.1.7 Venus Express

The ESA Venus Express (Titov *et al.*, 2006) was a planetary mission spacecraft launched in November 2005 which reached orbit around Venus in April 2006. It had a nominal mission duration of ~ 2 years, however, its lifetime was extended by 7 years up to December 2014. The Venus Express Magnetometer (MAG; Zhang *et al.*, 2007) instrument comprises two triaxial fluxgate magnetometers, one mounted on the end of a 90 cm boom and the other on the spacecraft body itself to eliminate the magnetic effects of the spacecraft. The default measurement range of the inboard magnetometer was ± 524 nT with a resolution of 0.016 nT and the outboard magnetometer had a default measurement range of ± 262 nT with a resolution of 0.008 nT. Both magnetometers sampled the magnetic field at a rate of 128 vectors per second. Data is publicly available via the ESA Planetary Science Archive (PSA; <https://>

`//www.cosmos.esa.int/web/psa/venus-express`).

2.2 Methods of ICME Analysis

Throughout this work, we use both multi-spacecraft and single spacecraft methods to analyse ICMEs. These include timing considerations between a constellation of spacecraft to determine a direction of propagation of the ICME shock (Section 2.2.1), minimum variance analysis to estimate (i) the propagation direction of the sheath region of the ICME at each spacecraft and (ii) the orientation of the magnetic flux rope of the ICME (Section 2.2.2), and force-free flux rope fitting methods to provide estimates of the magnetic flux rope axis orientation and other parameters such as the axial magnetic field strength, impact parameter, and modelled radial width of the flux rope (Section 2.2.3). The local expansion of the ICME can be assessed by calculating values such as the dimensionless expansion parameter (Section 2.2.4) and the distortion parameter (Section 2.2.5), and the global expansion can be assessed using different data scaling methods (Section 2.2.6).

2.2.1 Timing Considerations

Assuming a constant propagation velocity, $\mathbf{V}_s$, and a planar shock front of the ICME (or any other discontinuity), we can use timing considerations of the shock front between a constellation of spacecraft to calculate the normal direction to the plane of the shock, $\mathbf{n}_s$, and speed of the shock, ν :

$$(\mathbf{R}_x - \mathbf{R}_1) \cdot \mathbf{n}_s = \nu \cdot \Delta t_{x1}, \quad (2.1a)$$

$$\mathbf{V}_s = \nu \cdot \mathbf{n}_s, \quad (2.1b)$$

where $\mathbf{R}_x - \mathbf{R}_1$ is the position of a spacecraft, x , relative to the spacecraft at $\mathbf{R}_1$, and Δt_{x1} is the difference in shock arrival times (e.g. Russell *et al.*, 1983; Möstl *et al.*, 2012). This technique is used in Chapter 4, using ACE and Wind at L1 in combination with THEMIS B and C as the spacecraft constellation. The calculated shock propagation direction can be compared with that calculated using the magnetic field coplanarity theorem or if velocity data is available, the mixed mode method (see Kilpua *et al.*, 2015, for more details). It is also possible to calculate a normal direction to the sheath

region using MVA, detailed in Section 2.2.2.

2.2.2 Minimum Variance Analysis

Minimum variance analysis (MVA) can be performed on both the sheath region and the magnetic flux rope. The technique involves calculating the eigenvectors and eigenvalues of a covariance matrix of the magnetic field components. When applied to a planar magnetic structure (PMS; as in Nakagawa, Nishida, and Saito, 1989; Neugebauer, Clay, and Gosling, 1993) of the sheath region, the minimum variance eigenvector corresponds to the normal direction of the PMS (Paschmann and Daly, 1998). The normal to the PMS has been found to be in good agreement with the shock normal in sheath regions where the PMS is found close to the shock front (Palmerio, Kilpua, and Savani, 2016). The resulting normal is more reliable when applying MVA over a range of discontinuities rather than a single discontinuity, and thus could be considered a more reliable estimate than singular shock normal determinations.

When MVA is applied to a flux rope, the intermediate eigenvector corresponds to the direction of the flux rope axis (Goldstein, 1983). The flux rope orientations are well defined if the ratios of the maximum eigenvalue, λ_1 , and minimum eigenvalue, λ_3 , to the intermediate eigenvalue, λ_2 , meet the criteria defined by Siscoe and Suey (1972) of $\frac{\lambda_1}{\lambda_2} > 1.37$ and $\frac{\lambda_3}{\lambda_2} < 0.72$. The flux rope orientation estimated by MVA is sensitive to the defined flux rope boundaries (Démoulin, Dasso, and Janvier, 2018). It is also important to note that the closer to the axis a spacecraft crosses the flux rope, the more reliable the estimated MVA axis orientation has been found to be (e.g. Klein and Burlaga, 1982; Bothmer and Schwenn, 1998; Farrugia *et al.*, 1999; Xiao *et al.*, 2004; Gulisano *et al.*, 2007).

2.2.3 Force-Free Flux Rope Fitting

In a force-free system, the magnetic, plasma pressure and gravitational forces sum to zero. The magnetic flux rope structure of CMEs can be considered force-free due to the low plasma beta they exhibit, therefore the magnetic field dominates, and thus $\mathbf{J} \times \mathbf{B} = 0$. In such a case, the current density, $\mathbf{J}$, must be parallel to the magnetic field, and therefore it can be written that $\mathbf{J} = \alpha(\mathbf{r})\mathbf{B}$ where α is a scalar function of position $\mathbf{r}$. Ampere's law can be written as:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} = \mu_0 \alpha(\mathbf{r}) \mathbf{B} \quad (2.2)$$

We can redefine $\alpha(\mathbf{r})$ so that it includes μ_0 , thus $\nabla \times \mathbf{B} = \alpha(\mathbf{r}) \mathbf{B}$. Since the magnetic field is non-divergent ($\nabla \cdot \mathbf{B} = 0$), by taking the divergence of this equation we can write:

$$\mathbf{B} \cdot (\nabla \alpha) = 0 \quad (2.3)$$

proving that α is constant along a magnetic field line. Taking the curl of Equation 2.2 results in the Helmholtz equation for a constant α :

$$(\alpha^2 + \nabla^2) \mathbf{B} = 0. \quad (2.4)$$

Considering the cylindrical geometry of a magnetic flux rope and assuming the magnetic field only varies in the radial direction ($\mathbf{B} = \mathbf{B}(r)$, $\delta/\delta\theta = \delta/\delta z = 0$), the divergence of the magnetic field can be written as:

$$\nabla \cdot \mathbf{B} = \frac{1}{r^2} \frac{\delta(rB_r)}{\delta r}, \quad (2.5)$$

thus $B_r = 0$, and the magnetic field, $\mathbf{B} = (0, B_\theta, B_z)$. The solutions to the force-free field equation ($\nabla^2 \mathbf{B} = -\alpha^2 \mathbf{B}$) in cylindrical geometry are known as the Lundquist solutions (Lundquist, 1950):

$$B_r = 0, \quad (2.6a)$$

$$B_\phi = B_0 J_1(\alpha r), \quad (2.6b)$$

$$B_z = B_0 J_0(\alpha r). \quad (2.6c)$$

These solutions represent a force-free magnetic field with a constant α in a cylindrical configuration, where J_0 and J_1 are the zeroth and first order Bessel functions, B_0 is the magnetic field strength along the axis, and r is the radial distance from the flux rope axis. MVA can be also used as a starting point for the force-free model fit to the magnetic field components of the flux rope, and a least squares fitting procedure similar to that developed by Lepping, Jones, and Burlaga (1990) can be used, where the calculated MVA orientation initialises the χ^2 minimisation. Once a convergent fit is obtained, the minimisation process is repeated with this first solution as the initial

orientation estimate to obtain a final solution; further details of this technique are given in Good *et al.* (2019) and Kilpua *et al.* (2019). This method is used to fit the magnetic flux ropes observed in Chapter 4.

Another flux rope fitting method used in Chapter 4 considers the magnetic field to have a uniform twist across the flux rope cross-section: a ‘Gold-Hoyle’ tube (Gold and Hoyle, 1960). There has been recent interest (e.g. Hu *et al.*, 2014; Hu, Qiu, and Krucker, 2015; Wang *et al.*, 2016) in using the Gold-Hoyle model to fit flux ropes in situ. This has been motivated by evidence (Kahler, Krucker, and Szabo, 2011) indicating that magnetic field line lengths, as estimated from strahl electron travel times from the Sun, are too short to be consistent with the highly twisted (and hence very long) field lines in the outer layers of a Lundquist flux rope. In the Gold-Hoyle model, the azimuthal and axial field components are given as:

$$B_\phi = \frac{B_0 \tau r}{1 + \tau^2 r^2}, \quad (2.7a)$$

$$B_z = \frac{B_0}{1 + \tau^2 r^2}, \quad (2.7b)$$

where B_0 is the axial field strength, r is the radial distance from the rope axis, and τ is the angle a field line rotates about the axis from the leading edge of the flux rope to the trailing edge i.e. the field line twist. The Gold-Hoyle flux rope is therefore very different to the Lundquist flux rope, in which the field-line twist is at a minimum at the rope axis and infinite at the rope boundaries.

The closer to the axis a spacecraft crosses the flux rope, the more reliable the calculated force-free fitting parameters have been found to be (e.g. Gulisano *et al.*, 2005; Ruffenach *et al.*, 2012, 2015). By introducing different levels of noise to magnetic flux ropes, Lepping, Berdichevsky, and Ferguson (2003) assessed the uncertainty in the fitted flux rope orientations and found estimated errors of $\approx 13^\circ$ and $\approx 30^\circ$ in θ (the angle of inclination to the ecliptic plane) and ϕ (the angle that lies within the ecliptic plane), respectively. Previous studies investigating model performance and the importance of flux rope boundary selection include Riley *et al.* (2004), Dasso *et al.* (2006), Al-Haddad *et al.* (2013, 2018), and Janvier *et al.* (2015).

2.2.4 Dimensionless Expansion Parameter

The dimensionless expansion parameter (ζ) developed by Démoulin and Dasso (2009) and Gulisano *et al.* (2010) provides a measure of the local expansion of an ICME:

$$\zeta = \frac{\Delta V}{\Delta t} \frac{r_H}{V_c^2}, \quad (2.8)$$

where $\frac{\Delta V}{\Delta t}$ is the slope of the velocity profile inside the flux rope, r_H is the heliospheric distance at which the measurements are made, and V_c is the speed of the flux rope centre (cruise velocity).

Typically, values lie in the range $\zeta = 0.81 \pm 0.19$ for non-perturbed magnetic clouds at 1 AU (Gulisano *et al.*, 2010). Gulisano *et al.* (2010) found that the dimensionless expansion parameter is independent of radial distance and therefore could be used to relate to the global expansion of ICMEs, where the magnetic field strength would be expected to decrease as $r^{-2\zeta}$ and the radial size expected to increase as r^ζ (see Dumbović *et al.*, 2018, for discussion).

2.2.5 Distortion Parameter

The distortion parameter (DiP), introduced by Nieves-Chinchilla *et al.* (2018), quantifies the distortion of the magnetic flux rope cross section by considering the temporal average of the magnetic field profile:

$$\langle B(t) \rangle_t = \frac{1}{T_d} \int_{t_s}^t B(t) dt \quad (2.9)$$

where $B(t)$ is the magnetic field magnitude and T_d is the duration of the magnetic flux rope defined. The DiP is the fraction of the magnetic flux rope duration at which 50% of $\langle B(t) \rangle$ has been accumulated:

$$\frac{\int_0^{\text{DiP} \cdot T_d} B(t') dt'}{\int_0^{T_d} B(t') dt'} = 0.5. \quad (2.10)$$

This parameter is similar to others that quantify the asymmetry of magnetic field profiles by calculating the weighted mean position of a distribution (e.g. Janvier *et al.*, 2019).

Values of DiP range between 0 and 1, where a symmetric magnetic field profile would

have a DiP of approximately 0.5. Values < 0.5 indicate an asymmetric magnetic field profile where the magnetic field is stronger towards the front of the flux rope compared to the back, whereas values > 0.5 indicate the opposite case.

For faster ICMEs, the magnetic field profiles are often asymmetric, with a larger magnetic field strength at the front of the flux rope (Janvier *et al.*, 2019). This can be considered an effect of the time difference in observations between the leading and trailing edges of the flux rope where, in an expanding flux rope, the magnetic field weakens in the time taken to pass the observing spacecraft. Slow ICMEs with a small expansion velocity tend to have a more symmetric magnetic field profile (Masías-Meza *et al.*, 2016). The calculation of the DiP can be used to justify the cylindrical geometry assumed by the force-free flux rope fitting methods, especially for symmetrical non-expanding magnetic profiles.

2.2.6 ICME Scaling

ICMEs are often assumed to expand self-similarly. Alignment between spacecraft observing the same event allows observations of the ICME magnetic field at the inner spacecraft to be mapped to the heliocentric distance of the outer spacecraft, to assess the similarity between ICME flux ropes.

The simplest mapping method is to compare the duration of the magnetic flux rope between spacecraft to find a scaling factor, and apply this to the inner spacecraft data. The scaled times are then aligned at the leading edge of the magnetic flux rope so that the two magnetic flux ropes match both at the leading edge and trailing edge boundaries. This technique has the effect of assuming that each part of the flux rope expands at the same rate (e.g. Lugaz, Winslow, and Farrugia, 2020).

Another mapping technique developed by Good *et al.* (2018) involves the calculation of the mean propagation speeds of the leading and trailing edges between spacecraft, and assumes a linear decline in speed between calculated values. Mapping different points of the flux rope by different speeds does not assume a self-similar expansion, with features towards the leading edge more compressed than those towards the trailing edge.

Assessment of how the magnetic field strength varies with heliocentric distance provides a measure of the global expansion of the ICME. Previous studies have shown that for a self-similarly expanding cylindrical flux rope, the axial magnetic field is expected to decrease with heliocentric distance as r^{-2} and the poloidal field as r^{-1}

(Farrugia *et al.*, 1993; Leitner *et al.*, 2007; Manchester *et al.*, 2017; Dumbović *et al.*, 2018). This theory is explored further in Chapter 5.

In reality, CME evolution can be much more complex, with interactions between CMEs (e.g. Lugaz *et al.*, 2017a; Wang *et al.*, 2018) and with other features such as the HCS (Winslow *et al.*, 2016), magnetic reconnection occurring within the magnetic flux rope (e.g. Steed *et al.*, 2011; Ruffenach *et al.*, 2012; Jian *et al.*, 2018), and deformation by the solar wind environment (e.g. Owens, 2006; Savani *et al.*, 2010; Owens, Lockwood, and Barnard, 2017).

We apply the techniques described in this section to in situ observations of individual ICMEs at different spacecraft to analyse their evolution as they propagate. The analysis of the ICME which is the focus of Chapter 4 uses the techniques described in Sections 2.2.1, 2.2.2 and 2.2.3. Chapter 5 compares and contrasts the evolution and expansion of two ICMEs, using the techniques described in Sections 2.2.4, 2.2.5 and 2.2.6.

Chapter 3

A Catalogue of ICMEs Observed by Juno

In this chapter, a catalogue of some probable 33 ICMEs observed by the Juno spacecraft is presented. During its cruise phase, Juno spent ~ 5 years in the solar wind between September 2011 and June 2016, providing an excellent opportunity for studies of ICMEs beyond 1 AU.

Previous studies have discussed the identification of ICMEs near the Earth (e.g. Cane and Richardson, 2003; Richardson and Cane, 2010) and in the inner heliosphere (e.g. Bothmer and Schwenn, 1998; Cane, Richardson, and Wibberenz, 1997; Leitner *et al.*, 2007) based on a variety of solar wind signatures such as the occurrence of abnormally low proton temperatures and energetic particle decreases as primary identifiers. These studies used data from dedicated solar wind spacecraft such as ACE and the Helios mission. Other studies of ICMEs in the inner heliosphere include the use of planetary mission spacecraft such as MESSENGER and Venus Express (Winslow *et al.*, 2015; Good and Forsyth, 2016) where ICMEs were identified by their magnetic field signatures as neither spacecraft housed dedicated solar wind plasma analysers.

Similarly to the studies of Winslow *et al.* (2015) and Good and Forsyth (2016), this study primarily uses only magnetic field data. Although carrying a wide range of instruments suitable for observing solar transients, the Juno Magnetic Field Investigation instrument (MAG; Connerney *et al.*, 2017) was the only instrument providing data during the mission cruise phase. With the reliance on magnetic field signatures as identification criteria, ICMEs identified may well also be magnetic clouds, however,

the unavailability of temperature data prevents any explicit magnetic cloud identifications based on the definition of Burlaga *et al.* (1981). The plasma instrument onboard Juno, the Jovian Auroral Distributions Experiment (JADE; McComas *et al.*, 2017), was turned on during the final month of approach to Jupiter, aiding in the identification of one magnetic cloud.

The Ulysses mission (e.g. Wenzel *et al.*, 1992) provided comprehensive measurements of the heliosphere and solar wind beyond 1 AU and at high latitudes following its launch in October 1990. Several catalogues of ICMEs identified at Ulysses have been published, including Liu, Richardson, and Belcher (2005); Wang, Du, and Richardson (2005); Ebert *et al.* (2009); Du, Zuo, and Zhang (2010); and Richardson (2014). Similarly to the Richardson and Cane (2010) catalogue of ICMEs at Earth, Liu, Richardson, and Belcher (2005); Wang, Du, and Richardson (2005); and Richardson (2014) identify abnormally low proton temperatures as the primary identifying signature of an ICME. The Ebert *et al.* (2009) study focusses on the radial and latitudinal variations of the slow solar wind, fast solar wind, and ICMEs. Du, Zuo, and Zhang (2010) studies the occurrence rate of ICMEs and the interaction of ICMEs with solar wind at increasing heliocentric distances. Richardson (2014) provides a comparison of the number of ICMEs identified in their study with those of Ebert *et al.* (2009) and Du, Zuo, and Zhang (2010) finding that only 102 ICMEs are identified across all three catalogues (relative to 327 in total), demonstrating the highly subjective nature of ICME identification and dependence on identification criteria.

In this chapter, we also link ICMEs identified at Juno with the same signatures observed by spacecraft at 1 AU and the inner heliosphere such as Venus Express, STEREO-A and B, and Wind, providing the basis for many future multi-spacecraft studies. For each ICME observed by another spacecraft, we have tracked parameters such as the mean and maximum magnetic field strength to calculate relationships with increasing heliocentric distance. We then compare these relationships with more general catalogue statistical relationships and assess the evolution of ICMEs as they propagate through the heliosphere.

Section 3.1 provides an overview of the magnetometer data throughout Juno’s cruise phase, and Section 3.2 details the identification criteria used to compile the ICME catalogue presented in Section 3.3. A wider study of ICMEs observed at both Juno and other spacecraft is presented in Section 3.4.

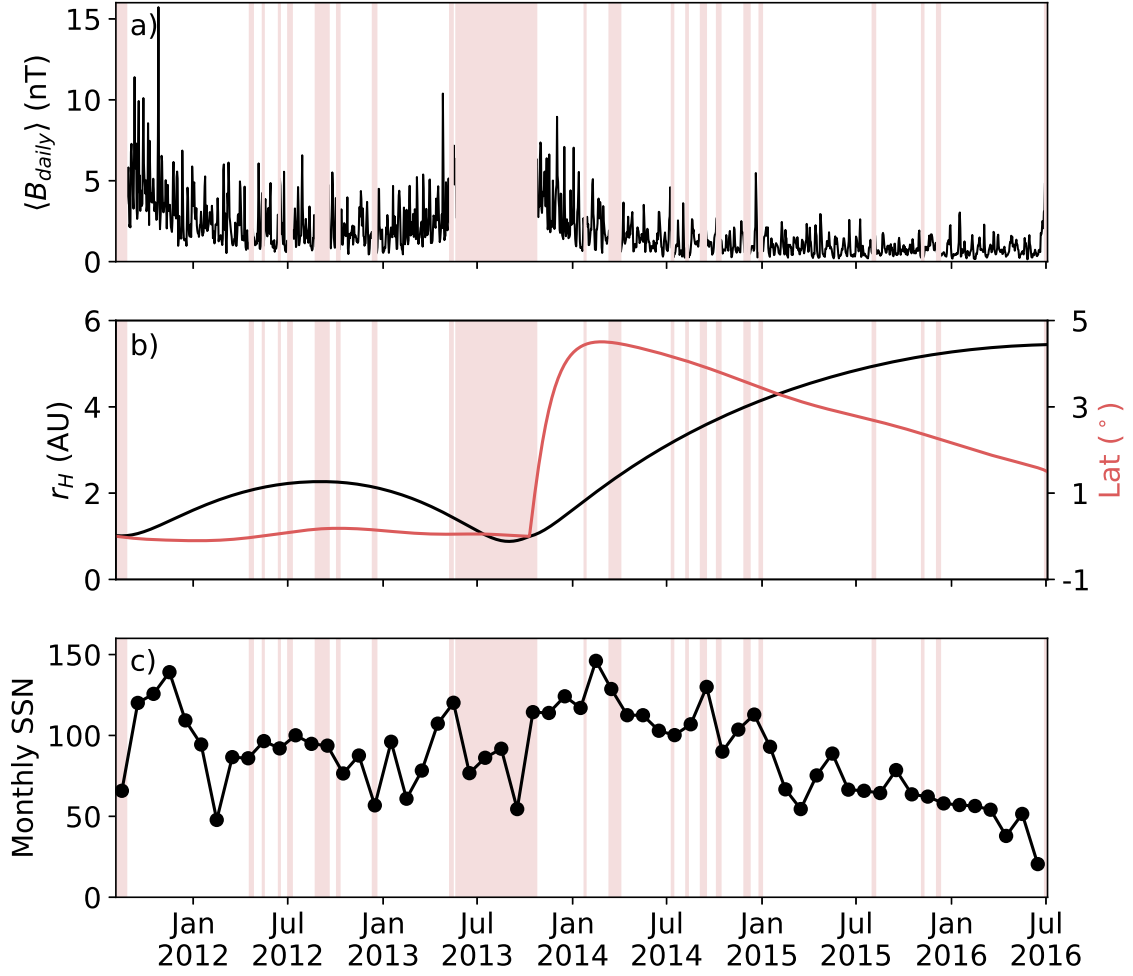


Figure 3.1: **a)** The mean daily magnetic field magnitude observed by Juno between launch on 5 August 2011 and orbital insertion at Jupiter on 4 July 2016. Vertical lines indicate days for which magnetometer data is unavailable. **b)** Heliocentric distance (left) and latitude (right) of the Juno orbit during its cruise phase. **c)** Monthly mean sunspot number.

3.1 Overview of Juno Cruise Data

Figure 3.1a presents an overview of the magnetic field data and its availability between launch on 5 August 2011 and orbital insertion at Jupiter on 4 July 2016. The middle panel (b) displays the spacecraft heliocentric distance and latitude, and the bottom panel (c) displays the monthly mean sunspot number (<http://www.sidc.be/silso/>) throughout the cruise phase. Following launch, Juno moved away from the Sun with an

aphelion of ~ 2 AU whilst remaining close to the ecliptic plane before a gravity assist at Earth redirected its trajectory towards Jupiter at 5.4 AU. The gravity assist at Earth resulted in raising the heliolatitude of the spacecraft to $\sim 4.5^\circ$ which gradually declined back towards the ecliptic plane with increasing heliocentric distance. During the months surrounding the gravity assist at Earth, the magnetometer instrument was turned off resulting in the largest data gap during the cruise phase between 23 May and 5 October 2013 inclusive. However, despite data gaps, Figure 3.1 shows that overall, there is good data availability over the cruise phase for the complete range of heliocentric distances covered.

Juno was launched as the solar activity of Solar Cycle 24 was increasing, with the first peak in sunspot number occurring in November 2011 only a few months later. Most of the cruise phase took place under solar maximum conditions with activity peaking in April 2014 and slowly declining thereafter. It is therefore not possible for this study to provide a comparison of CME occurrence rates and other parameters over the different stages of the solar cycle.

The magnetic field magnitude is inversely proportional to the heliocentric distance, r , well approximated by $B \propto \frac{\sqrt{1+r^2}}{r^2}$ which approaches $B \propto \frac{1}{r}$ with increasing heliocentric distance (e.g. Parker, 1958; Burlaga *et al.*, 1984). Gruesbeck *et al.* (2017) found that applying the expected $1/r$ relationship to the Juno cruise data resulted in a very good fit to the magnetic field data, which was also of lower magnitude in comparison to observations of previous solar cycles made by Voyager and Ulysses. This is consistent with observations of the radial magnetic field at 1 AU during Solar Cycle 24, where the magnitude was found to be $\sim 38\%$ lower than previous solar cycles observed between the mid-1970s to the mid-1990s (McComas *et al.*, 2013).

3.2 ICME Identification Criteria

With the absence of plasma data, we focus on identifying features in the magnetic field data that meet three main criteria: 1) an enhanced magnetic field magnitude at least twice that of the expected ambient solar wind, 2) coincident with a relatively smooth rotation of the magnetic field components, 3) with a duration of more than 12 hours. These criteria are similar to those of Burlaga *et al.* (1981) when defining a magnetic cloud.

As the heliocentric distance at which Juno observes events is continually changing, the expected magnetic field strength of the ambient solar wind with increasing heliocentric distance has been considered (see Gruesbeck *et al.*, 2017). Events are considered enhanced if they exceed twice the expected magnetic field magnitude at the heliocentric distance at which they are observed. This is consistent with the Richardson and Cane (2010) catalogue of ICMEs at Earth where events >10 nT were selected as the background solar wind at 1 AU is on the order of 5 nT.

The duration criterion of 12 hours differs from other catalogues near Earth where an ICME duration of ~ 1 day is commonplace. Catalogues of ICMEs in the inner heliosphere e.g. Good and Forsyth (2016) define shorter duration criteria (4 hours) to ensure large-scale flux ropes likely to be associated with CMEs are included, but smaller-scale flux ropes are excluded. The selection of flux ropes with durations of more than 12 hours provides a balance between capturing large-scale structures, but not too short as to exclude structures at larger heliocentric distances that have undergone more prolonged/likely interaction with the solar wind and other transients. The duration criterion also only applies to the flux rope, not to the ICME as a whole; this is to not exclude slower or more complex events where there may not be a clear shock or sheath region preceding the magnetic flux rope. Flux rope boundaries have been selected at discontinuities in magnetic field components, between which there is a clear rotation in the magnetic field. The criterion of a smooth rotation of the magnetic field components ensures that (purely) stream and co-rotating interaction regions are excluded, although it is possible that events listed may be ICMEs that have interacted with these transient solar wind features.

3.3 ICME Catalogue

Table 3.1 lists the 33 events identified in the Juno cruise magnetometer dataset that meet the criteria detailed in Section 3.2. Events are listed chronologically and can be identified by their corresponding identification number (ID#) which follows the date format ‘YYYYMMDD’ at which the shock front (t_S) of the ICME was first observed. If a shock is not associated with the event, it corresponds to the defined leading edge (t_L). Where two or more events are first observed on the same day, the ID# is given a letter suffix (e.g. ‘a’, ‘b’, etc.).

Columns 2 to 4 of Table 3.1 give the defined start of the shock associated with

the event (t_S), the leading edge of the magnetic flux rope (t_L) and the trailing edge of the magnetic flux rope (t_T) to the nearest minute. In some cases, the trailing edge is rather ambiguous to define; in these cases an alternative time has also been defined in parentheses. Events 20120512 and 20120616 are listed despite significant data gaps obscuring the magnetic flux rope, where the true trailing edge and leading edge are not identifiable. The missing data in these cases is indicated by an asterisk (*) following their ID#.

The spacecraft heliocentric distance (r_H), latitude and longitude in Heliocentric Aries Ecliptic (HAE) coordinates are listed in columns 5 to 7. Columns 8 and 9 list the maximum magnetic field (B_{max}) and mean magnetic field strength (B_{mean}) observed within the magnetic flux rope. Column 10 lists the type of flux rope, based on the classifications of Bothmer and Schwenn (1998) and Mulligan, Russell, and Luhmann (1998) (see Section 1.5.3 for a description of the different flux rope types) and column 11 lists the corresponding handedness, left (L) or right (R), of the magnetic flux rope. The final column provides a subjective indication of the quality of the event between 1 and 3, where 1 indicates a high quality event, and 3 indicates a weaker quality event. Considerations in assigning the quality of an event include the ease in defining flux rope boundaries, the magnetic field variance and smoothness of the rotation, and the presence/absence of data gaps: quality 1 events display a clear magnetic cloud structure with well defined boundaries and a smooth, low variance rotation of the magnetic field, and no data gaps. Events with large data gaps leading to obscured flux rope boundaries are automatically assigned a quality of 3, despite whether they contain other high quality features.

ID#	t_S	t_L	t_T (alt)	r_H [AU]	lat [°]	lon [°]	B_{max} [nT]	B_{mean} [nT]	Rope Type	H Q
20110917	17/09/2011 06:29	17/09/2011 19:59	18/09/2011 13:17 (18/09/2011 21:51)	1.07	-0.06	0.79	14.99	11.84	SEN	L 1
20111005	05/10/2011 21:28	06/10/2011 07:18	07/10/2011 04:40	1.14	-0.07	18.47	9.41	8.26	-	- 2
20111009	09/10/2011 02:46	10/10/2011 04:06	10/10/2011 20:33	1.16	-0.07	21.87	6.12	5.44	ENW	L 3
20111025	25/10/2011 14:22	26/10/2011 00:40	26/10/2011 13:36 (26/10/2011 15:27)	1.24	-0.08	34.72	21.04	19.70	SEN	L 1
20111229	29/12/2011 14:15	01/01/2012 08:28	01/01/2012 23:56	1.61	-0.10	74.00	3.86	3.37	ENW	L 2
20120307a	-	07/03/2012 00:32	07/03/2012 18:44	1.91	-0.08	98.63	5.41	4.72	ESW	R 1
20120307b	-	07/03/2012 21:49	08/03/2012 12:38	1.92	-0.08	98.91	4.88	3.96	NES	R 2
20120512*	12/05/2012 13:23	13/05/2012 15:43	14/05/2012 07:20	2.13	0.01	117.76	-	-	-	- 3
20120616*	-	-	16/06/2012 20:35 (17/06/2012 05:40)	2.20	0.06	126.22	-	-	-	- 3
20120728	28/07/2012 15:35	28/07/2012 23:54	31/07/2012 05:14	2.25	0.13	136.08	8.87	4.54	WSE/ SEN	L 1
20121115	15/11/2012 13:53	16/11/2012 13:37	18/11/2012 16:35	2.20	0.17	160.77	3.79	3.16	SWN	R 1
20121118	18/11/2012 23:10	19/11/2012 21:11	20/11/2012 19:49 (21/11/2012 07:29)	2.19	0.17	161.54	5.06	4.17	NES	R 1
20121129	29/11/2012 01:25	29/11/2012 19:19	30/11/2012 18:54	2.17	0.16	163.85	3.01	2.74	WNE	R 2
20130113	29/01/2013 10:50	31/01/2013 04:21	02/02/2013 07:34	1.98	0.10	179.82	4.76	4.14	SEN	L 2
20130219	19/02/2013 22:07	20/02/2013 20:05	22/02/2013 10:34	1.90	0.08	185.92	5.71	4.46	WNE	R 1
20130415	15/04/2013 18:21	17/04/2013 01:10	18/04/2013 13:04	1.61	0.05	205.83	5.28	4.41	ENW	L 1
20130502	-	02/05/2013 10:34	03/05/2013 06:07	1.52	0.05	212.81	6.03	5.54	NWS	L 3
20130516	16/05/2013 16:49	17/05/2013 06:36	18/05/2013 05:52	1.42	0.05	220.42	7.98	6.16	WNE	R 3
20131202	02/12/2013 03:04	02/12/2013 21:35	04/12/2013 12:57	1.35	3.62	70.13	6.12	5.39	WNE	R 1

Table 3.1 continued from previous page

ID#	t_S	t_L	t_T (alt)	r_H [AU]	lat [°]	lon [°]	B_{max} [nT]	B_{mean} [nT]	Rope Type	H	Q
20140207	-	07/02/2014 03:35	08/02/2014 00:17	1.95	4.49	102.21	4.50	3.62	WNE	R	3
20140209	-	09/02/2014 09:59	10/02/2014 00:01	1.97	4.49	102.96	6.14	5.11	SEN	L	3
20140301	01/03/2014 16:39	02/03/2014 15:03	03/03/2014 22:29	2.16	4.51	109.29	2.90	2.04	NES	R	2
20140422	22/04/2014 16:15	22/04/2014 21:42	26/04/2014 08:08	2.59	4.41	120.91	3.18	2.46	SEN	L	2
20151220	20/12/2014 04:24	21/12/2014 12:57	22/12/2014 03:43	4.11	3.48	148.87	5.02	4.37	-	-	3
20150206	06/02/2015 03:20	07/02/2015 02:37	07/02/2015 19:44	4.32	3.27	152.28	2.51	1.75	SEN	L	2
20150404	-	04/04/2015 16:10	05/04/2015 09:11	4.55	3.06	155.92	1.41	1.32	SEN	L	2
20150509	09/05/2015 16:30	09/05/2015 23:47	11/05/2015 07:18	4.68	2.94	158.01	2.01	1.79	NES	R	3
20150524	24/05/2015 15:19	25/05/2015 22:26	27/05/2015 03:29	4.73	2.89	158.91	1.45	1.17	SEN	L	2
20150729	29/07/2015 04:21	29/07/2015 07:15	30/07/2015 07:21	4.93	2.70	162.38	1.55	1.29	SWN	R	3
20151118	18/11/2015 10:56	22/11/2015 08:22	25/11/2015 07:55	5.20	2.31	168.06	1.77	1.68	ESW	R	1
20160114	14/01/2016 16:03	15/01/2016 05:12	15/01/2016 18:48	5.29	2.11	170.50	1.53	1.30	SEN	L	2
20160116	16/01/2016 02:32	17/01/2016 00:09	17/01/2016 19:11	5.30	2.10	170.58	3.60	3.32	NES	R	1
20160520	20/05/2016 10:56	21/05/2016 09:54	22/05/2016 02:26	5.42	1.67	175.85	1.68	1.48	ESW	R	1

Table 3.1: Catalogue of events identified in the Juno cruise dataset, where t_S is the time of the shock associated with the event (if present), t_L gives the leading edge and t_T the trailing edge of the magnetic flux rope. The spacecraft heliocentric distance (r_H), latitude and longitude in Heliocentric Aries Elliptic (HAE) coordinates are listed, along with the maximum magnetic field (B_{max}) and mean magnetic field (B_{mean}) observed within the magnetic flux rope. The type of magnetic flux rope is listed with the corresponding handedness (H) being either left-handed (L) or right-handed (R). The final column lists the quality of the event between 1 and 3, where 1 is high quality and 3 is the weakest.

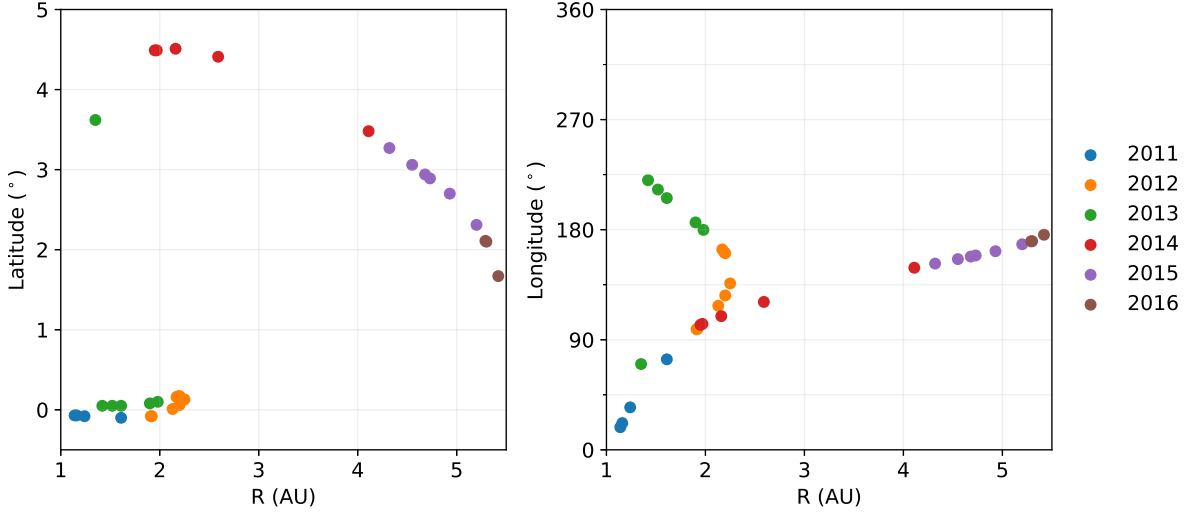


Figure 3.2: Location of the Juno catalogue events identified in this study in HAE coordinates. Latitude (left) and longitude (right) against heliocentric distance. Year of observation is indicated by the colour key.

3.3.1 Summary of Catalogue Events

Figure 3.2 shows the heliocentric distance and latitude/longitude at which the events in Table 3.1 were observed. The positions are well distributed in both latitude and heliocentric distance over the cruise phase. Prior to the Earth gravity assist in October 2013, event observations were measured very close to the ecliptic plane (within 0.2°). The Earth gravity assist increased the latitude of Juno; 5 events following the assist are measured with latitudes between 3.6° and 4.5° within 2.6 AU. The 10 remaining events at heliocentric distances > 4 AU decrease in latitude from 3.5° to 1.7° . Care should be taken in the interpretation of results at higher latitudes, especially when comparing multi-spacecraft observations in Section 3.4.

Table 3.2 provides a yearly summary of the events listed in Table 3.1. Years that are incomplete/ with significant data gaps are marked with asterisks (*). Column 2 lists the number of events per year (#Events) and column 3 lists the weighted number of events per days of data available for that year (#Events Weighted). No clear trend in number of events is observed, however, there is slight declining trend in the weighted number of events per year. Care must still be taken when interpreting this result due to the different data coverage across years and the increasing heliocentric distance at which events were observed.

Column 4 lists the mean heliocentric distance at which events were observed ($\langle r_H \rangle$),

Year	#Events	#Events Weighted	$\langle r_H \rangle$	$\langle B_{mean} \rangle$	$\langle B_{max} \rangle$	#LH	#RH	#High inclination	#Low inclination
2011*	5	0.039	1.24	9.72	11.09	4	0	2	2
2012	8	0.025	2.12	3.88	5.17	1	5	2	3
2013*	6	0.028	1.63	5.02	5.98	3	3	4	2
2014	4	0.013	2.17	3.31	4.18	2	2	1	3
2015	7	0.018	4.65	1.91	2.25	3	3	1	5
2016*	3	0.017	5.34	2.03	2.27	1	2	1	2
Total	33					14	15	11	17

Table 3.2: Yearly summary of the ICME catalogue. Years with asterisks (*) indicate an incomplete dataset for that year. Number of events (#Events), number of events per available days of data per year (#Events Weighted), mean heliocentric distance ($\langle r_H \rangle$), average maximum magnetic field ($\langle B_{max} \rangle$) and mean magnetic field ($\langle B_{mean} \rangle$), number of left-handed (#LH), right-handed (#RH), high inclination and low inclination magnetic flux ropes are summarised.

and columns 5 and 6 list the average maximum magnetic field strength ($\langle B_{max} \rangle$) and the average mean magnetic field strength ($\langle B_{mean} \rangle$) measured with the flux ropes. Comparing $\langle B_{max} \rangle$ and $\langle B_{mean} \rangle$ with $\langle r_H \rangle$, we see an overall decreasing trend each year with increasing heliocentric distance, discussed in more detail in Section 3.3.2.

Columns 7 and 8 list the number of left-handed and right-handed events per year, respectively. Out of the 33 events, it is possible to determine the handedness of 29. Table 3.2 shows that the number of left-handed and right-handed magnetic flux ropes observed by Juno were approximately equal: 14 left-handed and 15 right-handed. This result is to be expected as flux rope handedness can be associated with the solar hemisphere from which the CME originated (Rust, 1994), however, the location of CME initiation has no such preference. The final two columns compare the number of high inclination (ESW, WNE, ENW, WSE) and low inclination (SEN, NWS, SWN, NES) flux ropes (see Figure 1.15 for a visual representation of each flux rope type). We exclude event #20120728 as the classification is ambiguous, although certainly left-handed, leaving a total of 28 flux rope classifications. The total number of low inclination flux ropes is greater than high inclination flux ropes, in agreement with findings of previous studies (e.g. Bothmer and Schwenn, 1998; Good and Forsyth, 2016). As the heliocentric distance increases, the ratio of high inclination to low inclination flux rope types was found to decrease. Previous studies have found that ICMEs tend to deflect towards the solar equator, particularly during solar minimum when the solar wind is highly

structured (Plunkett *et al.*, 2001; Cremades, Bothmer, and Tripathi, 2006; Wang *et al.*, 2011). It has been suggested that ICME flux ropes may align with the HCS as they propagate (Yurchyshyn, 2008; Isavnin, Vourlidas, and Kilpua, 2014). Isavnin, Vourlidas, and Kilpua (2014) found that although most of the deflection occurs below 30 R_S , a significant amount of deflection and rotation also occurs between 30 R_S and 1 AU. The decrease in ratio of high inclination to low inclination flux rope types may therefore be consistent with the suggestion that the magnetic flux rope axis of an ICME tends towards the local HCS (often close to the ecliptic plane) and therefore a lower inclination as it propagates, even though ICMEs in this study have been identified at greater heliocentric distances than 1 AU.

3.3.2 Variation of Event Properties with Heliocentric Distance

Figure 3.3 shows the variation of the maximum and mean magnetic field strengths of each catalogued ICME with increasing heliocentric distance. Neglecting latitudinal variations, the radial dependence of the maximum magnetic field with heliocentric distance decreases as $r^{-1.38 \pm 0.56}$ and the mean magnetic field decreases as $r^{-1.50 \pm 0.63}$. Figure 3.3 also includes the 95% confidence intervals of each fit. In the top two panels, we observe a clear outlier related to the event #20111025. Excluding this value leads to relationships of $r^{-1.12 \pm 0.36}$ for the maximum magnetic field strength, and $r^{-1.17 \pm 0.31}$ for the mean magnetic field strength.

From the Ulysses catalogues, Ebert *et al.* (2009) found the relationship of mean magnetic field strength to decrease as $r^{-1.29 \pm 0.12}$ with increasing heliocentric distance, and similarly, Richardson (2014) found the relationship to decrease as $r^{-1.21 \pm 0.09}$. These relationships are directly comparable (calculated over a similar heliocentric distance range) to the mean magnetic field relationships in this study, and we find them to be in strong agreement with the mean magnetic field relationship (outlier excluded) in this study.

3.4 ICMEs Observed by Juno and Other Spacecraft

Eleven of the events listed in Table 3.1 were also observed by another spacecraft at 1 AU e.g. STEREO-A, STEREO-B or Wind. Two of these events were also observed by a third spacecraft, Venus Express at 0.7 AU, providing a link between the inner

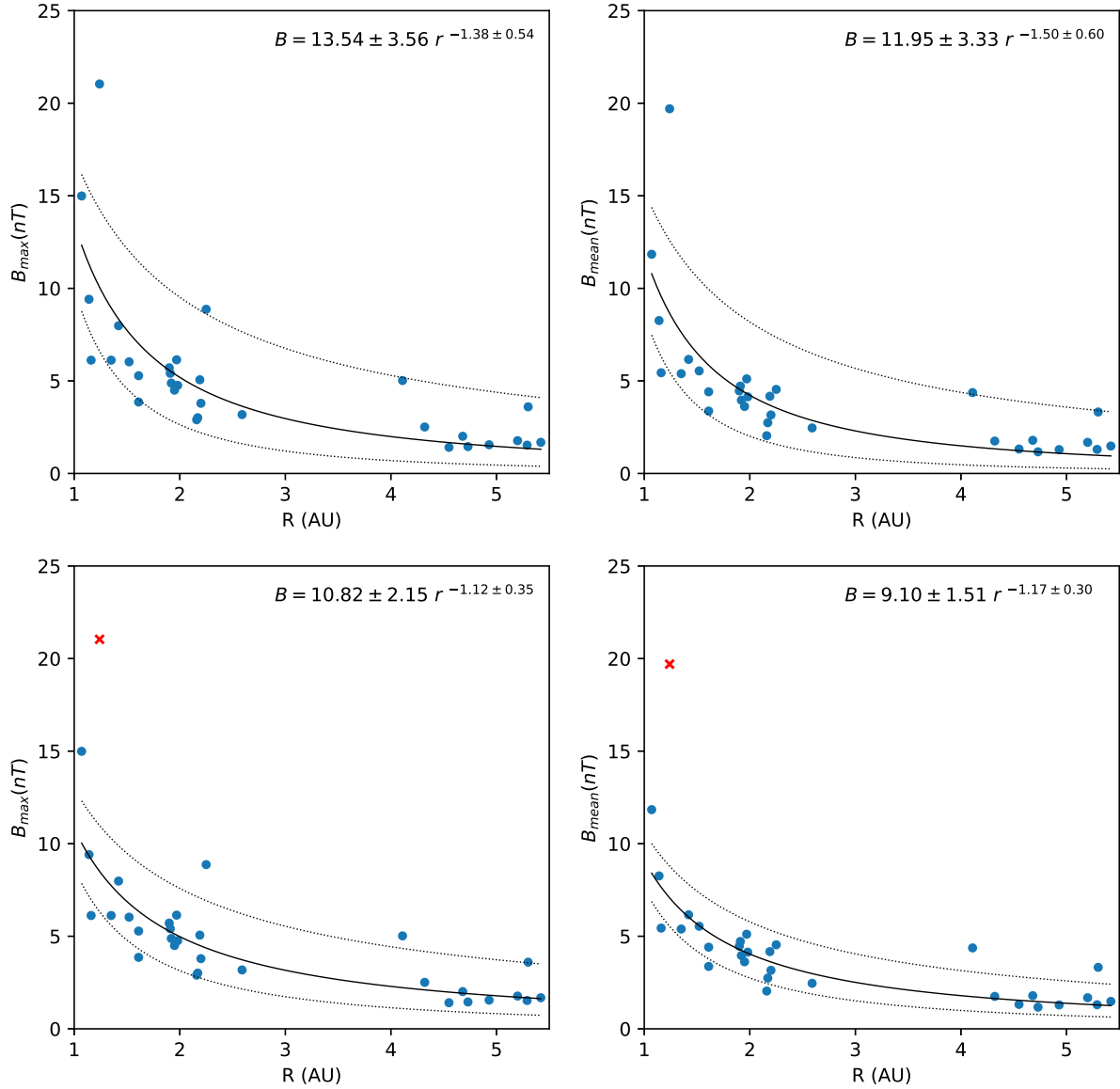


Figure 3.3: Variation with heliocentric distance of the maximum and mean magnetic field strengths of the catalogued ICMEs. Dashed lines indicate the 95% confidence prediction bounds. The bottom two panels exclude the clear outlier.

heliosphere, 1 AU, and Juno at 2.2 AU. Figure 3.4 presents the 6 events observed by both Wind and Juno, Figure 3.5 presents the 3 events observed by both STEREO-B and Juno, and Figure 3.6 presents the 2 events observed by Venus Express, STEREO-A and Juno. The 11 events are listed in Table 3.3 in the same format as Table 3.1, with the corresponding Juno ID# linking each entry.

Comparing events observed at Wind, STEREO-A, STEREO-B, and Venus Express

with those at Juno in Table 3.1, we note that the handedness of each individual event is consistent. However, for 3 cases we note that the flux rope type changes: for #20111025 the rope type changes from ENW at Wind to SEN at Juno, for #20121115 the rope type changes from WNE at Venus Express to SWN at STEREO-A and Juno, and for #20121118 the rope type changes from WNE at Venus Express to NES at STEREO-A and Juno. In each of these three cases, the rope type changes from a high inclination to low inclination flux rope with increasing heliocentric distance. This agrees with the earlier observation in Section 3.3.1 where the ratio of high inclination to low inclination flux rope types decreases with increasing heliocentric distance. However, in this case, the change in rope type may also be due to the location in which the event was observed: at different latitude/longitude separations, a different part of the flux rope is measured. Considering the simplified picture of a flux rope anchored at the Sun so as it forms a loop in the heliosphere as it propagates (as in Figure 1.16 in Section 1.5.3), a different flux rope axis orientation may be observed dependent on the location at which it is measured.

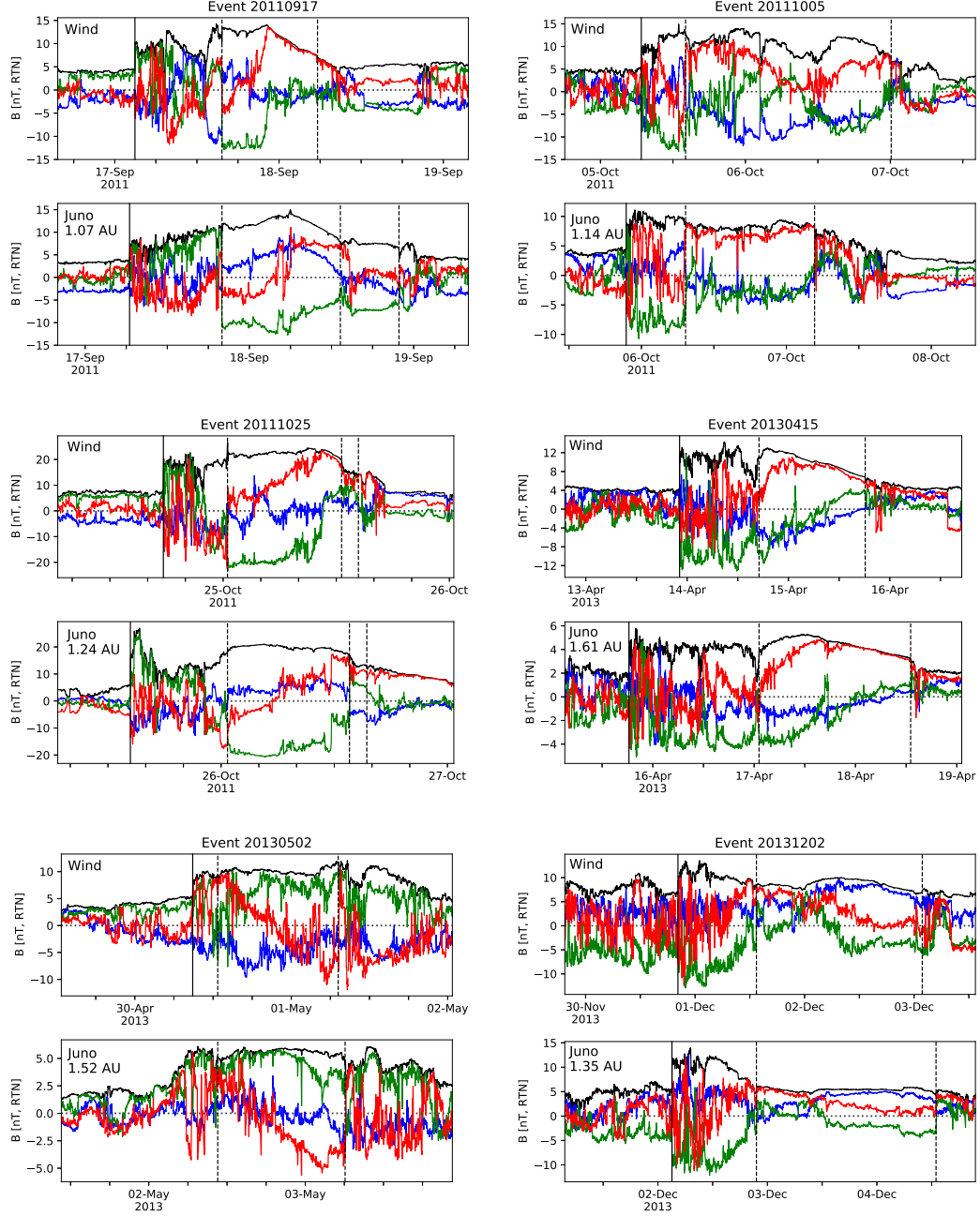


Figure 3.4: Magnetic field signatures of the 6 events observed by Wind and Juno presented in RTN coordinates, where the radial component (R) is shown in blue, the transverse component (T) in green, and the normal component (N) in red. Solid vertical lines mark the time at which a shock/discontinuity associated with the event was observed (t_s), and dashed vertical lines delineate the leading edge (t_L), trailing edge (t_T) and alternate trailing edge where defined, respectively.

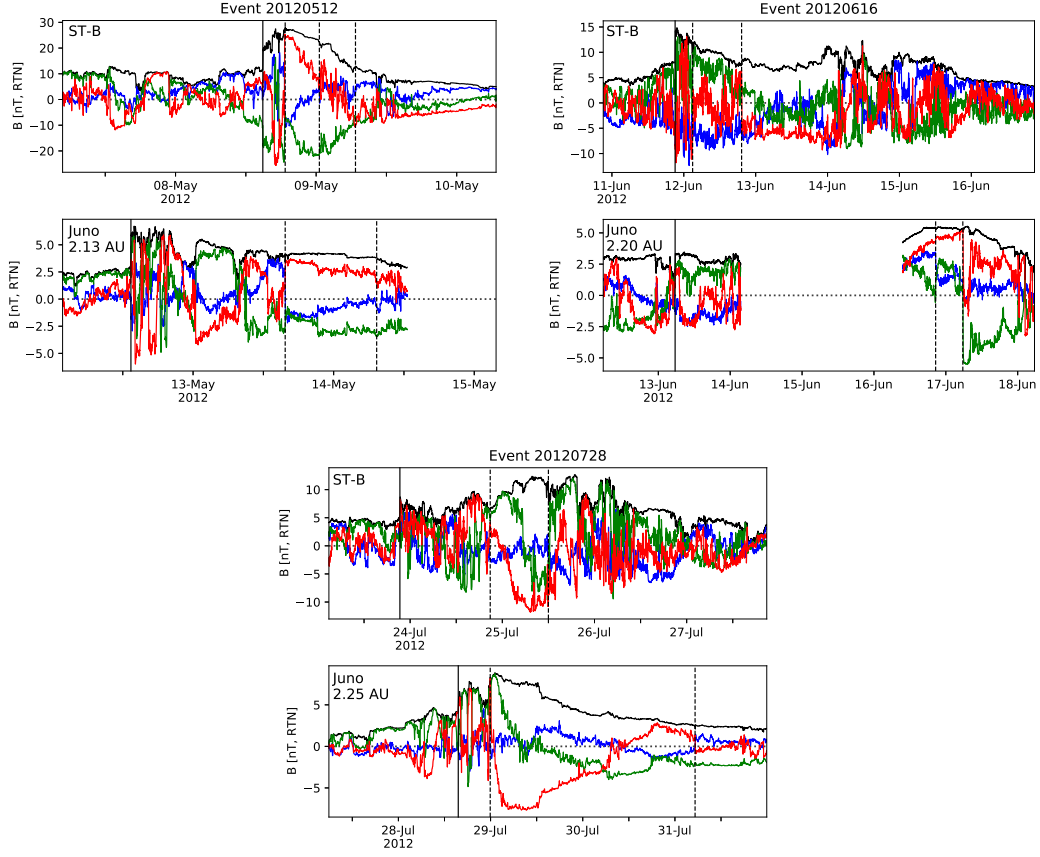


Figure 3.5: Magnetic field signatures of the 3 events observed by STEREO-B (ST-B) and Juno presented in RTN coordinates, in the same format to those in Figure 3.4.

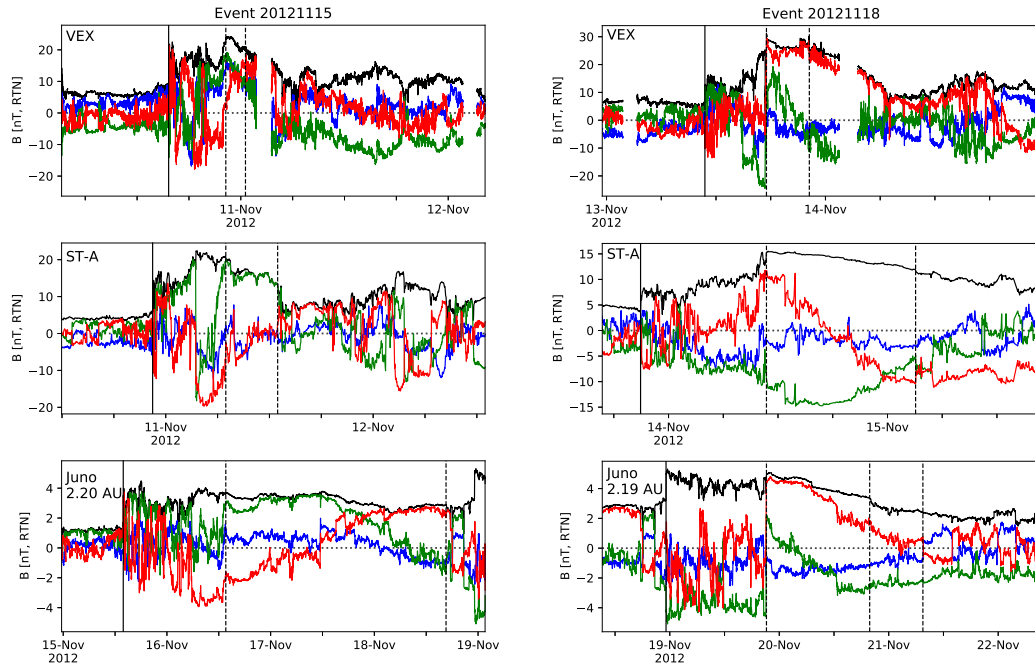


Figure 3.6: Magnetic field signatures of the 2 events observed by Venus Express (VEX), STEREO-A (ST-A) and Juno presented in RTN coordinates, in the same format to those in Figure 3.4.

Table 3.3: List of events observed by both Juno and another spacecraft. The corresponding Juno ID# is listed alongside the other observing spacecraft. Observed parameters follow the same format as Table 3.1.

Juno ID#	S/C	t_S	t_L	$t_T(alt)$	r_H [AU]	lat [°]	lon [°]	B_{max} [nT]	B_{mean} [nT]	Rope Type	H
20110917	Wind	17/09/2011 02:56	17/09/2011 15:39	18/09/2011 05:37	1.00	-0.01	354.17	14.06	11.46	SEN	L
20111005	Wind	05/10/2011 06:45	05/10/2011 14:05	07/10/2011 00:08	0.99	0.02	11.75	13.98	10.58	-	-
20111025	Wind	24/10/2011 17:40	25/10/2011 00:28	25/10/2011 12:34 (25/10/2011 14:21)	0.98	0.05	31.11	26.66	22.43	ENW	L
20120512	ST-B	08/05/2012 14:54	08/05/2012 18:43	09/05/2012 00:33 (09/05/2012 06:43)	1.00	0.21	110.60	28.03	25.28	NES	R
20120616	ST-B	11/06/2012 21:06	12/06/2012 02:57	12/06/2012 19:18	1.00	0.06	145.11	12.13	9.52	-	-
20120728	ST-B	23/07/2012 21:20	24/07/2012 20:51	25/07/2012 12:00	1.02	-0.15	187.16	12.38	10.30	WSE	L
20121115	VEX	10/11/2012 15:39	10/11/2012 22:15	11/11/2012 00:32	0.72	-3.72	148.14	24.22	22.09	WNE	R
20121115	ST-A	10/11/2012 22:29	11/11/2012 06:57	11/11/2012 12:57	0.97	-0.08	176.68	20.45	16.25	SWN	R
20121118	VEX	13/11/2012 10:47	13/11/2012 17:31	13/11/2012 22:13	0.72	-3.81	152.74	31.20	26.84	WNE	R
20121118	ST-A	13/11/2012 20:56	14/11/2012 10:44	15/11/2012 03:05	0.97	-0.07	179.89	15.52	13.98	NES	R
20130415	Wind	13/04/2013 22:12	14/04/2013 17:02	15/04/2013 18:10	0.99	0.05	204.84	12.99	10.18	ENW	L
20130502	Wind	30/04/2013 08:52	30/04/2013 12:43	01/05/2013 07:12	1.00	0.05	220.40	11.95	10.05	NWS	L
20131202	Wind	30/11/2013 20:14	01/12/2013 13:26	03/12/2013 01:47	0.98	0.02	69.76	10.05	8.64	WNE	R

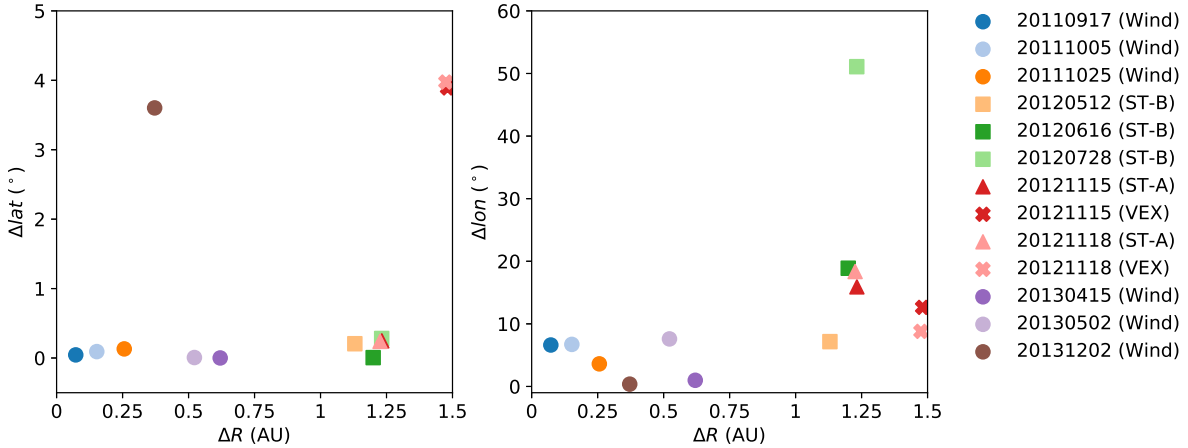


Figure 3.7: Overview of latitude (left) and longitude (right) separations with radial separation between Juno and other spacecraft for each event in Table 3.3. Marker shapes correspond to the spacecraft other than Juno at which the same event was observed: Wind (circle), STEREO-B (square), STEREO-A (triangle) and Venus Express (cross). Each colour corresponds to a different event identifier, given by the figure key.

Figure 3.7 gives a visual overview of the latitude, longitude and radial separations between each event measured at Juno and the corresponding event measured in Table 3.3. These separations are also summarised in Table 3.4. All but one of the linked events (#20131202) occurred before the Earth gravity assist performed by Juno, and therefore the latitudinal separations between events are very small in most cases, where events are measured close to the ecliptic plane. The observations of events #20121115 and #20121118 at Venus Express have the largest latitudinal separations in comparison to Juno, $\sim 4^\circ$, as Venus Express was located approximately 0.05 AU below the ecliptic plane. 10 of the 11 events are separated longitudinally by less than 20° , 8 of which can be considered in ‘radial alignment’ if we define that as longitude separations $< 10^\circ$.

Event #20120728 is an interesting case, observed by both STEREO-B and Juno, longitudinally separated by 51° . This event was observed during the same time period as the 23 July 2012 extreme CME (e.g. Baker *et al.*, 2013; Liu *et al.*, 2014; Desai *et al.*, 2020) that was observed by STEREO-A. The 23 July 2012 event has been likened to a ‘Carrington-like event’ with a particularly strong maximum magnetic field strength of 109 nT and propagation speed of $\sim 2000 \text{ kms}^{-1}$ at 1 AU. The full angular width of the CME, as measured using triangulation methods between the remote observations of STEREO-B and SOHO, was estimated to be $140 \pm 30^\circ$ (Baker *et al.*, 2013). During the event time period, Juno and STEREO-A were longitudinally separated by $\sim 73^\circ$

Juno ID #	S/C	Δr_H [AU]	Δlat [°]	Δlon [°]	ΔB_{max} [nT]	ΔB_{mean} [nT]
20110917	Wind	0.07	0.04	6.62	0.93	0.38
20111005	Wind	0.15	0.09	6.72	4.57	2.32
20111025	Wind	0.26	0.13	3.61	5.62	2.72
20120512	ST-B	1.13	0.21	7.16	-	-
20120616	ST-B	1.20	0.01	18.89	-	-
20120728	ST-B	1.23	0.28	51.09	3.51	5.75
20121115	VEX	1.48	3.89	12.63	20.43	18.93
20121115	ST-A	1.23	0.25	15.91	16.65	13.09
20121118	VEX	1.47	3.97	8.80	26.14	22.67
20121118	ST-A	1.23	0.24	18.36	10.46	9.81
20130415	Wind	0.62	0.00	0.99	7.71	5.76
20130502	Wind	0.52	0.01	7.59	5.93	4.52
20131202	Wind	0.37	3.60	0.37	3.92	3.25

Table 3.4: Summary table of the differences in heliocentric distance (Δr_H), latitude (Δlat), longitude (Δlon), and observed maximum and mean magnetic field strengths of the flux ropes (ΔB_{max} and ΔB_{mean} , respectively) between observing spacecraft of the same ICME.

and thus, in situ Juno observations could be used to help constrain the longitudinal extent of the 23 July 2012 CME (a study of which is in progress by the author).

Another interesting event is #20130415, where the latitudinal separation is negligible and the longitudinal separation between Juno and Wind is less than 1° during observations of the event. Studies of events whilst spacecraft were in such close alignment have previously only considered radial separations significantly smaller than the 0.6 AU observed in this case. A radial alignment study of this event is presented in Chapter 5.

Figure 3.8 presents the magnetic field strength of the individual events with increasing heliocentric distance at which the event was observed. The magnetic field strength shows a decrease with increasing heliocentric distance as expected for every event other than #20110917. This may be explained by the small radial separation of 0.07 AU between Wind and Juno during this event, but a larger longitudinal separation of 6.6° , meaning that significantly different parts of the magnetic flux rope were measured.

The radial dependence of the magnetic field has been determined by performing separate power law fits for each event (e.g. Farrugia *et al.*, 2005; Richardson, 2014; Good *et al.*, 2019). The mean fitting parameters for the 10 event fits (excluding event

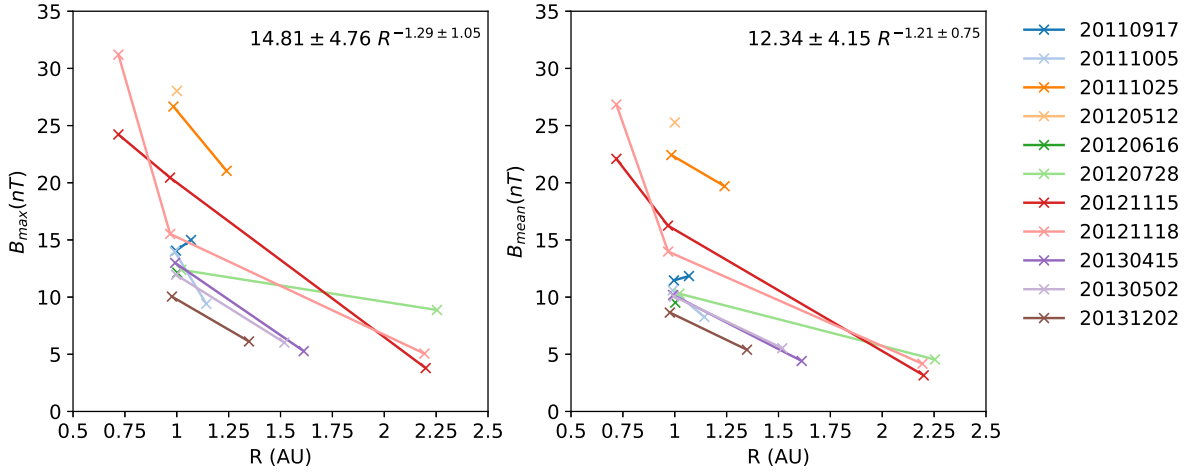


Figure 3.8: Variation with heliocentric distance of the maximum and mean magnetic field strengths of each event observed at Juno and at least one other spacecraft. Different colours correspond to each different event listed in Table 3.3, given by the key on the right hand side of the figure.

#20110917) give relationships for the maximum and mean magnetic field strength of $B_{max} \propto r^{-1.57 \pm 0.70}$ and $B_{mean} \propto r^{-1.41 \pm 0.44}$, respectively. The uncertainties given are the standard deviations, which show the large spread in radial dependencies presented. Richardson (2014) found that for 11 events observed at Earth and Ulysses, there may be two groups of events: those with strong fields at 1 AU that evolve to weak fields at Ulysses as $r^{-1.5}$ and those with weaker fields at 1 AU that evolve as $r^{-0.7}$. A similar split is not able to be determined in this dataset: the strongest magnetic field measured at 1 AU follows a power law of $r^{-0.56}$, however, this event (#20111025) has previously been noted as an outlier to the trend in Figure 3.3 and is discussed in more detail in Chapter 4.

Figure 3.9 presents the magnetic field relationships for the linked events (red) and total dataset (black). Considering the events listed in Table 3.3 and their corresponding events in Table 3.1 (all events presented in Figures 3.4, 3.5, and 3.6) as individual data points, we find fitted power law relationships of $B_{max} \propto r^{-1.61 \pm 0.68}$ and $B_{mean} \propto r^{-1.72 \pm 0.73}$. These relationships are very similar to those found considering every event in both Table 3.3 and Table 3.1: $B_{max} \propto r^{-1.69 \pm 0.38}$ and $B_{mean} \propto r^{-1.78 \pm 0.42}$.

The mean magnetic field relationship of Figure 3.9 can be compared to those of other studies using a similar heliocentric distance range, such as the Ulysses studies mentioned previously: Richardson (2014) found $B_{mean} \propto r^{-1.38 \pm 0.03}$, Liu, Richardson, and Belcher

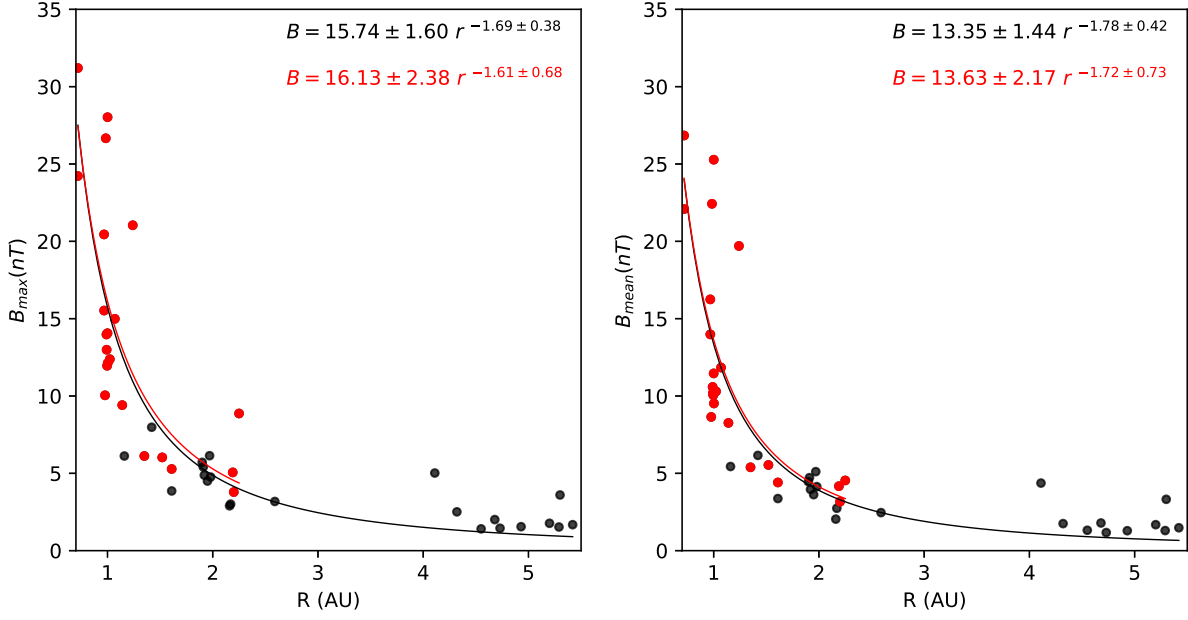


Figure 3.9: Variation with heliocentric distance of the maximum and mean magnetic field strengths of the 11 events observed at other spacecraft and Juno (red) and all the events in this chapter (black).

(2005) found $B_{\text{mean}} \propto r^{-1.40 \pm 0.08}$, and Wang, Du, and Richardson (2005) found $B_{\text{mean}} \propto r^{-1.52}$. These studies include ICMEs observed at Helios and ACE combined with those at Ulysses to create a dataset covering 0.3–5.4 AU. The powers of the mean magnetic field relationships are higher than observed in this study, although within the quoted uncertainty range. The difference in results may be due to the different heliocentric distance range covered (0.7–5.4 AU in this study) or sample population where the total number of events considered in this study is 42, in comparison to Richardson (2014) which considers 103 Helios events, the ~ 300 events identified at 1 AU of Richardson and Cane (2010) and 279 events at Ulysses.

3.5 Summary

We have identified 33 potential ICME/ magnetic clouds in the magnetometer data taken during the Juno mission cruise phase. Each event meets the criteria of an enhanced and rotating magnetic field, consistent with a magnetic flux rope structure. The catalogue of events covers a heliocentric distance range of 1–5.4 AU, the first opportunity to study ICMEs beyond 1 AU since the Ulysses mission.

For each event, the mean and maximum magnetic field strengths of the flux ropes have been recorded, the flux rope type/classification, and its handedness. We found that:

- The number of left-handed and right-handed magnetic flux ropes observed by Juno were approximately equal: 14 left-handed and 15 right-handed.
- As the heliocentric distance increases, the ratio of high inclination to low inclination flux rope types tends to decrease. This result may be consistent with previous studies that suggest the magnetic flux rope axis of an ICME tends towards the ecliptic plane as it propagates, but could also simply be a consequence of spacecraft location/ path measured through the ICME.
- Excluding outliers, the maximum and mean magnetic field strengths decrease with heliocentric distance as $B_{max} \propto r^{-1.12 \pm 0.36}$ and $B_{mean} \propto r^{-1.17 \pm 0.31}$, respectively. The mean magnetic field relationship is in strong agreement with those found in previous studies using Ulysses observations.

Eleven of the events observed at Juno were also observed at 1 AU by Wind, STEREO-A or STEREO-B; 2 of these events were also observed at 0.7 AU by Venus Express. A multi-spacecraft analysis of the in situ magnetic field observations found that:

- Most spacecraft observations of the same event occurred close to the ecliptic plane thus latitudinal separations are negligible.
- Most spacecraft observations of the same event were longitudinally separated by $< 20^\circ$, 8 of which were separated by $< 10^\circ$ and could be considered close to radial alignment.
- The handedness of the magnetic flux rope remains consistent between observing spacecraft.
- There were 3 events where the magnetic flux rope type changed from a higher inclination to a lower inclination between observing spacecraft in order of increasing heliocentric distance. This agrees with the earlier observation where the ratio of high inclination to low inclination magnetic flux rope type decreases with increasing heliocentric distance. However, the change in rope type could also be due to the location at which the event was observed.
- Performing separate power law fits of the magnetic field strength for each event and taking the mean of these relationships, $B_{max} \propto r^{-1.57 \pm 0.70}$ and $B_{mean} \propto$

$r^{-1.41 \pm 0.44}$. These relationships are within the broad range found by Richardson (2014).

- Combining events observed in conjunction with other spacecraft and the full Juno catalogue shows that the magnetic field strength decreases as $B_{max} \propto r^{-1.69 \pm 0.38}$ and $B_{mean} \propto r^{-1.78 \pm 0.42}$ over the heliocentric distance range of 0.7–5.4 AU. The value of the mean magnetic field power law fit is larger than previous studies, but within the uncertainty range calculated.

The work in the chapter could provide a basis for many further interesting studies and identifies individual events observed by multiple spacecraft of which further analysis could prove valuable. One such case study of event #20111025 is presented in Chapter 4, providing insight into why it may be an outlier to overall trends in this chapter. Other events of note include: #20130415, observed by Wind and Juno whilst the spacecraft were longitudinally separated by less than 1° , analysed in more detail in Chapter 5; #20120728 observed by STEREO-B and Juno, in situ observations of which may help towards constraining the angular extent of the extreme ICME observed by STEREO-A during the same time period; and events #20121115 and #20121118, observed by Venus Express, STEREO-A and Juno, which provide a good opportunity for a case study on ICME interaction and evolution over a large radial separation. Techniques used to analyse the individual events in Chapters 4 and 5 could also be applied to events identified in this chapter, providing further insight into their evolution e.g. how the flux rope axis of an ICME may change as it propagates, and how the solar wind environment may affect the expansion of ICMEs.

Chapter 4

The Radial Evolution and Longitudinal Variation of an ICME

In this chapter, we present observations and analysis of an ICME with a clear magnetic cloud structure registered during 24–26 October 2011 by ACE, Wind, and the ARTEMIS mission in the near-Earth environment, and Juno at a heliocentric distance of 1.24 AU shortly after commencing its cruise phase to Jupiter. The near-Earth spacecraft and Juno were separated longitudinally by a maximum angle of just 3.6° , with a maximum separation in latitude of only 0.1° . This ICME is of particular interest as it caused the strongest geomagnetic storm at Earth in 2011, peaking at a Dst index of -147 nT, driven by the southward magnetic fields preceding the magnetic cloud rather than the magnetic cloud itself where the magnetic fields were northward. The ICME is catalogued as event #20111025 in Chapter 3. This chapter is based upon the journal article published in Solar Physics, Davies *et al.* (2020).

The previous radial alignment case studies described in Chapter 1 have primarily used spacecraft at or within 1 AU. Radial alignment studies of ICMEs beyond Earth are particularly rare. One such study by Mulligan *et al.* (1999) compared four ICME events observed by the Near Earth Asteroid Rendezvous (NEAR) and Wind spacecraft, with radial separations between 0.18 and 0.63 AU and longitudinal separations between 1.2 and 33.4° . However, with the introduction of more spacecraft into the solar wind in recent years, including planetary mission spacecraft during their cruise phase or outside of their respective planetary environments, there have been more opportunities for radial alignments between spacecraft and at larger heliospheric distances (e.g. Good

et al., 2015; Winslow *et al.*, 2016).

In this chapter we use observations from the multiple near-Earth spacecraft to provide several independent fits indicating the degree of variability of the fits along different trajectories through the ICME. The inclusion of the ARTEMIS mission spacecraft creates a near-Earth spacecraft constellation, allowing the direction of propagation of structures such as the ICME shock to be determined using the timing at each spacecraft, using methodology presented in Chapter 2. The performance of the Lundquist and Gold-Hoyle force-free fitting models is compared and explored for the different trailing edge boundaries chosen. Previous studies investigating model performance and the importance of flux rope boundary selection include Riley *et al.* (2004), Dasso *et al.* (2006), Al-Haddad *et al.* (2013, 2018), and Janvier *et al.* (2015). The flux rope orientations and other kinematic properties of the ICME resulting from the fitting techniques in this study are compared between the near-Earth spacecraft and Juno to analyse the evolution of the ICME.

Section 4.1 presents the in situ observations of the ICME, and Section 4.2 investigates the solar source of the ICME and solar wind environment during its propagation to provide context to the in situ observations. Section 4.3 presents the analysis of the ICME, the results of which are summarised and discussed in Section 4.4.

4.1 Spacecraft Observations

In situ observations made by the ACE, Wind, ARTEMIS, and Juno spacecraft are presented. Figure 4.1 presents the configuration of the spacecraft, including STEREO-A and STEREO-B, on 25 October 2011 at 00:00 UT in HAE coordinates. Figure 4.1 demonstrates that Juno and the near-Earth spacecraft were in near radial alignment, with a maximum longitudinal separation of just 3.6° . The near-Earth spacecraft configuration itself has a maximum radial separation of < 0.01 AU and a maximum longitudinal separation of $< 0.2^\circ$.

To identify the ICME in situ near Earth, we use measurements of the magnetic field taken by the magnetometers onboard ACE, Wind, and the ARTEMIS mission. Measurements of the solar wind plasma were also used at ACE, Wind, and ARTEMIS to aid in the identification of the ICME in the near-Earth environment. To identify the ICME at Juno, only measurements of the magnetic field were used, as previously described in Chapter 3.

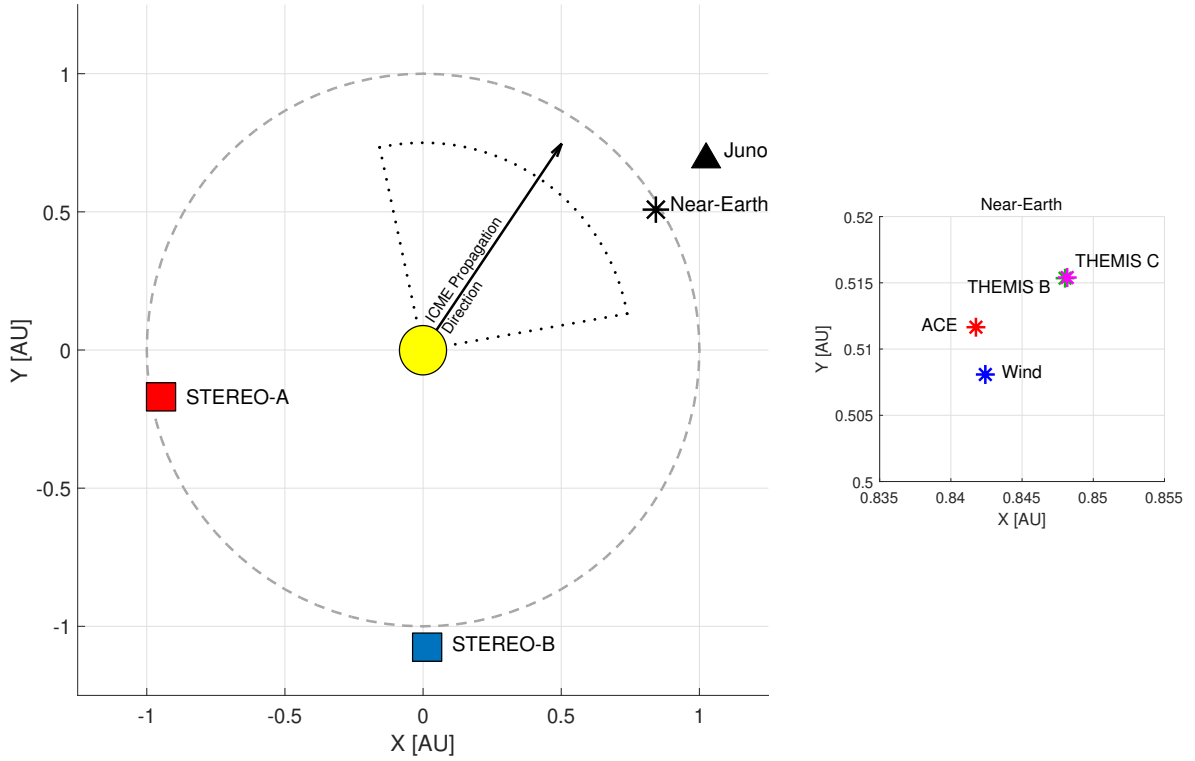


Figure 4.1: Location of the near-Earth spacecraft (ACE, Wind, and ARTEMIS), Juno, STEREO-A and STEREO-B on 25 October 2011 at 00:00 UT in HAE coordinates. Imagers onboard the STEREO spacecraft can be used to estimate the initial propagation direction and extent of the ICME, represented by the black arrow and dotted lines, respectively (for details, see Section 4.2). The near-Earth spacecraft are in near radial alignment with Juno, with a small maximum longitudinal separation of 3.6° . The inset shows a close up of the configuration of the near-Earth spacecraft: ACE (red), Wind (blue), THEMIS B (green) and THEMIS C (magenta). The near-Earth spacecraft configuration has a maximum radial separation of < 0.01 AU and a maximum longitudinal separation of $< 0.2^\circ$.

Figure 4.2 presents the magnetic field (1 minute resolution) and plasma (1 minute 38 second resolution) signatures observed at Wind. These observations are very similar in the large-scale to those at ACE and both THEMIS spacecraft (the in situ signatures observed by these spacecraft can be found in the Appendix) and are therefore representative of the near-Earth environment. The structure delineated by the dotted vertical lines displays features associated with an ICME such as the enhancement of the magnetic field (panel a), declining radial speed profile (panel e), and the decrease in both proton temperature (panel g) and density (panel h), which distinguish it from

the ambient solar wind. A shock (vertical dashed line) driven by the ICME was observed at Wind at 17:40 UT on 24 October 2011. Table 4.1 lists the shock arrival time, t_S , at each of the near-Earth spacecraft and the heliocentric distance, r_H , at which the spacecraft were located, which are used in Section 2.2.1 to infer the propagation direction of the shock. Figure 4.2 also displays the magnetic field components in radial tangential normal (RTN) coordinates (panel b), the angle of the magnetic field vector to the R-T plane, θ (panel c), and the angle of the magnetic field vector swept out anticlockwise from the Sun-Earth line, projected onto the R-T plane, ϕ (panel d). The ICME meets the criteria detailed by Burlaga *et al.* (1981) to classify magnetic clouds: a strong enhancement of the magnetic field, smooth rotation of the magnetic field components, a low variance of the magnetic field, and low proton temperature and density. Identifying the leading and trailing edges of the magnetic cloud flux rope can often be subjective and features are not always coincident (e.g. see discussion in Richardson and Cane, 2010; Kilpua *et al.*, 2013). In the case of this event, we identify two possible trailing edges: the first coincides with the earliest significant drop in magnetic field strength and a slight increase in proton temperature and density, the second coincides with the end of both the smooth magnetic field rotation and the declining radial speed profile. The leading edge of the flux rope is easier to identify, marking the start of the magnetic field enhancement, smooth rotation of the magnetic field, and the steady decline in radial speed. There is also a short substructure featured by a dip in the magnetic field magnitude (approximately 10 minutes in duration) at the leading edge of the ejecta observed at each spacecraft. Such substructures are generally reported at the leading edges of magnetic clouds and are thus a good indicator of the boundary (Wei *et al.*, 2003). These substructures can result from the interaction between the magnetic cloud and the preceding solar wind, or be relics of the CME release process at the Sun (Farrugia *et al.*, 2001; Kilpua *et al.*, 2013).

We define the sheath of the ICME as the region between the shock front and the leading edge of the flux rope. In Figure 4.2, the sheath region displays a variable and fluctuating magnetic field structure at Wind, followed by a region of low variance which begins at approximately 22:00 UT. This region of low variance is also observed across each of the near-Earth spacecraft and coincides with a change in electron pitch angle signature at ACE (not shown; available at http://www.srl.caltech.edu/ACE/ASC/DATA/level3/swepam/swepam_pa_summary/2011-297-12.png) where two oppositely directed strahls appear at both 0° and 180° pitch angles, meaning that counterstream-

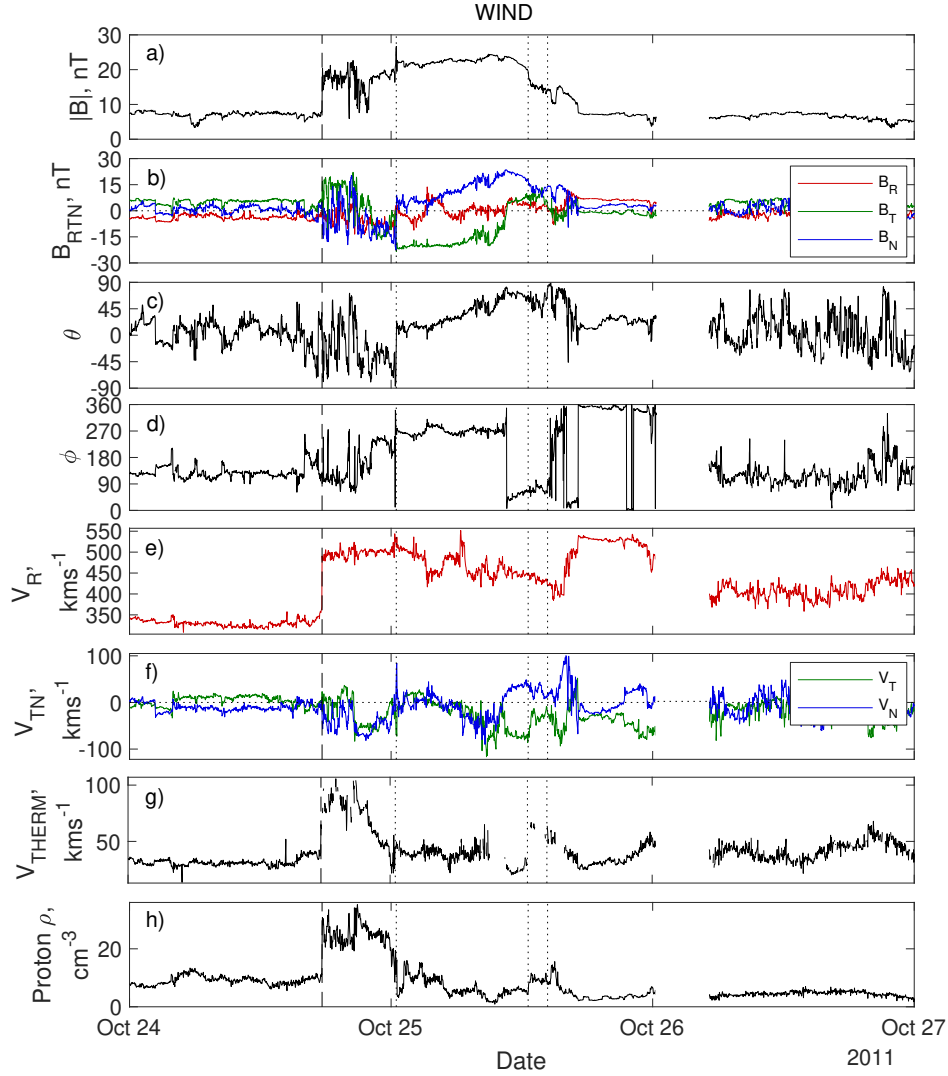


Figure 4.2: In situ magnetic field (1 minute resolution) and plasma (1 minute 38 second resolution) signatures observed by Wind. The vertical dashed line indicates the shock and the vertical dotted lines indicate the boundaries of the flux rope, with two possible trailing edge locations. The respective panels display a) the total magnetic field, b) the components of the magnetic field in RTN coordinates (the radial component is shown in red, the transverse component in green, and the normal component in blue), c) the calculated θ , and d) ϕ angles of the magnetic field, e) the radial proton speed, f) the transverse and normal components of the proton velocity, g) the thermal proton velocity, and h) proton density.

ing electrons are present, a feature often indicative of the closed magnetic field lines associated with an ICME (Gosling, 1990). The onset of the counterstreaming electron

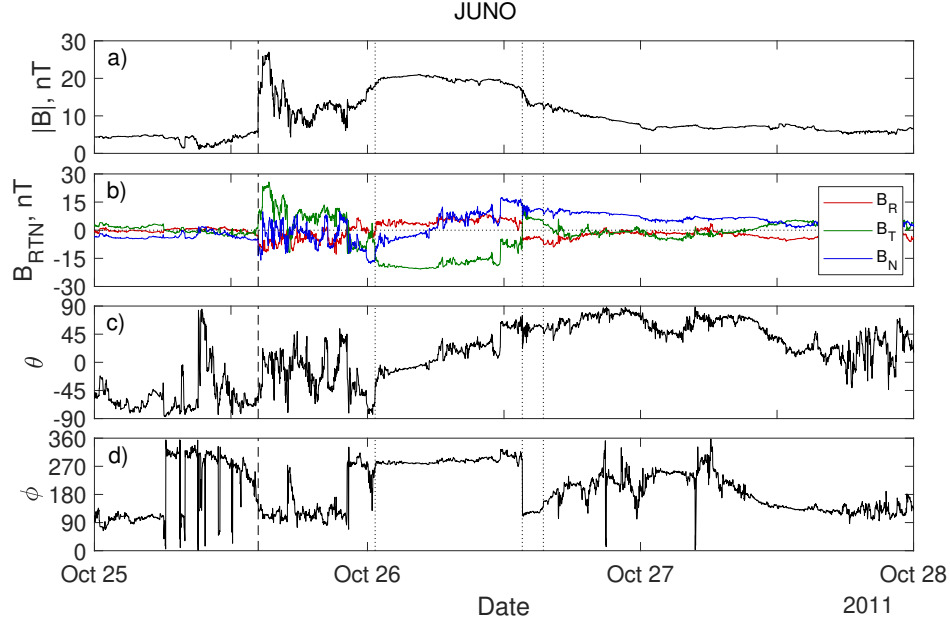


Figure 4.3: In situ magnetic field (1 minute resolution) signatures observed by Juno displayed in the same format as Figure 4.2.

flows, which extend through the flux rope, indicates the true start of the ICME (but not the flux rope itself), and is coincident with the fall of the proton temperature.

The radial component of the proton velocity in Figure 4.2 displays a declining speed profile from 527 km s^{-1} to 455 or 425 km s^{-1} , trailing edge boundary dependent, during this period indicating the expansion of the magnetic cloud. Following the flux rope, there is a steep increase in the radial component of the velocity to 540 km s^{-1} , and clear velocity deflections in the transverse and normal directions of -93 and 100 km s^{-1} , respectively. This feature is observed by each of the near-Earth spacecraft and is also reflected in the magnetic field data by a compressed region of magnetic field following the later trailing edge boundary, preceding features consistent with a reverse shock. It is possible that the compressed magnetic field region was the result of a weak ICME following the event as the magnetic field has a low variance and temperature, or a consequence of a transient coronal hole opened by the CME related to the magnetic cloud (e.g. Luhmann *et al.*, 1998). The dip in magnetic field at the later trailing edge of the flux rope is in magnetic and thermal pressure balance (not shown), indicating that this is likely the true ICME boundary. Previous studies have also defined the trailing edge to be this later boundary (Lepping *et al.*, 2015; Wood *et al.*, 2017), whilst Nieves-Chinchilla *et al.* (2019) define the ICME as a complex structure and extend

the boundary to the end of the region of increased radial velocity. It is probable that the cause of the ambiguity in trailing edge selection is due to the solar wind following the magnetic cloud having led to a compression and heating of the trailing part of the flux rope which moved the temperature increase forward into the flux rope, affecting observed features until the earlier trailing edge defined.

Figure 4.3 presents the magnetic field (1 minute resolution) signatures observed by Juno, in the same format as Figure 4.2. The structure observed is very similar to that of Figure 4.2, with an enhanced magnetic field (delineated by the vertical dotted lines) and similar behaviour of the magnetic field components during this enhancement, which display a clear flux rope structure. A shock front is registered by Juno at a heliocentric distance of 1.24 AU on 25 October at 14:23 UT, less than a day later than the shock at Wind. Assuming a constant velocity and radial propagation, the timing of the shock front between Wind and Juno gives an average velocity of 518 km s^{-1} , in reasonable agreement with the observed shock velocity of 489 km s^{-1} at Wind. Much of the sheath magnetic field is lower in magnitude in the Juno observations except for an initial increase behind the shock front in comparison to observations at Wind, and the low variance region is harder to distinguish. The duration of the sheath is longer at Juno than at Wind, suggesting that it has expanded as the ICME has propagated, although the difference could also be due to spatial variation at different measurement locations (Kilpua, Koskinen, and Pulkkinen, 2017). The mean magnetic field enhancement within the flux rope is 19.7/18.9 nT (depending on trailing edge definition) at Juno in comparison to 22.4/21.5 nT at Wind. The format of ‘earlier/later trailing edge’ is used to present dependent values throughout. The mean magnetic field values at each spacecraft are summarised in Table 4.1. The magnitude profiles, however, follow different trends: at Wind the magnitude slowly increases between the leading and earlier trailing edge, whereas the profile at Juno decreases slightly over the same boundaries. For faster ICMEs, the magnetic field profiles are often asymmetric, with a larger magnetic field strength at the front of the flux rope than the back (Janvier *et al.*, 2019), as we observe at Juno. This can be considered as an effect of the time difference in observations between the leading and trailing edges of the flux rope where, in an expanding flux rope, the magnetic field weakens in the time taken to pass the observing spacecraft. Whilst the assumed correlation between this asymmetric magnetic field profile and expanding structures tends to hold true, Nieves-Chinchilla *et al.* (2018) found in a study of 298 ICMEs with well structured magnetic topologies that 22%

of positively expanding structures had compression at the back of the flux rope, and suggested that this could be an effect of the curvature of the passing structure. The observations at Wind show a declining radial speed profile, and therefore a positive expansion of the flux rope. We suggest in this case that the increasing magnetic field profile at Wind is likely a product of magnetic field compression due to the increased radial speed of the solar wind following the flux rope. However, this compression is not observed at Juno and therefore, a more typical magnetic field profile is observed. The difference in the magnetic field components within the flux rope boundaries between Wind and Juno can be seen by comparing Figures 4.2 and 4.3: the normal component is similar in profile yet differs in value between the two heliocentric distances changing from negative (south) to positive (north) at Juno but remaining north at Wind, while the radial component shows more significant dissimilarities. The transverse component is the only component to remain of a similar shape and magnitude between Wind and Juno. The magnetic field angles are also interesting, as although very similar in profile, we note that the discontinuity in ϕ occurs later within the rope at Juno than at Wind relative to the trailing edges of the flux rope. By studying the magnetic field components and how they evolve throughout the flux rope, we can obtain a sense of handedness. Using the classification system following Bothmer and Schwenn (1998) and Mulligan, Russell, and Luhmann (1998), the flux rope can be classified as either SEN at Juno, or ENW at Wind. SEN means that at the leading edge of the flux rope the field points to the south, then rotates to point east at the axis and finally rotates to north at the trailing edge. Similarly for the ENW classification, the leading edge points to the east, rotates to point north at the axis, and finally rotates to point west at the trailing edge. Both classifications are left-handed. The consistency of the handedness is supporting evidence that the spacecraft observed the same event, as the handedness of a flux rope remains the same as it propagates (Marubashi *et al.*, 2015). Following the flux rope, the clear drop in field magnitude observed by Wind is not present in the Juno observations, although there is a region of modestly enhanced but declining magnitude. This decrease is smoother at Juno implying expansion after the trailing edge, although this may again be due to a difference in measurement location.

The arrival times of the shock front, t_S , and the flux rope leading, t_L , and trailing edges, t_{T1} and t_{T2} , observed at each spacecraft are presented in rows 2–5 of Table 4.1. The difference between the earlier/later trailing edge times and the leading edge time is consistent with the expansion of the flux rope as its duration is observed to be 12 hours

and 14 minutes/13 hours and 53 minutes at Wind and 12 hours and 56 minutes/14 hours and 47 minutes when observed at Juno. However, the difference in duration may also occur due to the different spacecraft trajectories through the ICME and the potentially different ICME propagation speeds at each spacecraft. The observed radial velocities at each boundary, v_L and v_T , are presented in rows 7 and 8 of Table 4.1, where there are two values for v_T as the parameter is dependent on the trailing edge used. The leading and trailing edge velocities are consistent for each of the near-Earth spacecraft. Row 9 of Table 4.1 presents the expansion velocity, v_E , calculated as half of the difference between the trailing and leading edge velocities. The mean expansion velocity, $\langle v_E \rangle$, is presented in row 11 of Table 4.1. It takes into account the timings and heliocentric distance between the leading and trailing edges at each of the near-Earth spacecraft and Juno to give the mean propagation speed of the leading and trailing edges. $\langle v_E \rangle$ is calculated as half the difference between these speeds. The mean expansion velocity between Wind and Juno was found to be $4.8/5.1 \text{ kms}^{-1}$; much smaller than the observed expansion velocity at Wind of $36/51 \text{ kms}^{-1}$. This indicates a slowing of the expansion velocity as the ICME propagates.

The observed radial width, D , can be calculated considering the cruise velocity of the flux rope and the time taken for a spacecraft to traverse the flux rope: $D = v_c(t_T - t_L)$. Here, the cruise velocity for each individual spacecraft is taken to be the solar wind velocity at the mid-point of the flux rope (Owens *et al.*, 2005) and is used as an approximation of the average propagation speed of the magnetic cloud. The cruise velocity, v_c , is noted in Table 4.1 for each of the near-Earth spacecraft. As there is no plasma data for Juno during this period, the mean cruise speed, $\langle v_c \rangle$, has been calculated between each of the near-Earth spacecraft and Juno using timing considerations of both leading and trailing edges observed. The mean of these values, $473.5/460.0 \text{ kms}^{-1}$, has been taken as the cruise velocity used to calculate the radial width of the flux rope at Juno. The calculated radial widths are also given in row 13 of Table 4.1. The radial width of the flux rope was calculated to be $0.137/0.156 \text{ AU}$ at Wind and $0.147/0.164 \text{ AU}$ at Juno, with associated errors of approximately $\pm 0.004 \text{ AU}$. The calculated widths are less than the average width of a flux rope at 1 AU of approximately 0.2 AU (Bothmer and Schwenn, 1998; Liu, Richardson, and Belcher, 2005; Gulisano *et al.*, 2010). Using the boundary times defined and expansion velocities given by Table 4.1, one would expect an expansion of $0.019/0.024 \text{ AU}$ between Wind and Juno, trailing edge dependent. We actually observe an expansion of the flux rope of $0.010/0.008 \text{ AU}$

	Wind	ACE	THEMIS B	THEMIS C	Juno
r_H [AU]	0.984	0.985	0.992	0.993	1.24
t_S (2011)	Oct 24 17:40 UT	Oct 24 17:48 UT	Oct 24 18:43 UT	Oct 24 18:44 UT	Oct 25 14:23 UT
t_L (2011)	Oct 25 00:28 UT	Oct 25 00:35 UT	Oct 25 01:12 UT	Oct 25 01:12 UT	Oct 26 00:40 UT
t_{T1} (2011)	Oct 25 12:34 UT	Oct 25 12:42 UT	Oct 25 13:23 UT	Oct 25 13:23 UT	Oct 26 13:36 UT
t_{T2} (2011)	Oct 25 14:21 UT	Oct 25 14:21 UT	Oct 25 15:04 UT	Oct 25 15:04 UT	Oct 26 15:27 UT
v_S [kms ⁻¹]	487	475	486	484	-
v_L [kms ⁻¹]	527	494	485	496	-
v_T [kms ⁻¹]	455/425	442/426	440/414	451/415	-
v_E [kms ⁻¹]	36/51	26/34	22/36	43/41	-
v_c [kms ⁻¹]	472/468	462/458	449/442	443/440	-
$\langle v_E \rangle$ [kms ⁻¹]	4.8/5.1	4.7/6.1	4.1/5.2	4.1/5.1	-
$\langle v_c \rangle$ [kms ⁻¹]	490/476	468/460	463/449	473/455	-
D [AU]	0.137/0.156	0.135/0.152	0.132/0.148	0.130/0.147	0.147/0.164
B_{max} [nT]	26.7	25.0	26.9	25.4	21.0
$\langle B \rangle$ [nT]	22.4/21.5	22.7/21.8	23.0/22.1	22.8/22.0	19.7/18.9

Table 4.1: Shock and flux rope parameters of the ICME observed at each spacecraft, including the heliocentric distance of the spacecraft (r_H) and the times at which the shock front, leading and trailing edges were observed (t_S , t_L , t_{T1} , t_{T2} , respectively). Shock front (v_S), leading edge (v_L), trailing (v_T), expansion (v_E), and cruise velocities (v_c) have been calculated for the near-Earth spacecraft where plasma data is available. The mean expansion ($\langle v_E \rangle$) and cruise ($\langle v_c \rangle$) velocities have been calculated considering the propagation times between the near-Earth spacecraft and Juno. The observed radial width of the flux rope (D), and the maximum and mean magnetic field magnitudes observed inside the flux rope are given ($\langle B \rangle$ and B_{max} , respectively). Two values separated by ‘/’ are presented where changing between trailing edge times, t_{T1} and t_{T2} , affects the parameters.

between Wind and Juno which is less than expected. The calculation of observed radial width does not take into account the orientation of the flux rope and therefore, is in real terms the length of the spacecraft trajectory through the rope. The mean cruise velocity of the ICME at each near-Earth spacecraft was also used as an approximate cruise velocity at Juno, and therefore it is perhaps unsurprising that the expected expansion is not observed.

The maximum magnetic field strength within the flux rope, B_{max} , and the mean magnetic field strength within the flux rope, $\langle B \rangle$, are given in rows 14 and 15 in Table 4.1, respectively. The mean magnetic field magnitudes decrease between the near-Earth spacecraft and Juno as $\langle B \rangle \propto r^{-0.63 \pm 0.24}$ for both trailing edge times defined, where r is the heliocentric distance. This relationship differs to that quoted in Chapter 3, Section 3.4 due to the inclusion of ACE and ARTEMIS datapoints, rather than only using observations at Wind. However, the Chapter 3 relationship is still within the uncertainty range quoted here. We also find that $B_{max} \propto r^{-0.94 \pm 0.23}$. As previously

discussed in Chapter 3, the mean magnetic field relationships are not in agreement with those previously derived by Ebert *et al.* (2009) who found $B \propto r^{-1.29 \pm 0.12}$ and Richardson (2014) who found $B \propto r^{-1.21 \pm 0.09}$. The B_{max} relationship is most similar to these relationships, with a slight overlap in associated errors. The disagreement with the mean magnetic field relationship derived in this study is likely due to the differences in the magnetic fields along the different paths taken by the near-Earth spacecraft and Juno through the flux rope. These longitudinal effects dominate over the expected small change in the field intensity due to the radial separation of 0.24 AU.

4.2 Solar Source of the In Situ Structures

To give context to the in situ observations, we try to locate the solar counterpart of the investigated magnetic cloud. Using the leading edge speed of the ICME at Wind and assuming a constant propagation speed from the Sun to L1, we find an estimated eruption time on 21 October, at 19:15 UT. Two potential candidate CMEs are listed in the Coordinated Data Analysis Workshop (CDAW) Solar and Heliospheric Observatory (SOHO) Large Angle and Spectrometric Coronagraph (LASCO) CME catalogue (https://cdaw.gsfc.nasa.gov/CME_list/) around this time. These were first observed in the LASCO C2 telescope field of view at 01:25 UT and 10:24 UT on 22 October, with 2nd-order speeds at 20 R_s of 663 and 1074 kms⁻¹, respectively. Both CMEs were also seen by the coronagraphs onboard STEREO-A and STEREO-B. Using the STEREO CME Analysis Tool (StereoCAT; <https://ccmc.gsfc.nasa.gov/stereocat/>) we find that the apex of the first CME had an initial propagation direction of 25° longitude west of the Earth-Sun line and 50° latitude north of the solar ecliptic (SE) plane with a half-width of 46°. The later CME had an initial propagation direction of 90° longitude and 52° latitude with a half-width of 55°. Based on these initial propagation directions, it is therefore likely that the source of the transient observed in situ at Earth and Juno is the first CME listed, in agreement with the Wood *et al.* (2017) STEREO survey of ICMEs observed in situ at Earth.

The identified CME is associated with a filament eruption, studied in detail by Gosain *et al.* (2016). The magnetic configuration of filaments is observed to be that of a flux rope (Guo *et al.* 2010). The filament was located in the solar northern hemisphere indicating that the flux rope should likely be left-handed (Rust, 1994), which is consistent with the ENW/SEN flux rope classifications observed in situ. The

propagation direction of the filament eruption stabilised at approximately 15° longitude and 45° latitude (Gosain *et al.*, 2016), consistent with the ICME propagation direction found using the STEREO CME Analysis Tool.

To further confirm the solar CME counterpart of the in situ magnetic cloud, we compare the observed ICME arrival times with those predicted by the Propagation Tool developed at the Institute of Research in Astrophysics and Planetology (IRAP) (Rouillard *et al.* (2017); <http://propagationtool.cdpp.eu/>). Inputting values to the Propagation Tool recorded by the CDAW SOHO LASCO CME catalogue with a background solar wind speed observed in situ at Wind of 320 km s^{-1} and an approximate drag parameter of $0.2 \times 10^{-7} \text{ km}^{-1}$ resulted in predicted arrival times of the flux rope leading edge of 25 October 2011 06:34 UT at Wind and 26 October 2011 04:58 UT at Juno. The drag parameter used was derived using solar wind and magnetic cloud densities in combination with the observed radial width of the flux rope at Wind as in Cargill (2004). The predicted times compare well with the observed leading edge arrival times of 25 October 2011 00:28 UT and 26 October 00:40 UT at Wind and Juno, respectively.

The source of the sudden increase in radial speed following the flux rope observed in situ by each of the near-Earth spacecraft remains inconclusive. Inspection of Solar Dynamics Observatory data (Atmospheric Imaging Assembly, AIA; Lemen *et al.*, 2012) shows a small coronal hole already present prior to the eruption, at a similar latitude close to the filament channel from which the source of the magnetic cloud originated. An ENLIL simulation at https://iswa.gsfc.nasa.gov/downloads/20111022_072000_anim.tim-vel.gif shows a slight narrow stream of higher speed solar wind around the time of the event at Earth, but care must be taken whether to trust such small features. The in situ data at Wind in Figure 4.2 shows a region of low temperature following the flux rope which could be evidence of a weak ICME following the event. Although there are no suitable CMEs listed in the CDAW SOHO LASCO CME catalogue, many ICMEs observed at Earth do not have clearly identifiable associated solar counterparts (Richardson and Cane, 2010; Kilpua *et al.*, 2014).

4.3 Analysis

We use five methods to analyse the ICME. These include using: (i) timing considerations between the near-Earth spacecraft to determine a direction of propagation of the

ICME shock, minimum variance analysis to estimate (ii) the propagation direction of the sheath region of the ICME at each spacecraft and (iii) the orientation of the flux rope, and (iv) the Lundquist and (v) Gold-Hoyle force-free flux rope fitting methods to provide independent determinations of the flux rope axis orientation and other parameters such as the axial magnetic field strength, impact parameter, and radial width scale value. Table 4.2 summarises the results of each method, and Figure 4.6 presents a visualisation of the calculated directions/orientations in terms of θ and ϕ for each analysis method and trailing edge definition.

4.3.1 Timing Considerations

Assuming a constant propagation velocity, $\mathbf{V}_s$, and a planar shock front, we use timing considerations of the shock front between the four near-Earth spacecraft to calculate the normal direction, $\mathbf{n}_s$, and speed of the shock, ν , using Equations 2.1a and 2.1b given in Chapter 2.

The calculated shock propagation direction is listed in Table 4.2 as $\theta_p = -9.4^\circ$ with respect to the solar ecliptic (SE) plane and $\phi_p = 11.0^\circ$ with respect to the Sun-Earth line, and has a propagation velocity of 514 kms^{-1} . This direction is visually presented in the first row of Figure 4.6 (shown in red). The observed shock velocity at each near-Earth spacecraft is given in Table 4.1, the mean of which was calculated to be 483 kms^{-1} . The calculated propagation velocity is therefore in reasonable agreement with observations.

4.3.2 Minimum Variance Analysis

Minimum variance analysis (MVA) has been performed on both the sheath region and flux rope. Table 4.2 summarises the results of the MVA, performed on the planar magnetic structure (PMS) within the sheath region that immediately follows the shock front, and also the magnetic flux rope of the ICME, where θ_a is the elevation angle out of the SE plane and ϕ_a is the angle from the Sun-Earth line anticlockwise in the SE plane. Figure 4.6 presents the orientations calculated by MVA in black. The mean normal direction to the sheath region at the near-Earth spacecraft was calculated to be $\theta = -11.9^\circ$ and $\phi = 7.4^\circ$. Comparing the calculated sheath normal with the direction of propagation of $\theta = -9.4^\circ$ and $\phi = 11.0^\circ$ calculated in Section 4.3.1, we find these to be consistent between the near-Earth spacecraft, shown in the first row of Figure

4.6. The sheath normal at Juno was calculated to be $\theta = -22.4^\circ$ and $\phi = 21.0^\circ$ and therefore there is a mean change in direction of $\theta = 10.6^\circ$ away from the SE plane and $\phi = 13.6^\circ$ anticlockwise in the SE plane between the near-Earth spacecraft and Juno.

The flux rope orientations obtained are well defined considering that the ratios of the maximum eigenvalue, λ_1 , and minimum eigenvalue, λ_3 to the intermediate eigenvalue, λ_2 (both also summarised in Table 4.2) meet the criteria defined by Siscoe and Suey (1972) of $\frac{\lambda_1}{\lambda_2} > 1.37$ and $\frac{\lambda_3}{\lambda_2} < 0.72$. The resulting flux rope orientations, given in Table 4.2 and presented in the second and third rows of Figure 4.6, are consistent within errors at the near-Earth spacecraft, with a mean orientation of $\theta = 52.4/70.0^\circ$ and $\phi = 220.2/245.8^\circ$ and a standard deviation from the mean of $\theta = 7.0/3.9^\circ$ and $\phi = 11.1/4.6^\circ$, where the first result is calculated using the earlier trailing edge time and the second uses the later trailing edge time. The flux rope orientation at Juno was calculated to be $\theta = 23.7/49.9^\circ$ and $\phi = 290.1/317.3^\circ$. Between the near-Earth spacecraft and Juno, the flux rope orientations display a clear mean change of $\theta = 28.7/20.1^\circ$ towards the SE plane and $\phi = 69.9/71.5^\circ$ anticlockwise in the SE plane. Although the calculated flux rope orientations at the near-Earth spacecraft are more moderately inclined than highly inclined, they support the flux rope classification of ENW at the near-Earth spacecraft and a lower inclination flux rope of SEN at Juno.

Table 4.2: The results of the analysis performed at each spacecraft, organised by method. Multi-spacecraft timing considerations at the near-Earth spacecraft determine a propagation direction of the ICME shock front. MVA has been applied to both the sheath to determine the normal direction to the sheath, and the flux rope to determine the flux rope axis orientation. The flux rope axis orientation is also determined by the force-free fitting methods (Lundquist and Gold-Hoyle). Both force-free flux rope fitting methods give estimates of the axial magnetic field strength, B_0 , handedness, H , impact parameter, p , minimised chi-squared, χ^2 , and modelled radial width, D' .

Analysis Method	Parameter	Wind	ACE	THEMIS B	THEMIS C	Jun0
Multi-S/C	Shock propagation direction					
			$\theta_p = -9.4^\circ$ $\phi_p = 11.0^\circ$			-
MVA	Sheath normal direction	$\theta_s = -11.4^\circ$ $\phi_s = 4.8^\circ$	$\theta_s = -15.3^\circ$ $\phi_s = 1.1^\circ$	$\theta_s = -10.2^\circ$ $\phi_s = 11.6^\circ$	$\theta_s = -10.5^\circ$ $\phi_s = 12.0^\circ$	$\theta_s = -22.4^\circ$ $\phi_s = 21.0^\circ$
	FR axis orientation	$\theta_a = 46.4^\circ / 70.1^\circ$ $\phi_a = 207.1^\circ / 251.5^\circ$	$\theta_a = 62.3^\circ / 75.4^\circ$ $\phi_a = 232.8^\circ / 245.3^\circ$	$\theta_a = 48.7^\circ / 66.7^\circ$ $\phi_a = 216.1^\circ / 240.3^\circ$	$\theta_a = 52.0^\circ / 67.6^\circ$ $\phi_a = 224.9^\circ / 246.2^\circ$	$\theta_a = 23.7^\circ / 49.9^\circ$ $\phi_a = 290.1^\circ / 317.3^\circ$
	FR eigenvalue ratios, $\frac{\lambda_1}{\lambda_2}, \frac{\lambda_3}{\lambda_2}$	7.56/6.36, 0.61/0.46	7.88/6.17, 0.42/0.26	7.92/6.74, 0.48/0.37	7.51/6.24, 0.48/0.34	13.80/3.68, 0.31/0.05
	FR axis orientation	$\theta_a = 25.8^\circ / 38.9^\circ$ $\phi_a = 213.1^\circ / 322.3^\circ$	$\theta_a = 28.5^\circ / 43.0^\circ$ $\phi_a = 215.7^\circ / 324.0^\circ$	$\theta_a = 26.9^\circ / 37.5^\circ$ $\phi_a = 212.1^\circ / 323.5^\circ$	$\theta_a = 27.3^\circ / 38.5^\circ$ $\phi_a = 218.2^\circ / 319.4^\circ$	$\theta_a = 12.5^\circ / 16.2^\circ$ $\phi_a = 309.6^\circ / 307.1^\circ$
Lundquist	Axial field strength, B_0 [nT]	30.8/27.9	30.8/28.3	32.0/29.0	30.8/28.3	23.4/23.5
	Handedness, H	-1/-1	-1/-1	-1/-1	-1/-1	-1/-1
	Impact parameter, p	0.476/0.341	0.475/0.346	0.477/0.341	0.452/0.322	0.047/0.181
	Minimised chi-squared, χ^2	0.125/0.124	0.089/0.108	0.131/0.122	0.113/0.114	0.234/0.120
	Modelled radial width, D' [AU]	0.102/0.131	0.107/0.131	0.100/0.121	0.104/0.125	0.115/0.136
Gold-Hoyle	FR axis orientation	$\theta_a = 44.1^\circ / 54.2^\circ$ $\phi_a = 270.9^\circ / 272.3^\circ$	$\theta_a = 50.9^\circ / 60.4^\circ$ $\phi_a = 270.5^\circ / 271.9^\circ$	$\theta_a = 44.6^\circ / 53.8^\circ$ $\phi_a = 271.5^\circ / 273.0^\circ$	$\theta_a = 44.1^\circ / 53.3^\circ$ $\phi_a = 271.5^\circ / 272.9^\circ$	$\theta_a = 18.2^\circ / 29.3^\circ$ $\phi_a = 278.6^\circ / 278.8^\circ$
	Axial field strength, B_0 [nT]	25.3/26.3	25.8/26.8	26.2/27.2	25.8/26.8	21.6/23.0
	Handedness, H	-1/-1	-1/-1	-1/-1	-1/-1	-1/-1
	Impact parameter, p	0.011/0.023	0.006/0.016	0.019/0.043	0.019/0.030	0.153/0.139
	Minimised chi-squared, χ^2	0.089/0.093	0.081/0.085	0.084/0.086	0.083/0.086	0.040/0.149
	Modelled radial width, D' [AU]	0.137/0.156	0.135/0.152	0.132/0.148	0.130/0.147	0.148/0.164

4.3.3 Force-Free Flux Rope Fitting

MVA was also used as a starting point for the first force-free flux rope model fit to the magnetic field components, based on the Lundquist solutions (Lundquist, 1950) detailed in Chapter 2. The magnetic field solutions were fitted to the data of ACE, Wind, THEMIS B, THEMIS C, and Juno using a least squares procedure similar to that developed by Lepping, Jones, and Burlaga (1990) where the calculated MVA orientation initialises the χ^2 minimisation; details of this technique are given in Good *et al.* (2019) and Kilpua *et al.* (2019).

The other flux rope fitting method used considers the magnetic field to have a uniform twist across the rope cross-section: a ‘Gold-Hoyle’ tube (Gold and Hoyle, 1960). There has been recent interest (e.g. Hu *et al.*, 2014; Hu, Qiu, and Krucker, 2015; Wang *et al.*, 2016) in using the Gold-Hoyle model to fit flux ropes in situ. This has been motivated by evidence (Kahler, Krucker, and Szabo, 2011) indicating that field line lengths, as estimated from strahl electron travel times from the Sun, are too short to be consistent with the highly twisted (and hence very long) field lines in the outer layers of a Lundquist flux rope. The Gold-Hoyle model solutions are also detailed in Chapter 2.

Figures 4.4 and 4.5 present the Lundquist (dashed line) and Gold-Hoyle (solid line) fits to the magnetic field data of the flux rope using both the earlier trailing edge boundary (left-hand side) and the later trailing edge (right-hand side) at Wind and Juno, respectively. The fitting at ACE, THEMIS B and C is presented in the Appendix. Visual inspection of Figure 4.4 shows that both models fit the magnetic field data to a good approximation. The main difference between the two models can be seen to be in how they represent the weakest radial component. The goodness of fit of the Lundquist model fits at Wind is marginally better than the Gold-Hoyle model using the earlier trailing edge, but is more similar using the later trailing edge. At Juno, Figure 4.5 shows that the Lundquist and Gold-Hoyle model fits are of a comparatively similar goodness using the later trailing edge, similar to those at Wind. At Juno, the largest difference in the fits arises when using the earlier trailing edge boundary - we find that the Gold-Hoyle model fits much better to the magnetic field data than the Lundquist model using this boundary. Looking at the large scale rope structure, inspection of the model fits shows that the two models follow similar patterns across both spacecraft and both trailing edges. The exception to this pattern is seen in the Lundquist fitting

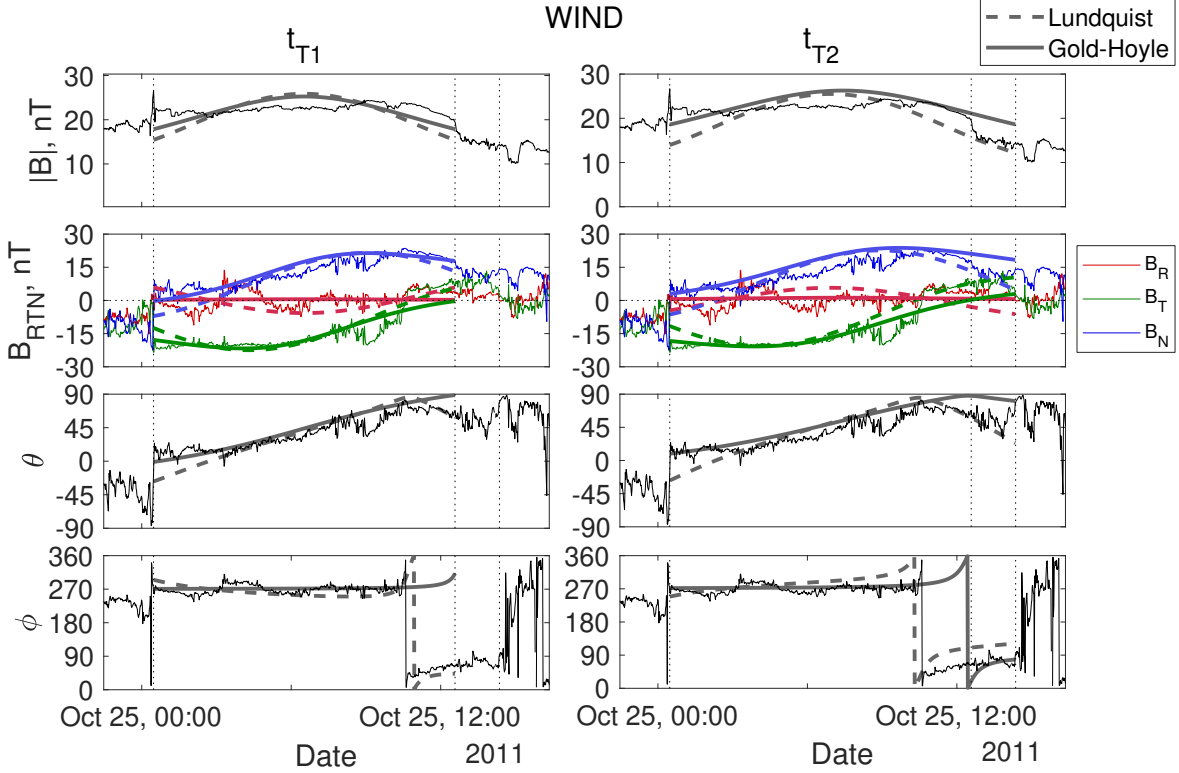


Figure 4.4: Force-free flux rope models fitted to the in situ magnetic field signatures observed by Wind, displayed in a similar format as Figure 4.2. The Lundquist model (dashed line) and Gold-Hoyle model (solid line) fitting is shown using both the earlier trailing edge (left-hand side) and the later trailing edge (right-hand side).

at Wind where the weakest radial component of the field is of opposite sign for the different trailing edge times.

Both force-free fitting methods allow for estimates to be made of various global cloud properties such as the axial field strength, B_0 , its radial width, D' , the normalised closest approach distance of the spacecraft to the flux rope axis known as the impact parameter, p , and the flux rope axis orientation.

Table 4.2 also summarises the results of the force-free fitting. Both the Lundquist and Gold-Hoyle fitting methods show that the rope is consistently left-handed ($H = -1$) at the near-Earth spacecraft and Juno. Figure 4.6 presents the flux rope orientations calculated using the earlier trailing edge (second row) and the later trailing edge (third row). The Lundquist fitting gives a mean flux rope orientation of $\theta = 27.1/39.5^\circ$ and $\phi = 214.8/322.3^\circ$ at the near-Earth spacecraft and an orientation of $\theta = 12.5/16.2^\circ$ and $\phi = 309.6/307.1^\circ$ at Juno. The Gold-Hoyle fitting gives a mean orientation of

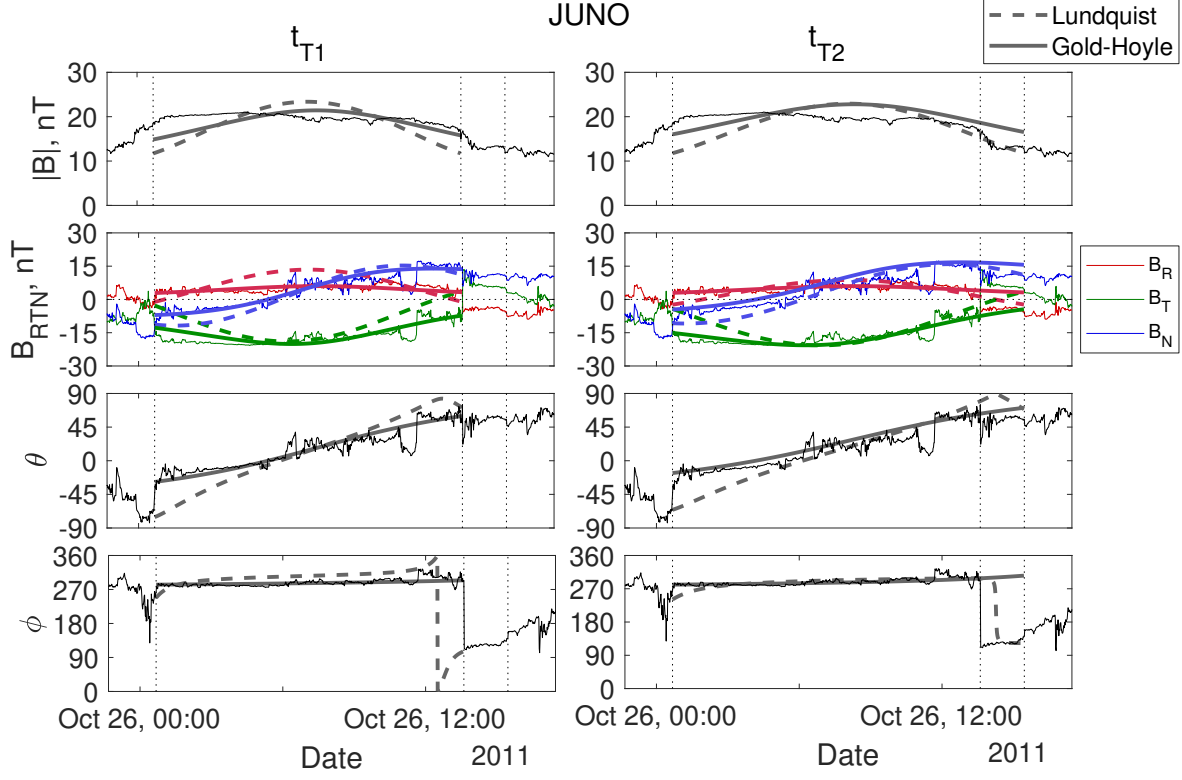


Figure 4.5: Force-free flux rope models fitted to the in situ magnetic field signatures observed by Juno, displayed in the same format as Figure 4.4.

$\theta = 45.9/55.4^\circ$ and $\phi = 271.1/272.5^\circ$ at the near-Earth spacecraft and an orientation of $\theta = 18.2/29.3^\circ$ and $\phi = 278.6/278.8^\circ$ at Juno. The Lundquist and Gold-Hoyle fits at each spacecraft meet the χ^2 and δ error requirements for reasonably accurate fits (see Good *et al.*, 2019, for further details on these parameters), i.e. they fit well to the data. For such fits, Lepping, Berdichevsky, and Ferguson (2003) estimated errors of $\approx 13^\circ$ and $\approx 30^\circ$ in θ and ϕ , respectively. The χ^2 values are listed in Table 4.2 and show comparable trends to those observed by visual inspection of the fitting: the Lundquist model fits at Juno are comparatively worse than at Wind using the later trailing edge but are of similar goodness of fit using the earlier trailing edge, whereas the Gold-Hoyle model fits at Juno are comparatively better than at Wind using the earlier trailing edge, but similar using the later trailing edge. The force-free fitting orientations at the near-Earth spacecraft are also in reasonable agreement with those found in previous studies for the same ICME that used Wind data; Lepping *et al.* (2015) found that $\theta = 40^\circ$ and $\phi = 291^\circ$ and Wood *et al.* (2017) found that $\theta = 45^\circ$ and $\phi = 286^\circ$. The

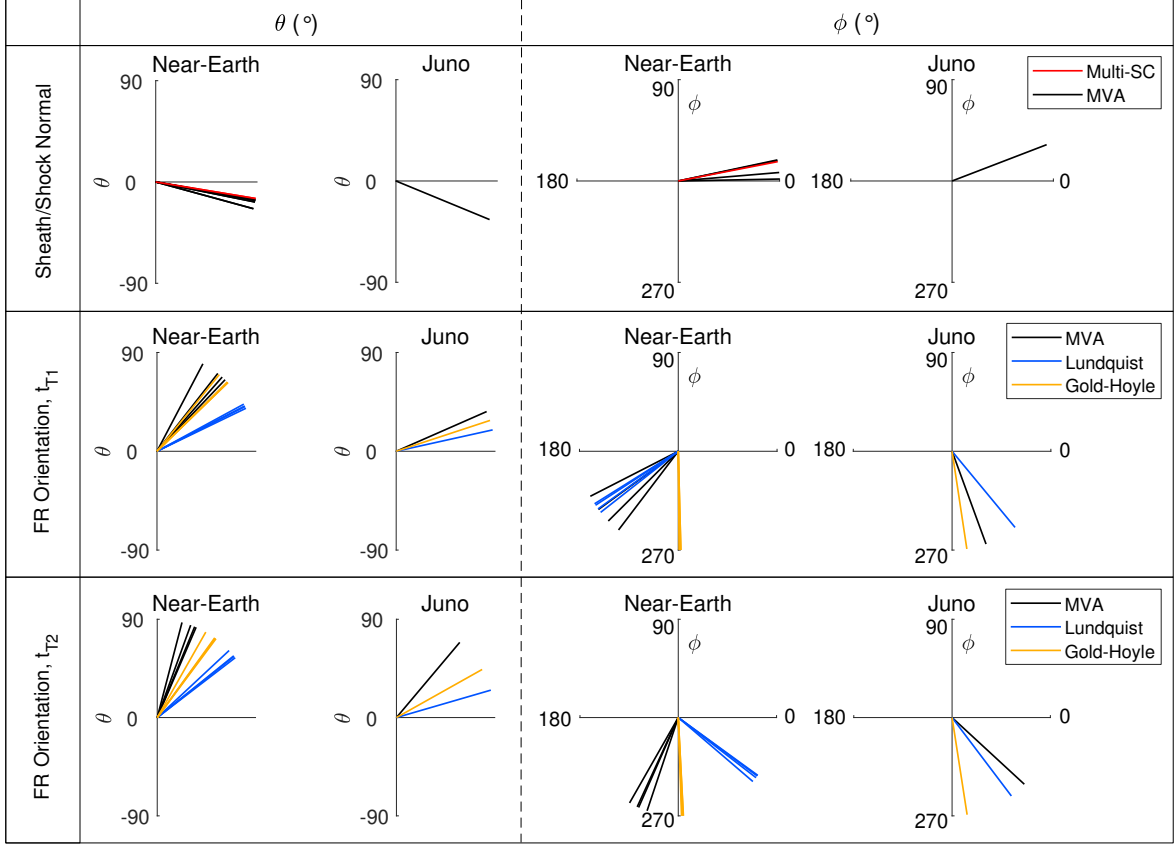


Figure 4.6: Calculated orientations presented in RTN coordinates, where θ is the angle to the R-T plane, and ϕ is the angle swept out anticlockwise from the Sun-Earth line, projected onto the R-T plane ($\phi = 180^\circ$ points Sunwards). θ is presented for the near-Earth spacecraft and Juno in the first column, and ϕ is presented for the near-Earth spacecraft and Juno in the second column. The normal directions to the sheath calculated using MVA (black) and the propagation direction of the shock calculated using timing considerations between the near-Earth spacecraft (red) are presented in the first row. The flux rope orientations calculated by MVA (black), Lundquist (blue), and Gold-Hoyle fitting (orange) using the earlier trailing edge are presented in the second row, and in the third row using the later trailing edge.

flux rope orientations and left-handedness are supported by the flux rope classifications observed in Section 4.1 (ENW at the near-Earth spacecraft and SEN at Juno).

Comparing the flux rope axis orientations for each of the force-free flux rope fitting methods and those calculated using MVA, we find:

- i) MVA results in the highest inclination to the SE plane for both flux rope trailing edges, with a mean $\theta = 52.4/70.0^\circ$ for the near-Earth spacecraft. This is in comparison to $\theta = 27.1/39.5^\circ$ for the Lundquist model, and $\theta = 45.9/55.4^\circ$ for the

Gold-Hoyle model. Comparing ϕ angles at the near-Earth spacecraft, we find that the mean $\phi = 220.2/245.8^\circ$ for MVA, $\phi = 214.8/322.3^\circ$ for the Lundquist model, and $\phi = 271.1/272.5^\circ$ for the Gold-Hoyle model. Note that the Lundquist model results in the highest and lowest mean value of ϕ given the different trailing edge times.

- ii) Comparing the results for each method at the near-Earth spacecraft to Juno, we find that the flux rope orientation differs by $\theta = 28.7/20.1^\circ$, $14.6/23.3^\circ$, and $27.7/26.1^\circ$ towards the SE plane, and $\phi = 69.9/71.5^\circ$, $94.8/ - 15.2^\circ$, $7.5/6.3^\circ$ anticlockwise in the SE plane, for MVA, Lundquist and Gold-Hoyle models, respectively. The overall trend in flux rope orientation between the near-Earth spacecraft and Juno is demonstrated clearly in Figure 4.6 by comparing the subplots of each panel: the orientation is closer to the SE plane at Juno, and rotates anticlockwise between the near-Earth spacecraft and Juno. The difference in θ exceeds the $\approx 13^\circ$ uncertainty found by Lepping, Berdichevsky, and Ferguson (2003) in the orientation for all methods/trailing edges. However, this is not the case for each ϕ angle where just MVA and the earlier Lundquist value exceed the $\approx 30^\circ$ uncertainty. The difference in orientation towards the SE plane is quite significant over a relatively small radial separation. As discussed in Section 4.2, the source of the faster solar wind following the event is unclear, but perhaps may have had an effect on the change in flux rope orientation between the near-Earth spacecraft and Juno. Different parts of an ICME can also evolve in a different manner in the structured solar wind which could lead to differences in flux rope properties, such as orientation, at spacecraft separated in longitude (e.g. Savani *et al.*, 2010; Owens, Lockwood, and Barnard, 2017). However, over the small longitudinal and radial separation in this case, such differences would not be expected to be large.
- iii) Changing between the two trailing edge times (comparing the second and third rows of Figure 4.6) produces the largest difference in θ with MVA - an average difference of 17.6° , compared to 12.4° and 9.5° using the Lundquist and Gold-Hoyle models, respectively. However, the largest difference in the ϕ angle is produced by the Lundquist model: 107.5° compared to 25.6° for MVA, and 1.4° for the Gold-Hoyle model. For these cases, the Gold-Hoyle model is least affected by the change in trailing edge time defined for the flux rope, whereas the Lundquist model is more sensitive to this, especially in the resulting fit to the radial component of the

magnetic field. A previous study by Démoulin, Dasso, and Janvier (2018) explores the sensitivity of flux rope orientation with changing flux rope boundaries for MVA and finds that similarly, the boundaries defined strongly affect the resulting flux rope orientation.

- iv) Considering the uncertainty in the orientations at the near-Earth spacecraft, the Lundquist model is the least variant in results for θ , with a standard deviation of $1.1/2.4^\circ$ in comparison to $7.0/3.9^\circ$ for MVA, and $3.3/3.3^\circ$ for Gold-Hoyle. However, the Gold-Hoyle model is the least variant in results for ϕ , with a standard deviation of $0.5/0.5^\circ$, compared with $11.1/4.6^\circ$ for MVA, and $2.7/2.1^\circ$ for Lundquist. This is clearly demonstrated by the spread of orientations in Figure 4.6. Overall, MVA produces the widest spread in results for the near-Earth spacecraft, with the force-free fitting models performing similarly.
- v) The difference between mean results at the near-Earth spacecraft across methods shows that for θ , the Gold-Hoyle model results are most similar to MVA, with a mean difference of $6.4/14.5^\circ$. This is in comparison with Lundquist and MVA with a mean difference of $25.2/30.5^\circ$, and Lundquist and Gold-Hoyle with a mean difference of $18.8/16.0^\circ$. The ϕ angle is more dependent on the trailing edge time, where the difference between MVA and Lundquist is $5.5/76.5^\circ$, MVA and Gold-Hoyle is $50.9/26.7^\circ$, and Lundquist and Gold-Hoyle is $56.3/49.8^\circ$.

The closer to the axis a spacecraft crosses the flux rope, the more reliable the estimated MVA axis orientation and calculated force-free fitting parameters have been found to be (Klein and Burlaga, 1982; Bothmer and Schwenn, 1998; Farrugia *et al.*, 1999; Xiao *et al.*, 2004; Gulisano *et al.*, 2005, 2007; Ruffenach *et al.*, 2012, 2015). Investigating the impact parameters at each spacecraft, we find that the Lundquist model suggests that Juno passes through the flux rope closer to the central axis than any of the near-Earth spacecraft (at Juno, $p = 0.047/0.181$, in comparison to the near-Earth spacecraft where the mean $p = 0.470/0.338$), whereas the Gold-Hoyle model suggests that the near-Earth spacecraft pass closest to the flux rope axis ($p = 0.153/0.139$ at Juno and the mean $p = 0.014/0.028$ at the near-Earth spacecraft). Comparing fitting methods, the impact parameters are most similar for Juno, with more of a contrast between values for the near-Earth spacecraft. The two fitting methods give very different impact parameters due to the magnetic field geometry: the Lundquist p values are higher than

the Gold-Hoyle values because an intermediate- p Lundquist flux rope encounter, in which the field is not observed to rotate by a full 180° between leading and trailing edges, is similar to a low- p Gold-Hoyle rope encounter.

If we consider the propagation of a perfectly cylindrical flux rope with a concentric sheath region draped ahead of the flux rope, the sheath normal and the flux rope axis should ideally be perpendicular to each other at each spacecraft. Comparing the flux rope axis orientations of each method/defined trailing edge to that of the normal direction to the sheath, we find the mean angle between these vectors for the near-Earth spacecraft as $\delta = 48.0/68.2^\circ$, $\delta = 30.1/66.6^\circ$, and $\delta = 77.0/77.3^\circ$, with the MVA, Lundquist, and Gold-Hoyle methods, respectively. This angle can be visualised by comparing the second and third rows of Figure 4.6 to the first. For the near-Earth spacecraft, we therefore find that the Gold-Hoyle model produced values closer to the ideal, and across all methods, using the flux rope axis from fits with the later trailing edge produced results consistently closer to the ideal than those using the earlier trailing edge. At Juno, $\delta = 80.4/88.5^\circ$, $\delta = 78.2/82.0^\circ$, and $\delta = 72.0/69.0^\circ$ for the MVA, Lundquist, and Gold-Hoyle methods, respectively. Overall, the values are closer to the ideal at Juno for each method/trailing edge time except for the Gold-Hoyle model.

The axial field strength estimated by the Lundquist model is consistently higher than the corresponding value estimated by the Gold-Hoyle model: the Lundquist fitting gives the mean $B_0 = 31.1/28.4$ nT at the near-Earth spacecraft and $B_0 = 23.4/23.5$ nT at Juno, and the Gold-Hoyle fitting gives the mean $B_0 = 25.8/26.8$ nT at the near-Earth spacecraft and $B_0 = 21.6/23.0$ nT at Juno. Investigating the relationship between the axial field strength given by the force-free fitting models and the heliocentric distance at which it was measured, we find a power law for the Lundquist results that suggests $B_0 \propto r^{-1.25 \pm 0.03} / r^{-0.83 \pm 0.03}$, and for the Gold-Hoyle results we find $B_0 \propto r^{-0.77 \pm 0.04} / r^{-0.67 \pm 0.04}$. The earlier and later trailing edge Gold-Hoyle fit relationships and the later trailing edge Lundquist fit relationship are similar to the relationships derived using in situ observations in Section 4.1. Interestingly, the relationship derived using the earlier trailing edge Lundquist fits is consistent with the previously mentioned relationships derived by Richardson (2014) and Ebert *et al.* (2009) as the radial dependence may be quite different for B_0 derived from fits in comparison to the field parameters observed in situ. However, as previously discussed, disagreement between the relationships derived in this study with previous studies is likely due to the small radial separation of 0.24 AU between spacecraft observations, and therefore the

difference in longitude between observations and thus the different path taken by the spacecraft through the flux rope is likely to be the dominant effect.

The observed radial width (D) does not take into account the orientation of the flux rope as it passes the spacecraft, nor the impact parameter. To correct for this, a scale factor, estimated from the force-free fitting may be applied to the observed radial width to give an estimate of the true flux rope width, D' . Hence $D' = SD = Sv_c(t_T - t_L)$, where S is the scale factor that can be less than, equal to, or greater than 1 and accounts for both the impact parameter and the rope orientation. The calculated modelled radial widths are listed in Table 4.2. For the Lundquist model, a scaling value less than 1 is given to correct for the orientation of the flux rope at each spacecraft. The Lundquist fitting gives the mean $D' = 0.103/0.127$ AU at the near-Earth spacecraft, and $D' = 0.115/0.136$ AU at Juno. The Gold-Hoyle fitting only produces a non-unity scale factor for Juno, however, these values are still very close to unity resulting in only a 0.001 AU difference from the radial width observed for the earlier trailing edge: $D' = 0.148/0.164$ AU, in comparison to $D = 0.147/0.164$ AU. The mean calculated radial width remains the same as the observed radial width at the near-Earth spacecraft, $D' = D = 0.134/0.151$ AU, likely due to the flux rope orientation lying close to perpendicular with the radial direction ($\phi = 271.1/272.5^\circ$) and the small impact parameter, and therefore little adjustment is necessary for the spacecraft path length through the flux rope. The modelled radial widths are similarly consistent between the near-Earth spacecraft, and show that there was very little expansion over the short distance between Earth and Juno for both models and trailing edges. The difference in modelled radial width between Wind and Juno is 0.013/0.005 AU for the Lundquist model and 0.011/0.008 for Gold-Hoyle. These values are consistent with the difference in observed radial width, and are less than the expected 0.019/0.024 AU calculated in Section 4.1.

4.4 Summary and Discussion

An ICME that caused a strong geomagnetic storm at Earth commencing on 24 October 2011 was observed in situ by ACE, Wind, ARTEMIS, and Juno. The geomagnetic storm was the strongest recorded in 2011, with a minimum Dst index of -147 nT at its peak. The ICME displayed a clear magnetic flux rope structure which has been analysed using two fitting models, Lundquist and Gold-Hoyle, and MVA.

Due to the positioning of the spacecraft in the near-Earth environment, ACE, Wind, and the two ARTEMIS spacecraft, THEMIS B and THEMIS C, have been used to perform multi-spacecraft analysis in conjunction with Juno which had recently commenced its cruise phase to Jupiter and was therefore close to radial alignment with the near-Earth spacecraft, longitudinally separated by only 3.6° throughout the event. During this time, the radial separation between Juno and the near-Earth spacecraft was 0.24 AU. Cases where spacecraft are separated by such radial distances and longitudinal separations are rare, and therefore these observations have allowed for an interesting analysis of the evolution of a magnetic cloud and evaluation of whether radial or longitudinal effects dominate.

We find that the overall magnetic field magnitude profiles, as well as the behaviour of the magnetic field components, are similar between the investigated spacecraft. However, we have also found that observations made in situ between the near-Earth spacecraft and Juno display some significant differences, despite the small longitudinal separation between the spacecraft; e.g. we observe a sudden increase in radial speed of the solar wind following the flux rope at the near-Earth spacecraft but not at Juno. These differences can arise from evolution in time or from longitudinal separation, although Juno and Earth are relatively close to each other both radially and longitudinally. Significant differences have previously also been reported in ICME flux rope properties over relatively small longitudinal separations of only a few degrees (Kilpua *et al.*, 2011; Winslow *et al.*, 2016). Lugaz *et al.* (2018) recently reported considerable differences in the magnetic field components for a magnetic cloud they observed near the Earth orbit where spacecraft were only 0.01 AU apart. Studies based on more widely separated (several degrees in longitude) spacecraft have reported highly different flux rope orientations, suggesting this to be a local rather than global parameter (e.g. Savani *et al.*, 2010; Farrugia *et al.*, 2011; Möstl *et al.*, 2012).

The flux rope orientation differs between the near-Earth spacecraft and Juno by $\theta = 28.7/20.1^\circ$, $14.6/23.3^\circ$, and $27.7/26.1^\circ$ (dependent on earlier/later trailing edge) towards the SE plane, and $\phi = 69.9/71.5^\circ$, $94.8/-15.2^\circ$, $7.5/6.3^\circ$ anticlockwise in the SE plane, for MVA, Lundquist and Gold-Hoyle models, respectively. The orientation of the flux rope axis has been shown to have a clear difference in θ despite the relatively small spacecraft separations, irrespective of analysis method or trailing edge defined. However, the difference in ϕ only exceeds uncertainties in orientation for the MVA values and the earlier trailing edge value for the Lundquist method. We propose that the

difference in flux rope orientation is not necessarily just due to the radial evolution of the ICME, but more so due to the longitudinal separation of the spacecraft, despite this being small. This ambiguity, inherent to the localised nature of in situ measurements, has been a clear feature of previous alignment studies up to 1 AU; we note, in agreement with a more limited number of previous studies (e.g. Mulligan *et al.*, 1999), that this ambiguity must also be taken into account when analysing ICMEs beyond 1 AU. Winslow *et al.* (2016) found that in situ observations of an ICME between the MESSENGER spacecraft and STEREO-A were significantly affected due to interactions between the ICME and a heliospheric plasma sheet/current sheet, despite a small longitudinal separation of just 3° . Similarly, in this study we note that differences between in situ observations may have arisen due to the sudden increase in solar wind speed following the flux rope observed at the near-Earth spacecraft but not at Juno, the source of which remains unclear.

Comparing the force-free fitting models, both the Lundquist and Gold-Hoyle methods give broadly similar axis directions that are consistent with the ENW/SEN flux rope classifications. At the near-Earth spacecraft, there is a mean difference of $\theta = 18.8/16.0^\circ$ and $\phi = 56.3/49.8^\circ$ between the fitting methods. The Lundquist model is least variant in θ , with a standard deviation of $1.1/2.4^\circ$ in comparison to $3.3/3.3^\circ$ for Gold-Hoyle. However, the Gold-Hoyle model is the least variant in ϕ , with a standard deviation of $0.5/0.5^\circ$, compared with $2.7/2.1^\circ$ for Lundquist. Despite the difference in results, the similar standard deviations and visual inspection of the fitting at the near-Earth spacecraft show that overall, both force-free fitting models performed similarly, and give comparatively good fits to the data.

As discussed in Sections 4.1 and 4.3, relationships found between the observed mean and maximum field strengths and axial field strengths given by the force-free fitting with heliocentric distance were mostly in disagreement with the relationships found in previous studies at distances greater than 1 AU (Ebert *et al.*, 2009; Richardson, 2014). The disagreement is likely the result of using observations/parameters calculated for five spacecraft over a relatively short radial separation of 0.24 AU, whereas the previous studies used a large number of events observed between 1 and 5.4 AU, thus differences in magnetic field due to the small longitudinal separation dominate.

This chapter further demonstrates that caution should be exercised in radial alignment studies and the solar wind background should be taken into consideration. The presence of increased solar wind speed following the event at Wind but not at Juno

shows that even small longitudinal separations of a few degrees between spacecraft can still result in significantly different observations and event properties.

Chapter 5

A Comparison of Isolated ICMEs in the Heliosphere

In this chapter, two separate ICMEs are tracked through the heliosphere and their evolution analysed in context with the background solar wind environment through which they propagated. We present observations of an ICME in April 2013 that was observed in situ by both Wind and Juno at a distance of 1.6 AU (event #20130415 catalogued in Chapter 3) and an ICME more recently observed by both Solar Orbiter and Wind in April 2020, whilst Solar Orbiter was located at 0.8 AU. This chapter is partly based on the journal article published in *Astronomy and Astrophysics*, Davies *et al.* (2021). The two ICMEs are good example events to compare and contrast as they occur under very different circumstances and propagate through very different solar wind environments.

To better understand ICME evolution in situ, it is useful to track signatures of specific ICMEs over large heliocentric distances whilst spacecraft are close to radial alignment (e.g. Burlaga *et al.*, 1981). Studies of ICMEs observed by spacecraft separated by less than 5° in longitude and separated by more than 0.2 AU in heliocentric distance are relatively rare but provide valuable insight into the properties, rotation, expansion, and interaction with other features of the solar wind environment as the ICME propagates (e.g. Good *et al.*, 2015, 2018; Winslow *et al.*, 2016; Kilpua *et al.*, 2019; Lugaz, Winslow, and Farrugia, 2020; Davies *et al.*, 2020).

The link between CMEs and ICMEs and their global structure and kinematics has previously been studied by using remote observations made by STEREO in combination

with in situ observations (e.g. Davis *et al.*, 2009; Möstl *et al.*, 2009a; Wood and Howard, 2009; Liu *et al.*, 2010; Rouillard *et al.*, 2010). The global structure of a CME is a complex issue affected by the interaction of the CME with the solar wind and other CMEs as it propagates. The kinematic distortion of the large-scale structure of the CME in a latitudinally structured solar wind leads to a flattening or ‘pancaking’ of the flux rope cross-section (Odstrčil and Pizzo, 1999; Riley and Crooker, 2004; Owens, 2006; Owens, Lockwood, and Barnard, 2017), which has previously been identified in remote white light observations by Savani *et al.* (2010).

Understanding the evolution of CMEs through the inner heliosphere is one of the objectives of the Solar Orbiter mission (Müller *et al.*, 2013, 2020), which launched on 10 February 2020. Solar Orbiter provides an opportunity to study CMEs both remotely and in situ, at closer heliocentric distances to the Sun (0.28 AU perihelion) and higher latitudes out of the ecliptic plane (up to 33°). In this chapter, we present the magnetic field observations of the first ICME measured in situ at Solar Orbiter on 19 April 2020 whilst Solar Orbiter was in close radial alignment with Wind. Solar Orbiter EPD observations of the energetic particle decrease (Forbush decrease) associated with the same ICME have recently been presented by von Forstner *et al.* (2021).

As previously discussed, the Juno mission provides an opportunity to study ICMEs beyond 1 AU, and over wider radial separations in heliocentric distance. In Chapter 3, we noted that the ICME observed during April 2013 (event #20130415) is an especially interesting case as the latitudinal separation is negligible and the longitudinal separation between Juno and Wind is less than 1° during observations of the event. Studies of events whilst spacecraft were in such close alignment have previously occurred over radial separations significantly smaller than the 0.6 AU observed in this case. The Sun-Earth connection of the April 2013 ICME has previously been studied in detail by Vemareddy and Mishra (2015). This particular event is well studied due to being the first large Fe-rich SEP event of Solar Cycle 24 (Cohen *et al.*, 2014; Lario *et al.*, 2014).

We compare and contrast analysis techniques and results obtained for both the ICME observed by Solar Orbiter and the ICME observed by Juno. Section 5.1 presents the in situ magnetic field and plasma observations of the ICMEs, and Section 5.2 presents the remote observations of the ICMEs and predicted background solar wind to provide context to the in situ observations. Section 5.3 presents the analysis of the ICMEs, where the radial evolution of the ICMEs has been assessed in context with the solar wind environment.

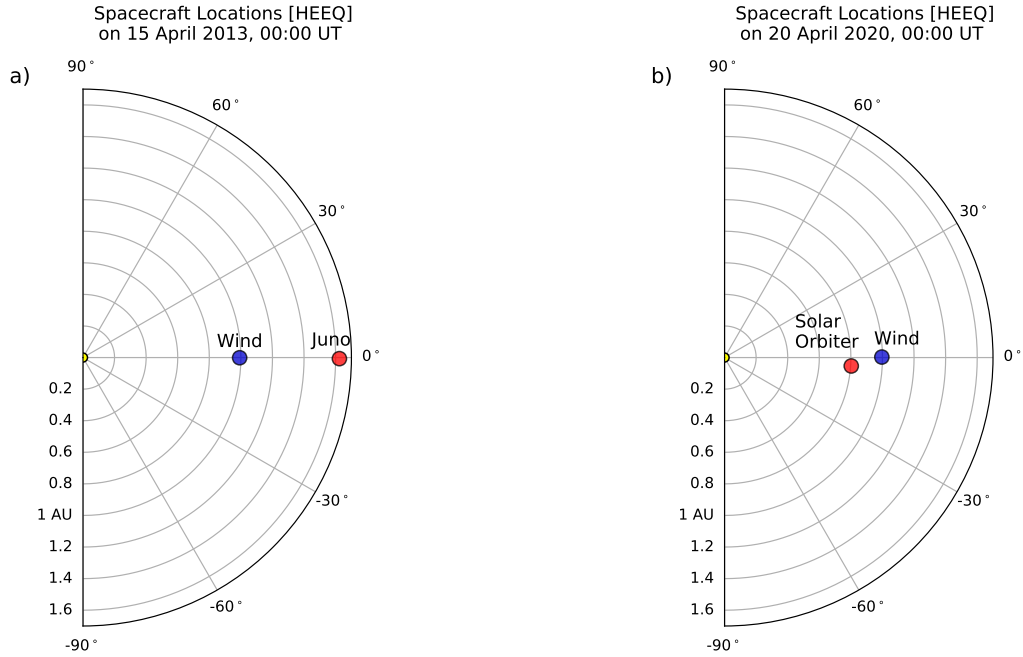


Figure 5.1: The spacecraft configuration in Heliocentric Earth Equatorial (HEEQ) coordinates of (a) Wind (blue) and Juno (red) at 00:00 UT on 15 April 2013 and (b) Solar Orbiter (red) and Wind (blue) at 00:00 UT on 20 April 2020.

5.1 In Situ Spacecraft Observations

Figure 5.1 gives an overview of spacecraft locations in Heliocentric Earth Equatorial (HEEQ) coordinates during the time period of each ICME. Figure 5.1a displays the positions of Wind and Juno at 00:00 UT on 15 April 2013. Wind and Juno were radially separated by a heliocentric distance of 0.63 AU and were longitudinally separated by 0.2° at this time. Figure 5.1b displays the positions of Solar Orbiter and Wind at 00:00 UT on 20 April 2020 at which time the spacecraft were radially separated by a heliocentric distance of 0.19 AU and were longitudinally separated by 4.0° . Although the spacecraft are considered radially aligned during both events, it is important to consider that a separation in longitude of just 1° at 1 AU corresponds to a spatial separation of 0.0175 AU, and at 1.6 AU corresponds to a spatial separation of 0.0279 AU, when interpreting the results of radial evolution analysis.

Table 5.1 summarises the arrival times of the shock, the leading and trailing edge of the magnetic flux rope, and the spacecraft separations at those times. Other ICME parameters are also listed and discussed in more detail throughout this chapter.

		April 2013 Event		April 2020 Event	
		Wind	Juno	Solar Orbiter	Wind
t_S	[UT]	Apr 13 22:12	Apr 15 18:21	Apr 19 05:06	Apr 20 01:34
t_L	[UT]	Apr 14 17:02	Apr 17 01:10	Apr 19 08:59	Apr 20 07:56
t_T	[UT]	Apr 15 18:10	Apr 18 13:04	Apr 20 09:15	Apr 21 11:18
Δ_{sheath}	[hrs]	19.9	35.0	3.88	6.37
Δ_{FR}	[hrs]	24.0	31.7	24.27	27.37
$\Delta_{sheath}/\Delta_{FR}$		0.83	1.11	0.16	0.23
$\Delta R_S, \Delta R_L, \Delta R_T$	[AU]	0.63, 0.62, 0.61		0.19, 0.19, 0.19	
$\Delta lat_S, \Delta lat_L, \Delta lat_T$	[°]	0.00, 0.00, 0.00		1.21, 1.21, 1.23	
$\Delta lon_S, \Delta lon_L, \Delta lon_T$	[°]	1.21, 0.99, 0.59		4.21, 4.16, 3.88	
$\langle B_{sheath} \rangle$	[nT]	10.3	3.9	9.9	6.8
$\langle B_{FR} \rangle$	[nT]	10.1	4.4	18.4	13.6
V_S	[kms ⁻¹]	468.4	-	-	335.8
V_L	[kms ⁻¹]	458.7	-	-	364.7
V_T	[kms ⁻¹]	381.5	-	-	335.1
V_C	[kms ⁻¹]	415.8	-	-	343.1
V_{exp}	[kms ⁻¹]	38.6	-	-	14.8
$V_{SW,preceding}$	[kms ⁻¹]	389.6	-	-	303.6
$V_{SW,following}$	[kms ⁻¹]	387.4	-	-	403.6
D	[AU]	0.24	-	-	0.23

Table 5.1: ICME parameters of the April 2013 ICME observed at Wind and Juno, and the April 2020 ICME observed at Solar Orbiter and Wind.

5.1.1 April 2013 ICME

Figure 5.2 presents the in situ magnetic field observations measured by Juno and Wind. Plasma measurements taken by the Solar Wind Experiment (SWE) of Wind are also presented.

The interplanetary shock driven by the April 2013 ICME was detected by Wind at 22:12 UT on 13 April with an observed shock velocity of 468 kms⁻¹, delineated by the vertical solid line in Figure 5.2. The shock was later observed by the Juno spacecraft, approximately 2 days later at 18:21 UT on 15 April. The Heliospheric Shock Database (IPshocks.fi; Kilpua *et al.*, 2015) lists the shock at Wind as quasi-parallel where the normal vector of the shock ($\hat{\mathbf{n}}$) was calculated using the mixed mode method (e.g. Schwartz, 1998) and is listed as $\hat{\mathbf{n}} = [-0.75, 0.33, 0.58]$ ($\theta_{Bn} = 35.5^\circ$, $\phi_{Bn} = 156.3^\circ$), with a speed of 479 kms⁻¹. The calculated shock speed is in close agreement with that observed in situ by Wind.

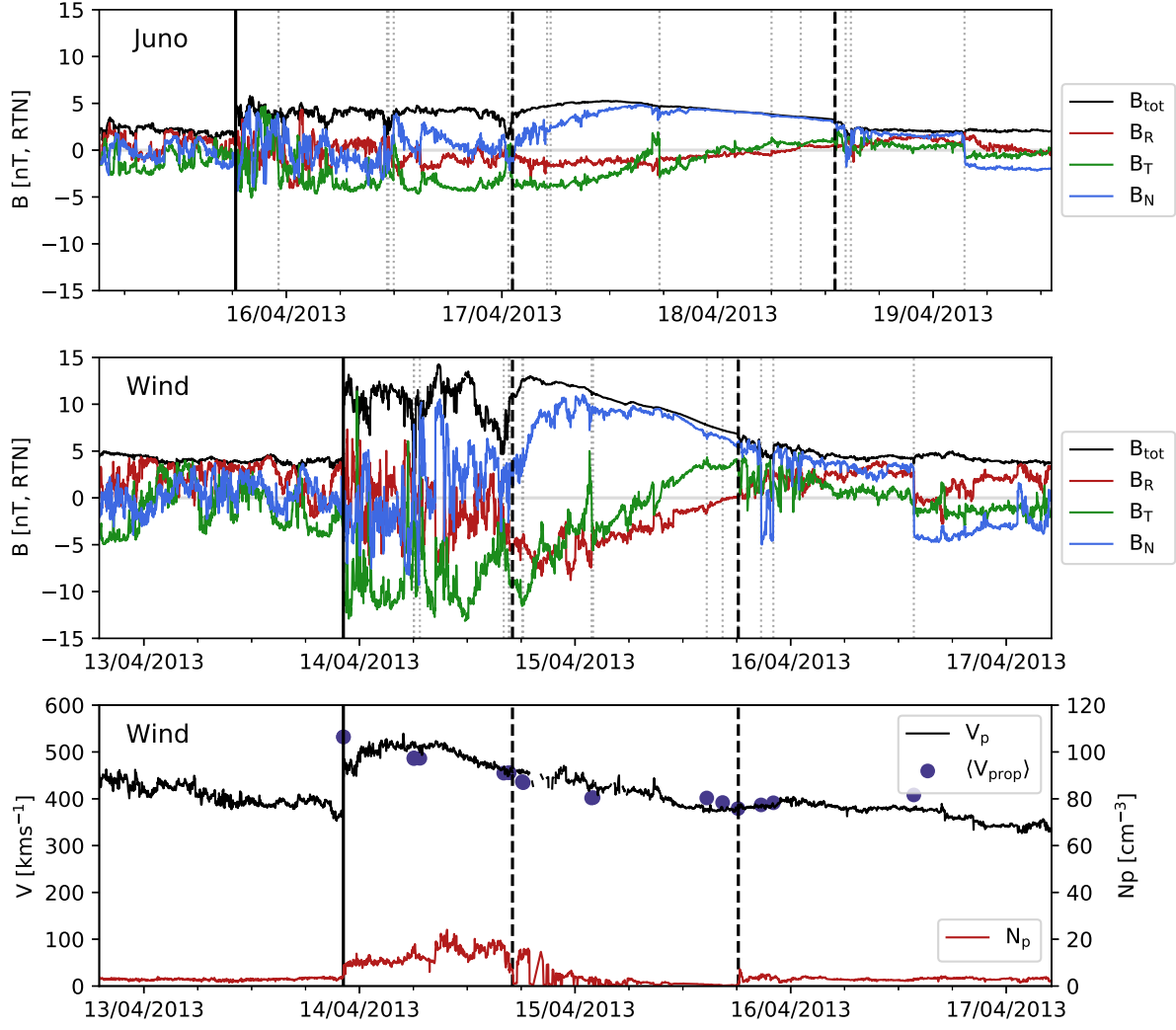


Figure 5.2: Magnetic field data observed by a) Wind and b) Juno, in RTN coordinates. Wind plasma data is displayed in panel c, where the proton velocity is shown in black (left axis), and the proton density is shown in red (right axis). The solid black vertical line, and dashed black vertical lines indicate the defined shock arrival, leading edge and trailing edge times, respectively. Dotted grey lines indicate times of magnetic features that have been mapped between spacecraft, used to calculate mean propagation velocities between features (purple markers in panel c).

The ICME can be considered a magnetic cloud, with a clear flux rope structure following the sheath and a low proton temperature measured by Wind (not shown). The vertical black dashed lines in Figure 5.2 constrain the magnetic flux rope, which can be classified as east-north-west (ENW) (Bothmer and Schwenn, 1998; Mulligan, Russell, and Luhmann, 1998) at both Wind and Juno. From this classification, the

magnetic flux rope is left-handed and we expect the flux rope to be of higher inclination to the ecliptic plane. Throughout the flux rope, the normal component of the magnetic field remains northwards, and therefore, the ICME had little effect on geomagnetic conditions at Earth, with activity measured at quiet to unsettled levels.

The ICME, observed at Earth, is listed in the catalogues of Richardson and Cane (2010); Lepping *et al.* (2018); Nieves-Chinchilla *et al.* (2018) and Nieves-Chinchilla *et al.* (2019). The shock arrival and leading edge times listed are similar across each study, in agreement with those listed in Table 5.1. Lepping *et al.* (2018) list a similar trailing edge of the magnetic flux rope to that listed in Table 5.1, however, Nieves-Chinchilla *et al.* (2018) lists the duration of the magnetic flux rope as 60.48 hours (equivalent to a trailing edge time of 05:31 UT on 17 April), in disagreement with Lepping *et al.* (2018) and Richardson and Cane (2010) where the ICME end time is listed as 23:00 UT on 15 April.

Table 5.1 also lists the observed durations of the sheath and magnetic flux rope. At Wind, the sheath is observed for 18.8 hours, and at Juno it is observed for 30.8 hours. Likewise, the magnetic flux rope is observed for 25.1 hours at Wind and 35.9 hours at Juno. At 1 AU, the sheath is typically one third of the magnetic ejecta, or 6–9 hours (Jian *et al.*, 2018) and the typical duration of magnetic ejecta is 18–26 hours (Gopalswamy *et al.*, 2015; Nieves-Chinchilla *et al.*, 2018). In this case, the sheath constitutes 42% of the ICME as measured by Wind and 46% at Juno.

The plasma data measured by Wind in Figure 5.2 displays a typical declining velocity profile, with a cruise velocity of 416 kms^{-1} . Considering the cruise velocity of the flux rope and the time taken for a spacecraft to traverse the flux rope, the radial width of the magnetic flux rope at Wind is calculated as 0.25 AU. This is quite different from the estimate listed in Lepping *et al.* (2018), where a model was used to calculate a diameter of 0.39 AU (note that Lepping *et al.* (2018) defines the magnetic flux rope as 2 hours longer). Considering a constant propagation of the ICME between Wind and Juno, the mean cruise velocity is calculated to be 406 kms^{-1} . Assuming that the mean cruise velocity is a good indicator of the true cruise velocity of the magnetic flux rope at Juno, the radial width at Juno is estimated to be 0.31 AU. This is in agreement with the expected expansion of the magnetic flux rope (by 0.05 AU) considering an observed expansion velocity of 38.6 kms^{-1} at Wind.

Due to the radial alignment between Wind and Juno, it was possible to match distinct magnetic field features in the two spacecraft datasets. These features are in-

indicated by the vertical dotted grey lines in Figure 5.2 and are well spread throughout the ICME. The timing and positions of these features have been used to calculate the mean propagation velocities of these features between the spacecraft. We can see that on the whole, the calculated mean propagation velocities match well with the velocity profile measured in situ at Wind, supporting our suggestion that the mean cruise velocity calculated is a good estimate of the cruise velocity at Juno. One particular feature of interest is the large discontinuity in the middle of the magnetic flux rope. Discontinuities such as this are consistent with the formation of a current sheet, which can naturally form when the flux rope cross-section flattens as the ICME propagates (Owens, 2009).

5.1.2 April 2020 ICME

Figure 5.3 presents the in situ magnetic field observations measured by the Solar Orbiter magnetometer, and both the MFI and SWE observations onboard Wind. The Solar Wind Analyzer (SWA) instrument onboard Solar Orbiter was not yet fully commissioned during the time period the ICME occurred, and therefore solar wind plasma data was only available at Wind.

The shock front (delineated by the vertical solid line in Figure 5.3) driven by the ICME was first observed in situ by Solar Orbiter at 05:06 UT on 19 April 2020 whilst the spacecraft was located at a heliocentric distance of 0.809 AU. The shock was then observed by Wind (0.996 AU) at 01:34 UT on 20 April 2020, 20 hours and 28 minutes later, arriving with a proton speed of 346 km s^{-1} . Kilpua *et al.* (2021) calculated the normal vector to the shock using the magnetic coplanarity method, and found $\hat{\mathbf{n}} = [0.97, -0.23, -0.0057]$ ($\theta_{Bn} = 43^\circ$) at Solar Orbiter and $\hat{\mathbf{n}} = [0.92, -0.025, 0.38]$ ($\theta_{Bn} = 73^\circ$) at Wind. These results indicate that the shock was quasi-perpendicular at Wind, and between the limit of quasi-parallel and quasi-perpendicular ($\theta_{Bn} = 45^\circ$) at Solar Orbiter. Kilpua *et al.* (2021) also calculated a shock speed of 353 km s^{-1} at Wind, in agreement with the Wind plasma observations.

The in situ data reveal a clear magnetic flux rope structure, constrained by the vertical dashed lines in Figure 5.3, where the leading edge times of the magnetic flux rope are 08:59 UT on 19 April 2020 at Solar Orbiter, and 07:56 UT on 20 April 2020 at Wind, 22 hours and 57 minutes later. Within the magnetic flux rope, the normal component of the magnetic field turns from southward to northward, causing geomagnetic

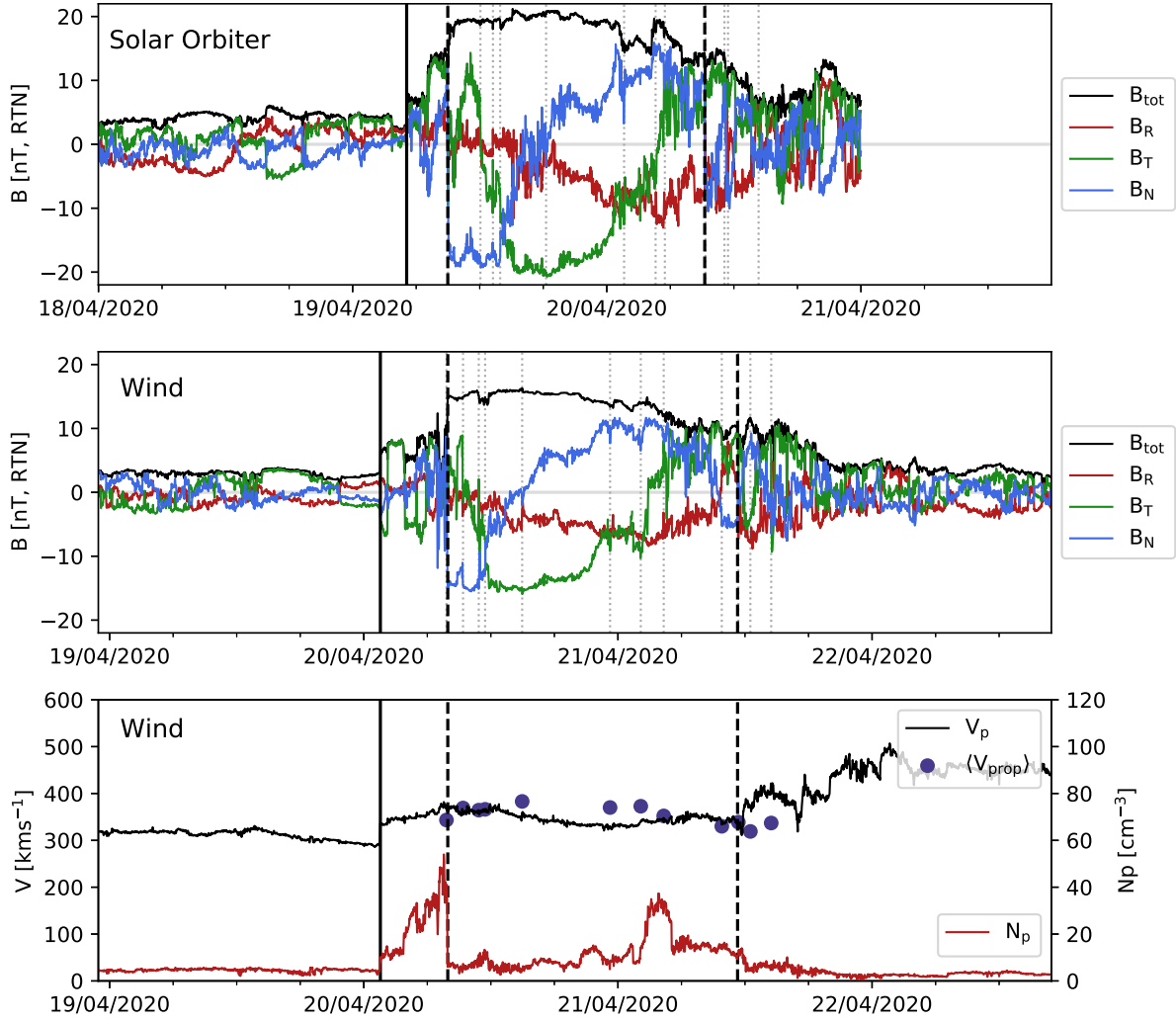


Figure 5.3: Magnetic field data observed by a) Solar Orbiter and b) Wind, in RTN coordinates. Wind plasma data is displayed in panel c, where the proton velocity is shown in black (left axis), and the proton density is shown in red (right axis). The solid black vertical line, and dashed black vertical lines indicate the defined shock arrival, leading edge and trailing edge times, respectively. Dotted grey lines indicate times of magnetic features that have been mapped between spacecraft, used to calculate mean propagation velocities between features (purple markers in panel c).

conditions at Earth to reach minor storm levels. The configuration of the magnetic flux rope can therefore be classified as south-east-north (SEN) and thus has left-handed chirality, with a flux rope axis of low inclination to the ecliptic plane.

The density of the magnetic flux rope measured at Wind was relatively low throughout, however, there is an increase in density towards the trailing edge. This is likely

due to a compression of the magnetic flux rope caused by the high speed stream that follows, which we observe at Wind to have a mean proton speed of $\sim 450 \text{ km s}^{-1}$.

The observed plasma velocity at Wind indicates a slow ICME with a cruise velocity of 343 km s^{-1} . The proton velocity profile shows only a small decline throughout the magnetic flux rope and therefore we can assume very little expansion of the ICME has occurred between Solar Orbiter and Wind. The defined flux rope durations are also similar, increasing by about 3 hours between Solar Orbiter and Wind, where the separation in longitude of the measuring spacecraft is likely to be a factor in the different measured duration. Considering the cruise velocity, the radial width of the ICME at Wind is estimated to be 0.23 AU.

The mean propagation velocities of distinct features (indicated by the vertical dotted grey lines in Figure 5.3) in the magnetic field data between Solar Orbiter and Wind, have been calculated and are shown by the corresponding purple markers. We can see that the calculated mean propagation velocities match well towards the leading and trailing edge with the velocity profile measured in situ at Wind, however, not so well during the middle of the flux rope. If the ICME is slowing as it travels, one would expect the mean propagation speeds to be slightly higher than at Wind, however, in this case the difference is likely due longitudinal separation effects between the spacecraft.

The duration of the magnetic flux rope is on the order of what is typically observed at 1 AU (Gopalswamy *et al.*, 2015; Nieves-Chinchilla *et al.*, 2018), however, the sheath constitutes just 14% of the ICME as measured by Solar Orbiter, and 19% at Wind. The structure of the sheath is also interesting, displaying a two-stepped structure at Solar Orbiter, dissimilar to the broken structure observed at Wind. Kilpua *et al.* (2021) has analysed the sheath region in more detail, observing many heliospheric current sheet (HCS) crossings in the sheath region at Wind, whilst at Solar Orbiter, a small magnetic flux rope was found to be embedded with the sheath prior to the leading edge.

5.2 The Solar Wind Environment

Comparing the solar wind conditions during April 2013 and April 2020, the activity of the Sun was at almost completely opposing stages of the solar cycle. During April 2013, the Sun was close to solar maximum, between the two peaks in sunspot number. In contrast, in April 2020 the Sun was in deep solar minimum where the solar wind is highly structured, with faster solar wind at higher latitudes emanating from polar

coronal holes, and slower solar wind near to the equator.

The solar source of the April 2013 ICME was a CME accompanying an M6.5 solar flare peaking at 07:16 UT on April 11, with the CME eruption taking place between 07:05 UT and 07:52 UT. The location of the flare occurred in active region (AR) 11719 and was associated with a pre-eruptive sigmoidal structure (Vemareddy and Mishra, 2015; Joshi *et al.*, 2017), coronal dimmings and EUV waves (Lario *et al.*, 2014). The observed inverse S-shaped morphology of the sigmoidal structure reveals that the associated magnetic flux rope is of left-handed chirality (Sarkar, Gopalswamy, and Srivastava, 2020), in agreement with the in-situ observations of the ICME. The CME has been well studied as it was the first large Fe-rich SEP event of Solar Cycle 24 (Cohen *et al.*, 2014; Lario *et al.*, 2014). The CME was observed by SOHO/LASCO C2 from 07:24 UT, decelerating from $\sim 950 \text{ km s}^{-1}$ to 800 km s^{-1} (https://cdaw.gsfc.nasa.gov/CME_list/UNIVERSAL/2013_04).

The source of the April 2020 ICME was much harder to determine, and can be considered a stealth CME where the pre-eruptive structure was found to be a dark cavity (O’Kane *et al.*, 2021a). The CME is observed in STEREO COR1 images as a faint enhancement, slowly rising from approximately 01:30 UT on 14 April 2020, and is clearly observed by 03:54 UT on 15 April in COR2 images following the brightening and swelling of a streamer. Between the fields of view of COR1 and COR2, the CME increased in speed from 18 to 53 km s^{-1} . The April 2020 CME is therefore very different to the April 2013 CME, as it was accelerated by drag forces whereas the April 2013 CME was decelerated.

The background solar wind during the passage of the April 2013 ICME was predicted using the ENLIL model, shown by the left hand panel of Figure 5.4. The model run shows the ICME propagating into a faster solar wind stream, where the speed of the solar wind preceding the ICME at 1 AU is predicted to be $\sim 475\text{--}500 \text{ km s}^{-1}$. In fact, Wind observed an average proton speed of $\sim 390 \text{ km s}^{-1}$ preceding the arrival of the ICME shock front, which was similar in speed to that following the magnetic flux rope.

The predicted background solar wind during the April 2020 ICME (right hand panel of Figure 5.4) shows the opposite scenario, where the Wang-Sheeley-Arge/Heliospheric Upwind eXtrapolation (WSA/HUX) model (Reiss *et al.*, 2019, 2020) reveals solar wind conditions typical of solar minimum with extended polar coronal holes and streamers confined within a narrow latitude band near the equator. A higher speed stream is also predicted to arrive right after the ICME impacts the Earth. This prediction is

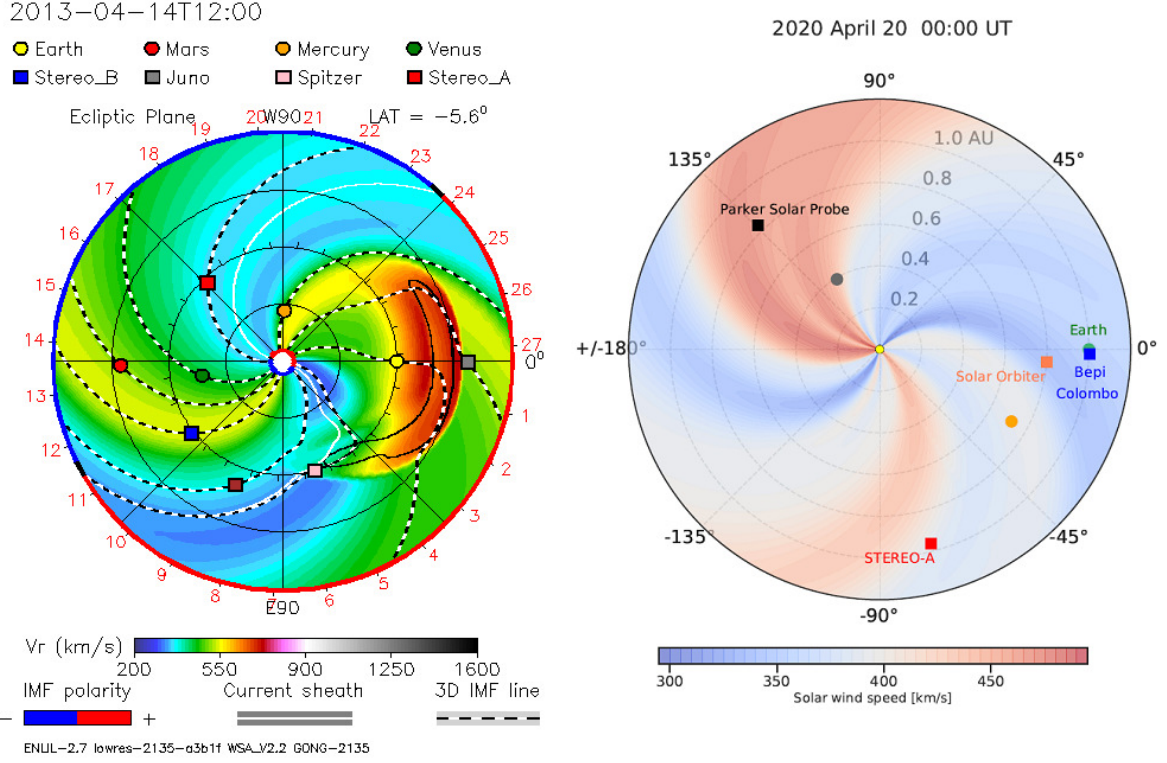


Figure 5.4: **Left:** Solar wind background during the propagation of the April 2013 ICME modelled by ENLIL (https://iswa.gsfc.nasa.gov/downloads/20130411_103700_anim.tim-vel.gif). **Right:** Solar wind background during the propagation of the April 2020 ICME modelled by the WSA/HUX model. Figure from Davies *et al.* (2021).

confirmed by the in situ Wind data, where a higher speed stream of $\sim 450 \text{ km s}^{-1}$ follows the ICME. The preceding solar wind was notably slow, with a speed of only $\sim 300 \text{ km s}^{-1}$.

Figure 5.5 shows the propagation of the ICMEs captured by the Heliospheric Imagers onboard STEREO-B and STEREO-A for the April 2013 and April 2020 ICMEs, respectively. The top row shows HI1-B images of the April 2013 ICME, where the ICME propagates quickly and expands in all directions, with perhaps some flattening towards the front of the ICME as one would expect in a uniformly structured solar wind (Owens, 2006). The bottom row shows the HI1-A images of the April 2020 ICME, where we observe a clear flattening and ‘pancaking’ of the ICME as it propagates, pushed from behind by the higher solar wind stream. Although predicted in previous work (e.g. Owens, 2006), this has only been captured previously in remote observations by Savani

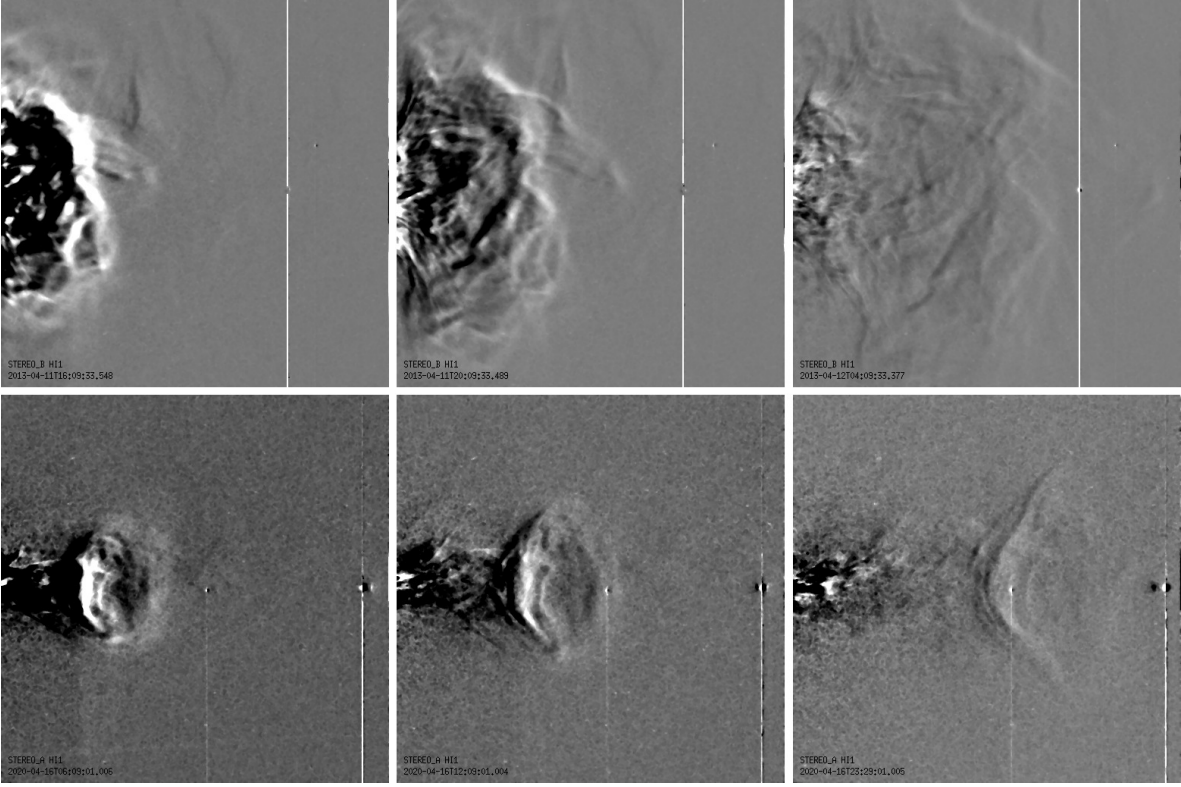


Figure 5.5: Top row: HI1-B images of the April 2013 ICME. Bottom row: HI1-A images of the April 2020 ICME.

et al. (2010).

5.3 Radial Evolution of the ICMEs

The small longitudinal and latitudinal separation between spacecraft during the passage of both ICMEs provides an opportunity to study their radial evolution using in situ measurements of the magnetic field. However, as previously mentioned, caution must still be applied when interpreting results as significant differences in ICME magnetic flux rope properties have previously been observed over small longitudinal separations (Kilpua *et al.*, 2011; Winslow *et al.*, 2016; Davies *et al.*, 2020) and therefore differences in observations and properties may also be due to the spatial variation of the ICME.

Figure 5.6 compares the magnetic field profiles at Wind and Juno. Comparing the duration of the magnetic flux rope at Wind with that of Juno, the scaling factor was found to be 1.43. The scaled times of the Wind data are aligned with the leading edge

of the magnetic flux rope at Juno, delineated by the first dashed line in Figure 5.6. Such a scaling factor indicates that the magnetic flux rope has undergone significant expansion as the ICME propagated between 1 and 1.6 AU. The same expansion rate has been applied to all magnetic data, including that of the sheath.

Features within the sheath seem to match well between spacecraft, especially towards the leading edge of the magnetic flux rope, despite having applied the magnetic flux rope expansion rate to all magnetic data. However, it is clear that the shock fronts do not match. This is due to the accumulation of solar wind material as the ICME propagates. Due to the exceptionally close alignment between Wind and Juno, what was the shock front at Wind has been matched to the same feature in the Juno observations, occurring at 15 April 23:08 UT. This time is not dissimilar to the scaled shock arrival time at 15 April 23:51 UT. From in situ observations, the sheath has therefore accumulated approximately 5 hours of material as it propagated 0.6 AU; just $\frac{1}{6}^{th}$ of its duration. Previous studies have investigated the accumulation of sheath material as an ICME propagates (e.g. Lugaz, Winslow, and Farrugia, 2020), however, such an exact duration has not previously been possible to determine.

The magnetic field strength of the flux rope at Wind has been scaled using a power law relationship found by fitting the observed maximum magnetic field strength against heliocentric distance at each spacecraft. The magnetic field of the flux rope reached maximum values of $B_{max} = 13.0$ and 5.3 nT and mean values of $B_{mean} = 10.2$ and 4.4 nT at Wind and Juno, respectively. Considering the location of each spacecraft, we find the relationships of maximum and mean magnetic field strength with increasing heliocentric distance, r , to be $B_{max} \propto r^{-1.86}$ and $B_{mean} \propto r^{-1.72}$, respectively. Previous studies that have used similar fitting to derive relationships of magnetic field strength with heliocentric distance beyond 1 AU include Ebert *et al.* (2009) ($r^{-1.29 \pm 0.12}$) and Richardson (2014) ($r^{-1.21 \pm 0.09}$), discussed in Chapter 3. The relationships found for this ICME are in disagreement with these relationships, however, are more in line with those found within 1 AU. Mean magnetic field relationships for the inner heliosphere include $r^{-1.85 \pm 0.07}$ found by Gulisano *et al.* (2010) and $r^{-1.95 \pm 0.19}$ found by Winslow *et al.* (2015).

For a self-similarly expanding cylindrical force-free magnetic flux rope, one would expect the axial field to decrease as r^{-2} and the poloidal field to decrease with distance as r^{-1} (Farrugia *et al.*, 1993). Calculating the root mean square error (RMSE) between the scaled Wind and Juno time series over the magnetic flux rope interval for the ideal

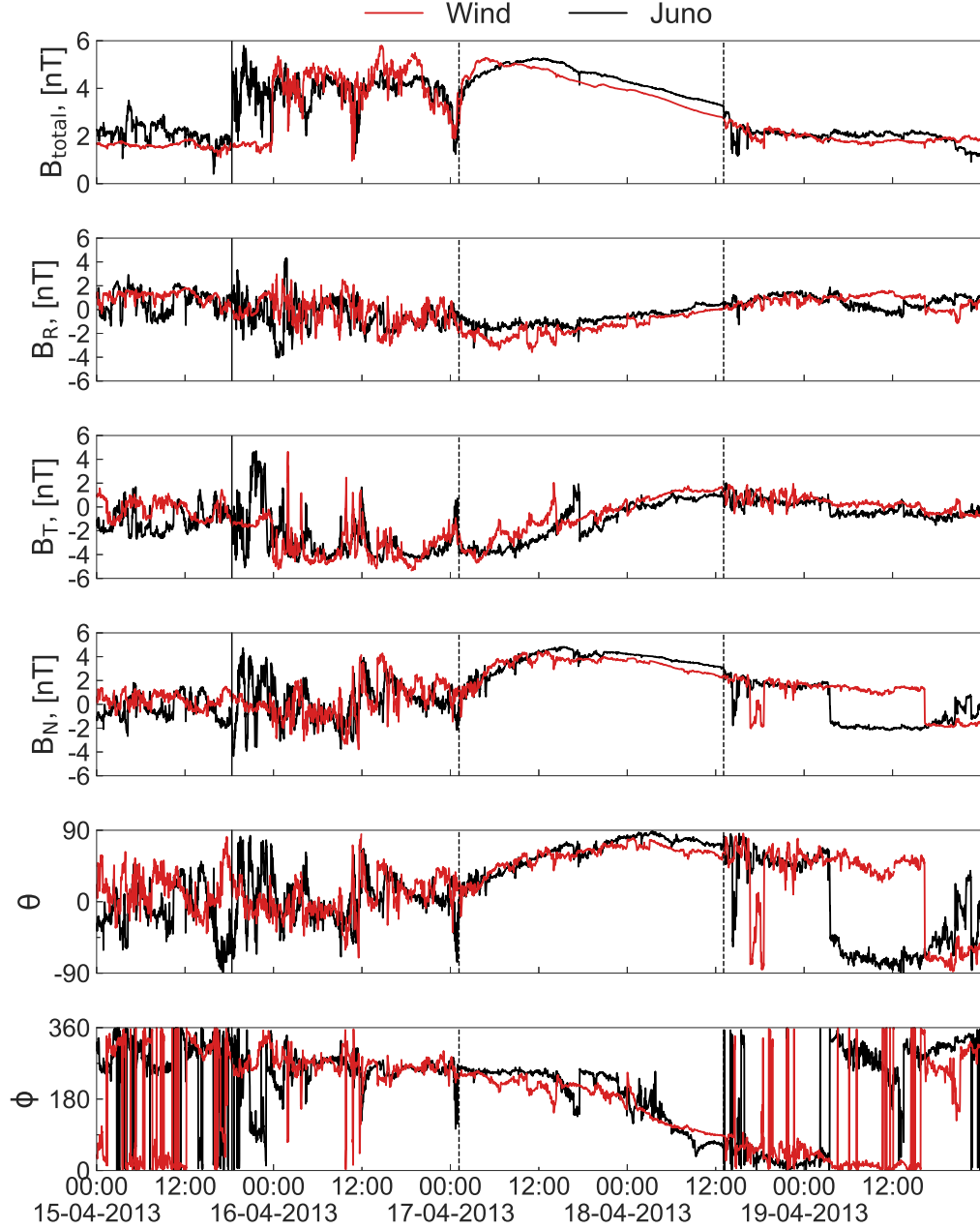


Figure 5.6: Magnetic field measurements at Juno (black), overlaid with the scaled magnetic field measurements of Wind (red). The vertical solid line indicates the time the shock front was measured at Juno, and the dashed lines constrain the flux rope.

axial and poloidal field relationships results in values of 0.88 and 1.61, respectively. By minimising the RMSE between the time series, the axial field scales as $r^{-2.20}$ and

the poloidal field scales as $r^{-1.68}$, with RMSE values of 0.86 and 0.51, respectively. This result implies that the expansion of the ICME is not self-similar nor cylindrically symmetric, and that the twist distribution changes as the ICME propagates.

The scaled magnetic data of Wind correlates well with that of Juno over the duration of the magnetic flux rope in Figure 5.6, with a high Pearson correlation coefficient of 0.88. However, we can see by eye that the expansion is not uniform or self-similar, as the timing of the distinct discontinuity in the transverse component of the magnetic field in the middle of the magnetic flux rope does not match between spacecraft. The magnetic field profile observed at Wind is also more asymmetric than that observed at Juno. An asymmetric magnetic field profile is often the case for faster ICMEs, with a higher magnetic field strength at the front of the flux rope than the back (Janvier *et al.*, 2019). To quantify the asymmetry, we calculate the distortion parameter (DiP) given by Equation 2.10 in Chapter 2 (see also Nieves-Chinchilla *et al.*, 2018, for more details). The DiP gives a measure of the fraction of the magnetic flux rope at which 50% of the magnetic flux has been measured. Values < 0.5 imply an asymmetric magnetic field profile with a higher magnetic field strength at the front of the flux rope, and a value around 0.5 implies a more symmetric magnetic field profile. In this case, the DiP = 0.43 at Wind, and the DiP = 0.45 at Juno, indicating that the magnetic field profile has perhaps relaxed a little as it propagated between 1 and 1.6 AU.

Using the solar wind speed time series at Wind, we can assess the local expansion of the ICME at 1 AU and compare this to the global expansion of the ICME. The dimensionless expansion parameter, ζ , (for more detail, see Démoulin and Dasso, 2009; Gulisano *et al.*, 2010) given by Equation 2.8 (Chapter 2) provides a measure of local expansion, typically around 0.81 ± 0.19 for non-perturbed magnetic clouds (Gulisano *et al.*, 2010). We find that for the April 2013 ICME, $\zeta = 0.94$ at Wind, within the range of uncertainty for typical values. Gulisano *et al.* (2010) found that the dimensionless expansion parameter is independent of radial distance and therefore could be used to relate to the global expansion of CMEs with the magnetic field strength. The magnetic field strength would be expected to decrease as $r^{-2\zeta}$ and radial size expected to increase as r^ζ . For this ICME, we would therefore expect the magnetic field strength to decrease with heliocentric distance as $r^{-1.88}$ and the size of the magnetic flux rope to scale as $r^{0.94}$. The expected magnetic field relationship is remarkably similar to those found observationally in this study ($B_{max} \propto r^{-1.86}$ and $B_{mean} \propto r^{-1.72}$). Considering the expansion velocity at Wind, we would expect the radial width to increase as $r^{0.72}$,

which is not too dissimilar to the expected expansion relationship. Below, we perform a similar analysis of the April 2020 ICME.

Figure 5.7 compares the magnetic field profiles at Solar Orbiter and Wind. Due to the interaction of the ICME with the following higher speed stream and the physical processes occurring towards the leading edge (see Kilpua *et al.*, 2021), this analysis focuses on the section of the unperturbed magnetic flux rope (UMFR), comparable to the definition given by Gulisano *et al.* (2010). The UMFR has been selected by considering matching features towards the leading and trailing edges in the magnetic field data across the spacecraft. We compare the durations between different features at each spacecraft to scale the times of the magnetic field time series and maximise the Pearson correlation coefficients. For scaled Solar Orbiter and Wind data the correlation coefficient was found to be 0.87. We define the start of the UMFR as 13:56 UT on April 19 at Solar Orbiter and 11:28 UT on April 20 at Wind, and the end of the UMFR as 04:36 UT on April 20 and 02:10 UT on April 21 at Solar Orbiter and Wind, respectively. Comparing the UMFR duration at Solar Orbiter to that of Wind gives a scaling factor of 0.998. As with Figure 5.6, the scaled times for Solar Orbiter are aligned with the start of the UMFR at Wind, delineated by the first dotted line in Figure 5.7. The scaling factor between Solar Orbiter and Wind is close to unity, which would indicate that the UMFR has undergone little to no expansion as it propagated beyond 0.8 AU to L1. Comparing the magnetic field profiles, we note that they are very similar across the UMFR. Calculation of the distortion parameter (DiP) shows that the profiles are slightly asymmetric, with values of 0.46 and 0.44 at Solar Orbiter and Wind, respectively. This is an interesting result as previous studies have found that slow ICMEs tend to have a weaker sheath and a more symmetric magnetic field profile (Masías-Meza *et al.*, 2016; Janvier *et al.*, 2019). Nieves-Chinchilla *et al.* (2018) previously suggested that asymmetric magnetic field profiles with a relatively small expansion may correspond to ICMEs with distorted structures. This implication is true in this case, where the distorted structure of the ICME has been confirmed by the HI1-A images presented in Figure 5.5.

The magnetic field strengths of the flux rope at Solar Orbiter have been scaled using a power law relationship found by fitting the observed maximum magnetic field strength against heliocentric distance at each spacecraft. The magnetic field of the UMFR achieved maximum values of $B_{max} = 21.2$ and 16.3 nT and mean values of $B_{mean} = 18.9$ and 14.9 nT at Solar Orbiter and Wind, respectively. Considering the location of each

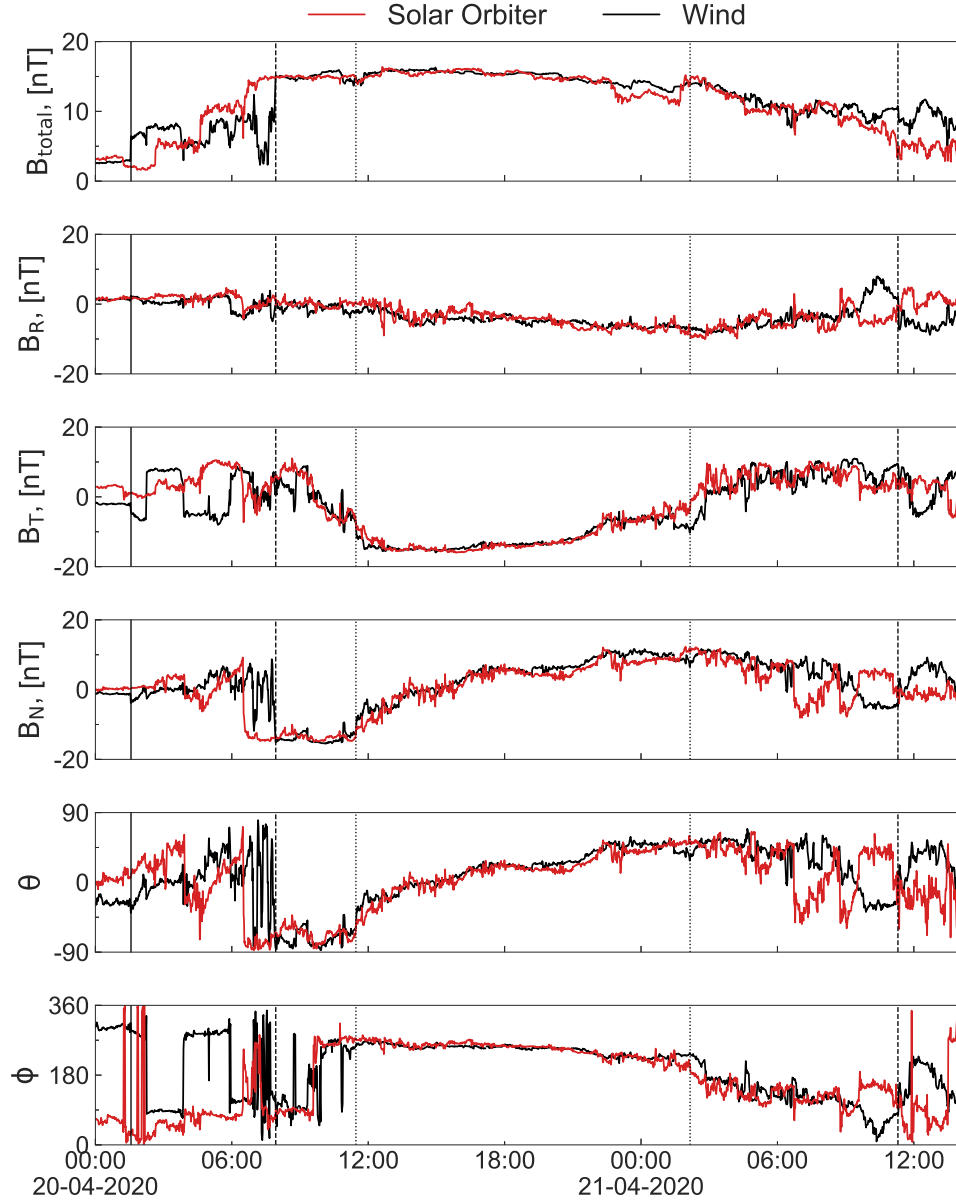


Figure 5.7: Magnetic field measurements at Wind (black), overlaid with the scaled magnetic field measurements of Solar Orbiter (red). The vertical solid line indicates the time the shock front was measured at Wind, and the dashed lines constrain the flux rope. The vertical dotted lines within constrain the unperturbed magnetic flux rope (UMFR), where the magnetic field measurements are well correlated between the spacecraft.

spacecraft, we find the relationships of maximum and mean magnetic field strength with increasing heliocentric distance, r , to be $B_{max} \propto r^{-1.24}$ and $B_{mean} \propto r^{-1.12}$, respectively. Previous studies that have used similar fitting to derive relationships of magnetic field strength with heliocentric distance in the inner heliosphere include Gulisano *et al.* (2010) and Winslow *et al.* (2015). Gulisano *et al.* (2010) used Helios 1 and 2 observations to obtain a mean magnetic field relationship of $\langle B \rangle \propto r^{-1.85 \pm 0.07}$. Winslow *et al.* (2015) considered ICMEs observed by MESSENGER and ACE to obtain a relationship of $\langle B \rangle \propto r^{-1.95 \pm 0.19}$. Neither the B_{max} nor B_{mean} relationship calculated in this study agree with previous relationships obtained suggesting that this event is an outlier to overall trends, perhaps due to a more complex interaction with the solar wind and distortion of the flux rope, and the possible spatial variation of the magnetic flux rope over the small longitudinal/latitudinal separation between spacecraft.

To assess whether the magnetic flux rope expands self-similarly, the RMSE between the scaled Solar Orbiter and Wind time series over the UMFR interval was calculated. Scaling using the ideal axial and poloidal field relationships results in RMSE values of 1.98 and 1.97, respectively. By minimising the RMSE between the time series, the axial field scales as $r^{-1.52}$ and the poloidal field scales as $r^{-0.75}$, with RMSE values of 1.75 and 1.92, respectively. Similarly to the April 2013 ICME, this result implies that the expansion of the ICME is not self-similar nor cylindrically symmetric.

To assess the local expansion of the ICME at 1 AU, the dimensionless expansion parameter was calculated. The speed at the mid-point of the UMFR, or the cruise velocity, V_c is measured to be 343 km s^{-1} and the rate of expansion, $\Delta V/\Delta t$, or in this case, $\Delta V_{UMFR}/\Delta t_{UMFR} = 7.5 \times 10^{-4} \text{ km s}^{-2}$. The heliocentric distance, d , of Wind at the mid-point of the flux rope is 0.996 AU. For the UMFR at Wind, we find that $\zeta = 0.95$, and therefore would expect the magnetic field strength to decrease with heliocentric distance as $r^{-1.91}$ and the size of the UMFR to scale as $r^{0.95}$.

The expansion velocity at Wind, calculated as half the difference between the velocities at the front and the back of the UMFR is $\Delta V_{UMFR} = 19.9 \text{ km s}^{-1}$, and therefore assuming the expansion speed remained constant between Solar Orbiter and Wind, the radial diameter of the flux rope would be expected to increase by 0.01 AU or as $r^{0.87}$. The observed relationship for the radial expansion agrees well with the expected relationship using the dimensionless expansion parameter, however, the magnetic field strength relationships are not in agreement ($r^{-1.91}$ using the dimensionless expansion parameter, in comparison to $r^{-1.12}/r^{-1.24}$ found using the observed mean/maximum

magnetic field). This discrepancy may be due to compression of the flux rope as a whole by the higher speed stream following the ICME, highlighting the importance in considering the solar wind environment through which an ICME propagates.

5.4 Summary and Discussion

In this chapter, we have compared and contrasted two ICMEs observed in situ during April 2013 and April 2020 by radially aligned spacecraft. The situation surrounding the ICMEs is very different: the April 2013 ICME was observed during solar maximum, whereas the April 2020 ICME was observed during solar minimum where the solar wind is much more structured, with faster solar wind towards the poles and slower solar wind towards the equatorial plane. The April 2013 ICME was also a fast, positively expanding ICME, whereas the April 2020 ICME could be considered a slow ICME which displayed little to no expansion by the time it reached 1 AU.

The solar source of the ICMEs were also very different and perhaps in line with the stage of the solar cycle. The magnetic flux rope of the April 2013 CME was formed over a sigmoidal structure in the active region AR 11719, and the CME was associated with a large M class solar flare. In contrast, the April 2020 CME can be considered a stealth CME, with very little on-disk signatures visible. The pre-eruptive structure was formed in a quiet dark cavity, and launched associated with a streamer blowout.

The effects of the different solar wind environments through which the ICMEs propagated are shown by the HI images captured by the STEREO spacecraft. The April 2013 ICME displays a more typical propagation, whereas the April 2020 ICME displays a clear flattening and ‘pancaking’ of its structure as it propagated, highlighted so visibly due to the higher speed stream following which increased the density shell surrounding the ICME. We confirm these conditions with the in situ observations, where Wind measures a similar solar wind speed preceding and following the April 2013 ICME of $\sim 390 \text{ km s}^{-1}$, whereas the April 2020 ICME propagates through an especially slow solar wind ($\sim 300 \text{ km s}^{-1}$) but is followed by a higher speed stream ($\sim 450 \text{ km s}^{-1}$).

Due to the slow nature of the April 2020 ICME, we observe that it has been accelerated up to the speed of the ambient solar wind, perhaps by processes in the solar corona and drag forces (e.g. Cargill, 2004), but also by the higher speed stream following. The observed expansion velocity in situ is small, indicating that little to no expansion occurred between Solar Orbiter and Wind. This is confirmed by comparing the magnetic

flux rope durations, where a difference of approximately 3 hours is likely to be due to the difference in measurement location. The distortion parameters (DiP) calculated at both Solar Orbiter and Wind are very similar, with values indicating that the magnetic flux rope profile is slightly asymmetric. This is in agreement with the suggestion that asymmetric magnetic field profiles with a relatively small expansion may correspond to ICMEs with distorted structures (Nieves-Chinchilla *et al.*, 2018).

The April 2013 ICME is more typical of a fast ICME decelerated by the ambient solar wind, with initial speeds of $\sim 800 \text{ km s}^{-1}$ and an in situ cruise velocity of 416 km s^{-1} at Wind. The magnetic field profile looks to be more asymmetric at Wind than at Juno with DiP values of 0.43 and 0.45, respectively, as one would expect as the ICME relaxes as it expands (Janvier *et al.*, 2019).

Due to the radial alignment between spacecraft, the change in magnetic field strength with increasing heliocentric distance can be assessed. We find that for the April 2013 ICME, the magnetic field strength is observed to follow $B_{max} \propto r^{-1.86}$ and $B_{mean} \propto r^{-1.72}$. This is interesting as the observed relationships are in disagreement with previous studies which have calculated the relationship of the magnetic field strength with increasing distance beyond 1 AU as $r^{-1.29 \pm 0.12}$ (Ebert *et al.*, 2009) and $r^{-1.21 \pm 0.09}$ (Richardson, 2014). The observed relationships are more in line with those found within the inner heliosphere such as $r^{-1.85 \pm 0.07}$ (Gulisano *et al.*, 2010) and $r^{-1.95 \pm 0.19}$ (Winslow *et al.*, 2015).

In comparison, for the April 2020 ICME the magnetic field strength is observed to follow $B_{max} \propto r^{-1.24}$ and $B_{mean} \propto r^{-1.12}$. Again these relationships do not follow those found in previous studies considering the inner heliosphere, but they do seem more similar to those found beyond 1 AU. It is likely that the higher speed stream following the April 2020 ICME influenced the expansion and decline in magnetic field strength as it propagated. However, perhaps the disagreement between relationships observed for both the April 2013 and April 2020 ICMEs and respective previous relationships over heliocentric distances greater than and less than 1 AU may be due to the nature of the different ICMEs; on the whole, ICMEs $< 1 \text{ AU}$ are faster than those beyond 1 AU as ICMEs tend towards the ambient solar wind speed and are likely to have faster expansion velocities, whereas in this case the April 2013 ICME is a fast ICME and the April 2020 ICME is very slow with very little expansion observed between Solar Orbiter and Wind. It might therefore be interesting to compare magnetic field strength relationships with heliocentric distance between fast and slow (or accelerating

and decelerating) ICMEs in future studies.

The dimensionless expansion parameter, ζ , was also calculated for both ICMEs using plasma data at Wind. We found that $\zeta = 0.94$ for the April 2013 ICME and $\zeta = 0.95$ for the April 2020 ICME. Both values are very similar, and within the higher uncertainty range of typical values (0.81 ± 0.19) for non-perturbed magnetic clouds at 1 AU (Gulisano *et al.*, 2010). Using these values, the magnetic field would be expected to decrease as $r^{-2\zeta}$. This is the case for the April 2013 ICME, where the observed relationships were remarkably similar to the expected relationship ($r^{-1.86}$ and $r^{-1.72}$ in comparison with $r^{-1.88}$). However, this is far from the case for the April 2020 ICME ($r^{-1.24}$ and $r^{-1.12}$ in comparison with $r^{-1.91}$) despite considering the unperturbed section of the magnetic flux rope (UMFR) in the analysis. It is clear that the solar wind environment through which the ICME propagates influences the expansion of the ICME. In this case, the solar wind preceding and following the April 2013 ICME is balanced in both velocity and density, in contrast to that of the April 2020 ICME, which has been compressed and likely accelerated by the following higher speed stream.

Despite the April 2013 ICME being considered as an isolated ICME that follows expected expansion relationships, neither ICME has been found to expand self-similarly as one would expect if we consider the magnetic flux ropes to be cylindrical and force-free. We can see this especially clearly in Figure 5.2 where the distinctive discontinuity in the middle of the magnetic flux rope does not match between the scaled spacecraft data of Wind and the observed data at Juno, indicating that different parts of the magnetic flux rope may expand at different rates (e.g. Good *et al.*, 2018).

To investigate the relationship between local and global expansion further, we could extend the analysis and techniques applied to the two ICMEs in this chapter to the 11 radially aligned events identified in Chapter 3. Investigating the solar wind environment of each ICME and possible relationship with parameters such as the dimensionless expansion parameter, distortion parameter, expansion and cruise velocities, and magnetic field strengths over a range of heliocentric distances, may help further understanding of the propagation and evolution of interplanetary coronal mass ejections.

Chapter 6

Conclusions and Outlook

The kinematic and structural magnetic properties of ICMEs as they evolve with distance in the heliosphere has been presented in this thesis. In situ observations of the magnetic field taken by the Juno mission spacecraft have been used throughout this work, often in conjunction with other spacecraft observations: both in situ and remote. During its cruise phase to Jupiter, Juno spent a total of 5 years in the solar wind and therefore presents the most recent opportunity to study ICME evolution beyond 1 AU since the Ulysses mission.

In Chapter 3, a catalogue and statistical analysis of ICMEs identified at Juno was presented. 33 potential ICME magnetic cloud candidates were identified from the Juno cruise phase magnetic field dataset where each event meets the criteria of an enhanced and rotating magnetic field, consistent with a magnetic flux rope structure. The number of left-handed and right-handed ICME magnetic flux ropes observed by Juno were approximately equal, as would be expected: flux rope handedness often correlates with the solar hemisphere from which the CME originated, whereas the location of CME initiation follows no such pattern. The ratio of high inclination to low inclination flux ropes was found to decrease with increasing heliocentric distance. Considering the magnetic field strength within the identified flux ropes, the maximum and mean magnetic field strength (excluding outliers) decreases with heliocentric distance as $B_{max} \propto r^{-1.12 \pm 0.36}$ and $B_{mean} \propto r^{-1.17 \pm 0.31}$, respectively. The mean magnetic field relationship is directly comparable with those of previous studies using Ulysses observations and was found to be in strong agreement.

Eleven of the catalogued events were also observed by other spacecraft situated at a

heliocentric distance of 1 AU or below, allowing for a wider multi-spacecraft study to be conducted. Six events were also observed by Wind, three by STEREO-B, and two were observed by both Venus Express and STEREO-A. The handedness of the magnetic flux rope was found to remain consistent between observing spacecraft, as would be expected. Interestingly, there were 3 events where the magnetic flux rope type changed from a higher inclination to a lower inclination between observing spacecraft in order of increasing heliocentric distance. The change in rope type may have been due to the location at which the event was observed. However, this observation may also be related to the general trend of decreasing high to low inclination ratio found in the analysis of the whole catalogue. It has previously been suggested that the magnetic flux rope axis of an ICME tends towards the ecliptic plane (or HCS) as it propagates (Yurchyshyn, 2008; Isavnin, Vourlidas, and Kilpua, 2014). Understanding the rotation of ICMEs has important implications for space weather forecasting, helping to determine how geoeffective an ICME may be. Determining whether such rotation continues beyond 1 AU could be explored further by applying flux rope fitting methods such as the Lundquist and Gold-Hoyle solutions detailed in Chapter 2 to the catalogued events. The evolution of the orientation of the magnetic flux rope with heliocentric distance could also be determined on a case by case basis when applied to the 11 events observed by both Juno and other spacecraft. Such analysis would also provide an estimate of the magnetic field strength at the magnetic flux rope axis and direct comparisons of the axial magnetic field strength with increasing heliocentric distance could be made with studies such as Leitner *et al.* (2007).

The evolution of the magnetic field strength within the flux ropes was also calculated and compared to overall statistical trends. Performing separate power law fits of the magnetic field strength for each event and taking the mean of these relationships, it was found that $B_{max} \propto r^{-1.57 \pm 0.70}$ and $B_{mean} \propto r^{-1.41 \pm 0.44}$. These relationships are within the broad range found by Richardson (2014) which considered ICMEs identified by Ulysses and other spacecraft, and demonstrates the large variability in magnetic field strength evolution displayed by individual ICMEs.

Considering the dataset of only the linked events (the events observed by Wind, STEREO-A and B, Venus Express and the corresponding Juno events), we found that the magnetic field strength decreases as $B_{max} \propto r^{-1.61 \pm 0.68}$ and $B_{mean} \propto r^{-1.72 \pm 0.73}$ over the heliocentric distance range of 0.7–2.2 AU. Fitting a power law relationship over the combined datasets of events observed in conjunction with other spacecraft

and the full Juno catalogue, we found that the magnetic field strength decreases as $B_{max} \propto r^{-1.69 \pm 0.38}$ and $B_{mean} \propto r^{-1.78 \pm 0.42}$ over the heliocentric distance range of 0.7–5.4 AU. The value of the mean magnetic field power law fit is larger than previous studies, but within the uncertainty range calculated. The larger variability in magnetic field strengths of events at lesser heliocentric distances (< 1 AU) seems to have a stronger influence on the result of the power law fitting than events beyond 1 AU. This may explain why there is such a disparity between power law fits found in previous studies using events identified in the inner heliosphere in comparison to those studies beyond 1 AU.

Further analysis of the outlier event, event #20111025, was presented in Chapter 4. The ICME was observed by spacecraft in the near-Earth environment (ACE, Wind, and the two ARTEMIS spacecraft, THEMIS B and THEMIS C) and at Juno at a heliocentric distance of 1.24 AU. The near-Earth spacecraft and Juno were therefore separated radially by 0.24 AU during the event, and were separated in longitude by just 3.6° . The location of the spacecraft during the event have allowed for an assessment of both the radial evolution and longitudinal variation of the ICME.

The magnetic field magnitude profiles and the behaviour of the magnetic field components were similar between the investigated spacecraft, however, there were also some significant differences between the in situ observations at the near-Earth spacecraft and Juno. The observed magnetic field profiles were slightly different in that at the near-Earth spacecraft the magnetic field strength increased slightly between the leading and trailing edges, whereas at Juno it decreased slightly. An asymmetric, decreasing magnetic field profile would be expected for an expanding magnetic flux rope as the magnetic field decreases in strength during the time taken for the ICME to pass over the spacecraft. The most significant difference between the near-Earth and Juno observations was the compressed region of magnetic field towards the trailing edge of the flux rope, present in the near-Earth spacecraft observations but not at Juno. Both of these differences were likely due to the sudden increase in radial speed of the solar wind following the flux rope, only observed at the near-Earth spacecraft.

The ICME displayed a clear magnetic flux rope structure which was analysed using MVA and two fitting models, Lundquist and Gold-Hoyle. Observations taken by the multiple near-Earth spacecraft provide several independent fits indicating the degree of variability of the fits along different trajectories through the ICME. The orientation of the flux rope axis was shown to have a clear difference in θ despite the relatively

small spacecraft separations, irrespective of analysis method or trailing edge defined. We propose that the difference in flux rope orientation is not necessarily just due to the radial evolution of the ICME, but more so due to the longitudinal separation of the spacecraft, despite this being small.

Chapter 4 therefore demonstrates that caution should be exercised in radial alignment studies and the solar wind background should be taken into consideration when analysing ICMEs. The presence of increased solar wind speed following the event at Wind but not at Juno shows that even small longitudinal separations of a few degrees between spacecraft can still result in significantly different observations and event properties.

Chapter 5 explored the effect of the solar wind environment on ICME observations further. It compared and contrasted two isolated ICMEs observed in situ during April 2013 and April 2020 by radially aligned spacecraft. The April 2013 ICME was observed by both Wind and Juno, separated radially by 0.6 AU and in longitude by less than 1° , and is listed as event #20130415 in the catalogue of Chapter 3. The April 2020 ICME was observed by Solar Orbiter and Wind, separated radially by 0.2 AU and in longitude by less than 4° , and was the first ICME to be observed by the Solar Orbiter mission.

The two ICMEs are good examples to compare and contrast as they occurred under very different circumstances. The April 2013 ICME was observed during solar maximum, the source of which was a CME accompanying an M6.5 solar flare occurring from an active region and associated with a pre-eruptive sigmoidal structure. The CME was observed by the SOHO/LASCO C2 coronagraph, decelerating from ~ 950 to 800 km s^{-1} . In contrast, the April 2020 ICME occurred during solar minimum, the source of which was much harder to determine; the pre-eruptive structure was found to be a quiet dark cavity. The CME was observed in STEREO COR1 as a faint enhancement, slowly rising, which erupted following the brightening and swelling of a streamer. It was accelerated from 18 to 53 km s^{-1} between the COR1 and COR2 fields of view, and was followed by a higher speed stream of solar wind.

The April 2013 ICME is typical of a fast ICME decelerated by the ambient solar wind, with initial speeds of $\sim 800 \text{ km s}^{-1}$ and an in situ cruise velocity of 416 km s^{-1} at Wind, where the ambient solar wind both preceding and following the ICME were similar speeds ($\sim 390 \text{ km s}^{-1}$). The magnetic field profile at Wind was more asymmetrical than that at Juno, as one would expect due to the relaxation and expansion

of ICMEs as they propagate. The April 2013 ICME was found to follow expected magnetic field relationships based on the calculation of the dimensionless expansion parameter, providing an example of consistency between a local measure of expansion (the dimensionless expansion parameter) and a global measure of expansion (the change in magnetic field strength with heliocentric distance).

In contrast, the April 2020 ICME could be considered a slow ICME, which was accelerated up to the speed of the ambient solar wind by drag forces. The preceding ambient solar wind speed was especially slow ($\sim 300 \text{ km s}^{-1}$), however, the ICME was followed by a higher speed stream ($\sim 450 \text{ km s}^{-1}$). The ICME was observed to have an in situ cruise velocity of 343 km s^{-1} at Wind, and the velocity profile displayed little to no expansion. The distortion parameters calculated at both Solar Orbiter and Wind are very similar, with values indicating that the magnetic flux rope profile was slightly asymmetric. Asymmetric magnetic field profiles with a relatively small expansion may correspond to ICMEs with distorted structures (Nieves-Chinchilla *et al.*, 2018). This implication was confirmed by the HI images of the ICME, where it displayed a clear flattening and ‘pancaking’ of its structure as it propagated, highlighted so visibly due to the higher speed stream following which increased the density shell surrounding the ICME. Perhaps unsurprisingly, the April 2020 ICME did not follow expected magnetic field relationships based on the calculation of the dimensionless expansion parameter, demonstrating the inconsistency between local and global measures of ICME expansion, in line with the results of Lugaz *et al.* (2020). These results indicate that ICMEs cannot be considered in isolation from the solar wind environment.

The change in magnetic field strength with heliocentric distance was investigated for both ICMEs. For the April 2013 ICME the magnetic field strength is observed to follow $B_{mean} \propto r^{-1.72}$, whereas for the April 2020 ICME it follows $B_{mean} \propto r^{-1.12}$. It is interesting that neither relationship calculated is in agreement with those found by previous studies over corresponding heliocentric distance ranges (either within 1 AU or beyond 1 AU). In fact, the opposite seems to be true: the April 2013 ICME relationship is more in agreement with those calculated over heliocentric distances $<1 \text{ AU}$, and the April 2020 ICME relationship is more in agreement with those calculated over heliocentric distances $>1 \text{ AU}$. The disagreement may be due to the nature of the different ICMEs. Generally, ICMEs $< 1 \text{ AU}$ are faster than those beyond 1 AU as ICMEs tend towards the ambient solar wind speed, and are also likely to have faster expansion velocities. In this case, the April 2013 was a fast ICME and the April 2020 ICME was very slow

with very little expansion observed between Solar Orbiter and Wind. In future studies, it might therefore be interesting to compare magnetic field strength relationships with heliocentric distance between fast and slow (or accelerating and decelerating) ICMEs, attempting to determine the reason behind such different relationships within 1 AU and beyond 1 AU.

Despite the April 2013 ICME following expected expansion relationships, neither ICME was found to expand self-similarly as one would expect if we consider the magnetic flux ropes to be cylindrical and force-free. This result may have important implications for space weather forecasting and modelling, as most current models of ICME propagation assume self-similar expansion.

The Juno catalogue and the 11 events also observed by other aligned spacecraft provide a valuable basis for future studies. To investigate the relationship between local and global expansion further, the analysis and techniques applied to the two ICMEs in Chapter 5 could be extended to the 11 radially aligned events. Investigating the solar wind environment of each ICME and possible relationship with parameters such as the dimensionless expansion parameter, distortion parameter, expansion and cruise velocities, and magnetic field strengths over a range of heliocentric distances, may help further understanding of the propagation and evolution of interplanetary coronal mass ejections and the extent to which they are affected by the solar wind background.

The study of ICMEs observed by Juno has contributed towards our understanding of ICME evolution and forms a good basis on which other future missions to the outer planets, such as JUICE, may build upon. The recent dedicated solar wind missions such as Solar Orbiter and Parker Solar Probe, and planetary missions such as BepiColombo, have already provided interesting observations of ICMEs and will continue to do so closer to the Sun than ever before. The radial alignments between these spacecraft and those located at 1 AU (and perhaps beyond) signify an exciting future for multi-spacecraft studies of ICMEs.

Bibliography

- Acuña, M.H., Curtis, D., Scheifele, J.L., Russell, C.T., Schroeder, P., Szabo, A., Luhmann, J.G.: 2008, The STEREO/IMPACT Magnetic Field Experiment. *Space Sci. Rev.* **136**(1-4), 203. DOI. ADS.
- Al-Haddad, N., Nieves-Chinchilla, T., Savani, N.P., Möstl, C., Marubashi, K., Hidalgo, M.A., Roussev, I.I., Poedts, S., Farrugia, C.J.: 2013, Magnetic Field Configuration Models and Reconstruction Methods for Interplanetary Coronal Mass Ejections. *Solar Phys.* **284**(1), 129. DOI. ADS.
- Al-Haddad, N., Nieves-Chinchilla, T., Savani, N.P., Lugaz, N., Roussev, I.I.: 2018, Fitting and Reconstruction of Thirteen Simple Coronal Mass Ejections. *Solar Phys.* **293**(5), 73. DOI. ADS.
- Alfven, H.: 1977, Electric currents in cosmic plasma. *Reviews of Geophysics and Space Physics* **15**, 271. DOI. ADS.
- Altschuler, M.D., Newkirk, G.: 1969, Magnetic Fields and the Structure of the Solar Corona. I: Methods of Calculating Coronal Fields. *Solar Phys.* **9**(1), 131. DOI. ADS.
- Amari, T., Luciani, J.F., Mikic, Z., Linker, J.: 2000, A Twisted Flux Rope Model for Coronal Mass Ejections and Two-Ribbon Flares. *Astrophys. J. Lett.* **529**(1), L49. DOI. ADS.
- Angelopoulos, V.: 2008, The THEMIS Mission. *Space Sci. Rev.* **141**(1-4), 5. DOI. ADS.
- Angelopoulos, V.: 2011, The ARTEMIS Mission. *Space Sci. Rev.* **165**(1-4), 3. DOI. ADS.

- Antiochos, S.K., DeVore, C.R., Klimchuk, J.A.: 1999, A Model for Solar Coronal Mass Ejections. *Astrophys. J.* **510**(1), 485. DOI. ADS.
- Auster, H.U., Glassmeier, K.H., Magnes, W., Aydogar, O., Baumjohann, W., Constantinescu, D., Fischer, D., Fornacon, K.H., Georgescu, E., Harvey, P., *et al.*: 2008, The THEMIS Fluxgate Magnetometer. *Space Sci. Rev.* **141**(1-4), 235. DOI. ADS.
- Babcock, H.W.: 1961, The Topology of the Sun's Magnetic Field and the 22-Year Cycle. *Astrophys. J.* **133**, 572. DOI. ADS.
- Baker, D.N.: 1996, Solar wind-magnetosphere drivers of space weather. *J. Atmos. Terr. Phys.* **58**(14), 1509. DOI. ADS.
- Baker, D.N., Li, X., Pulkkinen, A., Ngwira, C.M., Mays, M.L., Galvin, A.B., Simunac, K.D.C.: 2013, A major solar eruptive event in July 2012: Defining extreme space weather scenarios. *Space Weather* **11**(10), 585. DOI. ADS.
- Balogh, A.: 2010, Planetary Magnetic Field Measurements: Missions and Instrumentation. *Space Sci. Rev.* **152**(1-4), 23. DOI. ADS.
- Bame, S.J.: 1972, Spacecraft Observations of the Solar Wind Composition. In: Sonett, C.P., Coleman, P.J., Wilcox, J.M. (eds.) *Solar Wind, NASA Special Publication* **308**, 535. ADS.
- Bame, S.J., McComas, D.J., Barraclough, B.L., Phillips, J.L., Sofaly, K.J., Chavez, J.C., Goldstein, B.E., Sakurai, R.K.: 1992, The ULYSSES solar wind plasma experiment. *Astron. Astrophys. Suppl.* **92**(2), 237. ADS.
- Biermann, L.: 1951, Kometenschweife und solare Korpuskularstrahlung. *Z. Astrophys.* **29**, 274. ADS.
- Billings, D.E.: 1966, *A guide to the solar corona*. ADS.
- Bolton, S.J., *et al.*: 2010, The Juno Mission. *Proceedings of the International Astronomical Union* **6**(S269), 92. DOI. ADS.
- Bolton, S.J., Lunine, J., Stevenson, D., Connerney, J.E.P., Levin, S., Owen, T.C., Bagenal, F., Gautier, D., Ingersoll, A.P., Orton, G.S., *et al.*: 2017, The Juno Mission. *Space Sci. Rev.* **213**(1-4), 5. DOI. ADS.

- Bothmer, V., Schwenn, R.: 1998, The structure and origin of magnetic clouds in the solar wind. *Ann. Geophys.* **16**, 1. DOI. ADS.
- Burlaga, L.F.: 1988, Magnetic clouds and force-free fields with constant α . *J. Geophys. Res.* **93**(A7), 7217. DOI. ADS.
- Burlaga, L.F., Klein, L., Sheeley, J. N. R., Michels, D.J., Howard, R.A., Koomen, M.J., Schwenn, R., Rosenbauer, H.: 1982, A magnetic cloud and a coronal mass ejection. *Geophys. Res. Lett.* **9**(12), 1317. DOI. ADS.
- Burlaga, L.F., Klein, L.W., Lepping, R.P., Behannon, K.W.: 1984, Large-scale interplanetary magnetic fields: Voyager 1 and 2 observations between 1 AU and 9.5 AU. *J. Geophys. Res.(Space Physics)* **89**(A12), 10659. DOI.
- Burlaga, L., Sittler, E., Mariani, F., Schwenn, R.: 1981, Magnetic loop behind an interplanetary shock: Voyager, Helios, and IMP 8 observations. *J. Geophys. Res.* **86**(A8), 6673. DOI. ADS.
- Cane, H.V., Richardson, I.G.: 2003, Interplanetary coronal mass ejections in the near-Earth solar wind during 1996-2002. *J. Geophys. Res.(Space Physics)* **108**(A4), 1156. DOI. ADS.
- Cane, H.V., Richardson, I.G., Wibberenz, G.: 1997, Helios 1 and 2 observations of particle decreases, ejecta, and magnetic clouds. *J. Geophys. Res.* **102**(A4), 7075. DOI. ADS.
- Cargill, P.J.: 2004, On the Aerodynamic Drag Force Acting on Interplanetary Coronal Mass Ejections. *Solar Phys.* **221**(1), 135. DOI. ADS.
- Chamberlain, J.W.: 1961, Interplanetary Gas. III. a Hydrodynamic Model of the Corona. *Astrophys. J.* **133**, 675. DOI. ADS.
- Chen, J.: 1989, Effects of Toroidal Forces in Current Loops Embedded in a Background Plasma. *Astrophys. J.* **338**, 453. DOI. ADS.
- Chen, P.F.: 2011, Coronal Mass Ejections: Models and Their Observational Basis. *Living Rev. Sol. Phys.* **8**(1), 1. DOI. ADS.

- Cohen, C.M.S., Mason, G.M., Mewaldt, R.A., Wiedenbeck, M.E.: 2014, The Longitudinal Dependence of Heavy-ion Composition in the 2013 April 11 Solar Energetic Particle Event. *Astrophys. J.* **793**(1), 35. DOI. ADS.
- Connerney, J.E.P., Benn, M., Bjarno, J.B., Denver, T., Espley, J., Jorgensen, J.L., Jorgensen, P.S., Lawton, P., Malinnikova, A., Merayo, J.M., *et al.*: 2017, The Juno Magnetic Field Investigation. *Space Sci. Rev.* **213**(1-4), 39. DOI. ADS.
- Cremades, H., Bothmer, V., Tripathi, D.: 2006, Properties of structured coronal mass ejections in solar cycle 23. *Adv. Space Res.* **38**(3), 461. DOI. ADS.
- Crooker, N.U., Antiochos, S.K., Zhao, X., Neugebauer, M.: 2012, Global network of slow solar wind. *J. Geophys. Res.(Space Physics)* **117**(A4), A04104. DOI. ADS.
- Dasso, S., Mandrini, C.H., Démoulin, P., Luoni, M.L.: 2006, A new model-independent method to compute magnetic helicity in magnetic clouds. *Astron. Astrophys.* **455**(1), 349. DOI. ADS.
- Davies, E.E., Forsyth, R.J., Good, S.W., Kilpua, E.K.J.: 2020, On the Radial and Longitudinal Variation of a Magnetic Cloud: ACE, Wind, ARTEMIS and Juno Observations. *Solar Phys.* **295**(11), 157. DOI. ADS.
- Davies, E.E., Möstl, C., Owens, M.J., Weiss, A.J., Amerstorfer, T., Hinterreiter, J., Bauer, M., Bailey, R.L., Reiss, M.A., Forsyth, R.J., *et al.*: 2021, In situ multi-spacecraft and remote imaging observations of the first CME detected by Solar Orbiter and BepiColombo. *Astron. Astrophys.* DOI.
- Davis, C.J., Davies, J.A., Lockwood, M., Rouillard, A.P., Eyles, C.J., Harrison, R.A.: 2009, Stereoscopic imaging of an Earth-impacting solar coronal mass ejection: A major milestone for the STEREO mission. *Geophys. Res. Lett.* **36**(8), L08102. DOI. ADS.
- Delaboudinière, J.-P., Artzner, G.E., Brunaud, J., Gabriel, A.H., Hochedez, J.F., Millier, F., Song, X.Y., Au, B., Dere, K.P., Howard, R.A., *et al.*: 1995, EIT: Extreme-Ultraviolet Imaging Telescope for the SOHO Mission. *Solar Phys.* **162**(1-2), 291. DOI. ADS.
- Démoulin, P., Dasso, S.: 2009, Causes and consequences of magnetic cloud expansion. *Astron. Astrophys.* **498**(2), 551. DOI. ADS.

- Démoulin, P., Dasso, S., Janvier, M.: 2018, Exploring the biases of a new method based on minimum variance for interplanetary magnetic clouds. *Astron. Astrophys.* **619**, A139. DOI. ADS.
- Dere, K.P., Brueckner, G.E., Howard, R.A., Koomen, M.J., Korendyke, C.M., Kreplin, R.W., Michels, D.J., Moses, J.D., Moulton, N.E., Socker, D.G., *et al.*: 1997, EIT and LASCO Observations of the Initiation of a Coronal Mass Ejection. *Solar Phys.* **175**(2), 601. DOI. ADS.
- Dere, K.P., Brueckner, G.E., Howard, R.A., Michels, D.J., Delaboudiniere, J.P.: 1999, LASCO and EIT Observations of Helical Structure in Coronal Mass Ejections. *Astrophys. J.* **516**(1), 465. DOI. ADS.
- Desai, R.T., Zhang, H., Davies, E.E., Stawarz, J.E., Mico-Gomez, J., Iváñez-Ballesteros, P.: 2020, Three-Dimensional Simulations of Solar Wind Preconditioning and the 23 July 2012 Interplanetary Coronal Mass Ejection. *Solar Phys.* **295**(9), 130. DOI. ADS.
- Dessler, A.J.: 1967, Solar Wind and Interplanetary Magnetic Field. *Rev. Geophys. Space. Ge.* **5**, 1. DOI. ADS.
- D’Huys, E., Seaton, D.B., Poedts, S., Berghmans, D.: 2014, Observational Characteristics of Coronal Mass Ejections without Low-coronal Signatures. *Astrophys. J.* **795**(1), 49. DOI. ADS.
- Domingo, V., Fleck, B., Poland, A.I.: 1995, SOHO: The Solar and Heliospheric Observatory. *Space Sci. Rev.* **72**(1-2), 81. DOI. ADS.
- Du, D., Zuo, P.B., Zhang, X.X.: 2010, Interplanetary Coronal Mass Ejections Observed by Ulysses Through Its Three Solar Orbits. *Solar Phys.* **262**(1), 171. DOI. ADS.
- Dumbović, M., Heber, B., Vršnak, B., Temmer, M., Kirin, A.: 2018, An Analytical Diffusion-Expansion Model for Forbush Decreases Caused by Flux Ropes. *Astrophys. J.* **860**(1), 71. DOI. ADS.
- Eastwood, J.P.: 2008, The science of space weather. *Phil. Trans. R. Soc. A.* **366**(1884), 4489. DOI. ADS.

- Ebert, R.W., McComas, D.J., Elliott, H.A., Forsyth, R.J., Gosling, J.T.: 2009, Bulk properties of the slow and fast solar wind and interplanetary coronal mass ejections measured by Ulysses: Three polar orbits of observations. *J. Geophys. Res.(Space Physics)* **114**(A1), A01109. DOI. ADS.
- Eddington, A.S.: 1910, The Envelopes of Comet Morehouse (1908 c). *Monthly Notices of the Royal Astronomical Society* **70**(5), 442. DOI.
- Eyles, C.J., Harrison, R.A., Davis, C.J., Waltham, N.R., Shaughnessy, B.M., Mapson-Menard, H.C.A., Bewsher, D., Crothers, S.R., Davies, J.A., Simnett, G.M., *et al.*: 2009, The Heliospheric Imagers Onboard the STEREO Mission. *Solar Phys.* **254**(2), 387. DOI. ADS.
- Farrugia, C.J., Burlaga, L.F., Osherovich, V.A., Richardson, I.G., Freeman, M.P., Lepping, R.P., Lazarus, A.J.: 1993, A study of an expanding interplanetary magnetic cloud and its interaction with the Earth's magnetosphere: The interplanetary aspect. *J. Geophys. Res.* **98**(A5), 7621. DOI. ADS.
- Farrugia, C.J., Janoo, L.A., Torbert, R.B., Quinn, J.M., Ogilvie, K.W., Lepping, R.P., Fitzenreiter, R.J., Steinberg, J.T., Lazarus, A.J., Lin, R.P., *et al.*: 1999, A uniform-twist magnetic flux rope in the solar wind. In: Habbal, S.R., Esser, R., Hollweg, J.V., Isenberg, P.A. (eds.) *Solar Wind Nine, American Institute of Physics Conference Series* **471**, 745. DOI. ADS.
- Farrugia, C.J., Vasquez, B., Richardson, I.G., Torbert, R.B., Burlaga, L.F., Biernat, H.K., Mühlbachler, S., Ogilvie, K.W., Lepping, R.P., Scudder, J.D., *et al.*: 2001, A reconnection layer associated with a magnetic cloud. *Adv. Space Res.* **28**(5), 759. DOI. ADS.
- Farrugia, C.J., Berdichevsky, D.B., Möstl, C., Galvin, A.B., Leitner, M., Popecki, M.A., Simunac, K.D.C., Opitz, A., Lavraud, B., Ogilvie, K.W., *et al.*: 2011, Multiple, distant (40°) in situ observations of a magnetic cloud and a corotating interaction region complex. *J. Atmos. Solar-Terr. Phys.* **73**(10), 1254. DOI. ADS.
- Farrugia, C.J., Leiter, M., Biernat, H.K., Schwenn, R., Ogilvie, K.W., Matsuil, H., Kucharek, H., Jordanova, V.K., Lepping, R.P.: 2005, Evolution of interplanetary magnetic clouds from 0.3 AU to 1 AU: A joint Helios-Wind investigation. In: *Solar Wind 11/SOHO 16, Connecting Sun and Heliosphere* **592**, 723.

- Fazakerley, A.N., Schwartz, S.J., Paschmann, G.: 1998, Measurement of Plasma Velocity Distributions. *ISSI Scientific Reports Series* **1**, 91. ADS.
- Forsyth, R.J., Marsch, E.: 1999, Solar Origin and Interplanetary Evolution of Stream Interfaces. *Space Sci. Rev.* **89**, 7. DOI. ADS.
- Gold, T., Hoyle, F.: 1960, On the origin of solar flares. *Mon. Not. Roy. Astron. Soc.* **120**, 89. DOI. ADS.
- Goldstein, H.: 1983, On the field configuration in magnetic clouds. In: *Solar Wind Five, NASA Conference Publication* **228**, 0.731. ADS.
- Good, S.W., Forsyth, R.J.: 2016, Interplanetary Coronal Mass Ejections Observed by MESSENGER and Venus Express. *Solar Phys.* **291**(1), 239. DOI. ADS.
- Good, S.W., Forsyth, R.J., Raines, J.M., Gershman, D.J., Slavin, J.A., Zurbuchen, T.H.: 2015, Radial Evolution of a Magnetic Cloud: MESSENGER, STEREO, and Venus Express Observations. *Astrophys. J.* **807**(2), 177. DOI. ADS.
- Good, S.W., Forsyth, R.J., Eastwood, J.P., Möstl, C.: 2018, Correlation of ICME Magnetic Fields at Radially Aligned Spacecraft. *Solar Phys.* **293**(3), 52. DOI. ADS.
- Good, S.W., Kilpua, E.K.J., LaMoury, A.T., Forsyth, R.J., Eastwood, J.P., Möstl, C.: 2019, Self-Similarity of ICME Flux Ropes: Observations by Radially Aligned Spacecraft in the Inner Heliosphere. *J. Geophys. Res.(Space Physics)* **124**(7), 4960. DOI. ADS.
- Gopalswamy, N., Lara, A., Lepping, R.P., Kaiser, M.L., Berdichevsky, D., St. Cyr, O.C.: 2000, Interplanetary acceleration of coronal mass ejections. *Geophys. Res. Lett.* **27**(2), 145. DOI. ADS.
- Gopalswamy, N., Yashiro, S., Xie, H., Akiyama, S., Mäkelä, P.: 2015, Properties and geoeffectiveness of magnetic clouds during solar cycles 23 and 24. *J. Geophys. Res.(Space Physics)* **120**(11), 9221. DOI. ADS.
- Gosain, S., Filippov, B., Ajor Maurya, R., Chandra, R.: 2016, Interrupted Eruption of Large Quiescent Filament Associated with a Halo CME. *Astrophys. J.* **821**(2), 85. DOI. ADS.

- Gosling, J.T.: 1990, Coronal mass ejections and magnetic flux ropes in interplanetary space. *Washington DC American Geophysical Union Geophysical Monograph Series* **58**, 343. DOI. ADS.
- Gosling, J.T., Thomsen, M.F., Bame, S.J., Zwickl, R.D.: 1987, The eastward deflection of fast coronal mass ejecta in interplanetary space. *J. Geophys. Res.* **92**(A11), 12399. DOI. ADS.
- Gosling, J.T., McComas, D.J., Phillips, J.L., Bame, S.J.: 1991, Geomagnetic activity associated with earth passage of interplanetary shock disturbances and coronal mass ejections. *J. Geophys. Res.* **96**(A5), 7831. DOI. ADS.
- Green, L.M., Kliem, B., Török, T., van Driel-Gesztelyi, L., Attrill, G.D.R.: 2007, Transient Coronal Sigmoids and Rotating Erupting Flux Ropes. *Solar Phys.* **246**(2), 365. DOI. ADS.
- Green, L.M., Török, T., Vršnak, B., Manchester, W., Veronig, A.: 2018, The Origin, Early Evolution and Predictability of Solar Eruptions. *Space Sci. Rev.* **214**(1), 46. DOI. ADS.
- Gringauz, K.I., Bezrokh, V.V., Ozerov, V.D., Rybchinskii, R.E.: 1960, A Study of the Interplanetary Ionized Gas, High-Energy Electrons and Corpuscular Radiation from the Sun by Means of the Three-Electrode Trap for Charged Particles on the Second Soviet Cosmic Rocket. *Soviet Physics Doklady* **5**, 361. ADS.
- Gruesbeck, J.R., Gershman, D.J., Espley, J.R., Connerney, J.E.P.: 2017, The interplanetary magnetic field observed by Juno enroute to Jupiter. *Geophys. Res. Lett.* **44**(12), 5936. DOI. ADS.
- Gulisano, A.M., Dasso, S., Mandrini, C.H., Démoulin, P.: 2005, Magnetic clouds: A statistical study of magnetic helicity. *J. Atmos. Solar-Terr. Phys.* **67**, 1761. DOI. ADS.
- Gulisano, A.M., Dasso, S., Mandrini, C.H., Démoulin, P.: 2007, Estimation of the bias of the Minimum Variance technique in the determination of magnetic clouds global quantities and orientation. *Adv. Space Res.* **40**(12), 1881. DOI. ADS.

- Gulisano, A.M., Démoulin, P., Dasso, S., Ruiz, M.E., Marsch, E.: 2010, Global and local expansion of magnetic clouds in the inner heliosphere. *Astron. Astrophys.* **509**, A39. DOI. ADS.
- Gurnett, D.A., Kurth, W.S., Burlaga, L.F., Ness, N.F.: 2013, In Situ Observations of Interstellar Plasma with Voyager 1. *Science* **341**(6153), 1489. DOI. ADS.
- Hapgood, M.A.: 1992, Space physics coordinate transformations: A user guide. *Planet. Space Sci.* **40**(5), 711. DOI. ADS.
- Hapgood, M., Angling, M.J., Attrill, G., Bisi, M., Cannon, P.S., Dyer, C., Eastwood, J.P., Elvidge, S., Gibbs, M., Harrison, R.A., et al.: 2021, Development of Space Weather Reasonable Worst Case Scenarios for the UK National Risk Assessment. *Space Weather*, e2020SW002593. DOI.
- Harra, L.K.: 2009, On-disk signatures of eruptive activity from the Hinode mission. *Advances in Space Research* **44**(4), 446. DOI. ADS.
- Harrison, R.A.: 1995, The nature of solar flares associated with coronal mass ejection. *Astron. Astrophys.* **304**, 585. ADS.
- Heber, B., Sanderson, T.R., Zhang, M.: 1999, Corotating interaction regions. *Advances in Space Research* **23**(3), 567. DOI. ADS.
- Hoffmeister, C.: 1943, Physikalische Untersuchungen an Kometen. I. Die Beziehungen des primären Schweifstrahls zum Radiusvektor. Mit 2 Abbildungen. *Z. Astrophys.* **22**, 265. ADS.
- Horbury, T.S., O’Brien, H., Carrasco Blazquez, I., Bendyk, M., Brown, P., Hudson, R., Evans, V., Oddy, T.M., Carr, C.M., Beek, T.J., et al.: 2020, The Solar Orbiter magnetometer. *Astron. Astrophys.* **642**, A9. DOI. ADS.
- Howard, R.A., Brueckner, G.E., St. Cyr, O.C., Biesecker, D.A., Dere, K.P., Koomen, M.J., Korendyke, C.M., Lamy, P.L., Llebaria, A., Bout, M.V., et al.: 1997, Observations of CMEs from SOHO/LASCO. *Washington DC American Geophysical Union Geophysical Monograph Series* **99**, 17. DOI. ADS.
- Hu, Q., Qiu, J., Krucker, S.: 2015, Magnetic field line lengths inside interplanetary magnetic flux ropes. *J. Geophys. Res.(Space Physics)* **120**(7), 5266. DOI. ADS.

- Hu, Q., Qiu, J., Dasgupta, B., Khare, A., Webb, G.M.: 2014, Structures of Interplanetary Magnetic Flux Ropes and Comparison with Their Solar Sources. *Astrophys. J.* **793**(1), 53. DOI. ADS.
- Hundhausen, A.J.: 1993, Sizes and locations of coronal mass ejections: SMM observations from 1980 and 1984-1989. *J. Geophys. Res.* **98**(A8), 13177. DOI. ADS.
- Hundhausen, A.J.: 1995, In: Kivelson, M.G., Russell, C.T. (eds.) *The Solar Wind*, Cambridge University Press, Cambridge, 91. DOI.
- Huttunen, K.E.J., Schwenn, R., Bothmer, V., Koskinen, H.E.J.: 2005, Properties and geoeffectiveness of magnetic clouds in the rising, maximum and early declining phases of solar cycle 23. *Ann. Geophys.* **23**(2), 625. DOI. ADS.
- Illing, R.M.E., Hundhausen, A.J.: 1985, Observation of a coronal transient from 1.2 to 6 solar radii. *J. Geophys. Res.* **90**(A1), 275. DOI. ADS.
- Isavnin, A., Vourlidas, A., Kilpua, E.K.J.: 2014, Three-Dimensional Evolution of Flux-Rope CMEs and Its Relation to the Local Orientation of the Heliospheric Current Sheet. *Solar Phys.* **289**(6), 2141. DOI. ADS.
- Jacobs, C., Roussev, I.I., Lugaz, N., Poedts, S.: 2009, The Internal Structure of Coronal Mass Ejections: Are all Regular Magnetic Clouds Flux Ropes? *Astrophys. J. Lett.* **695**(2), L171. DOI. ADS.
- Janvier, M., Dasso, S., Démoulin, P., Masías-Meza, J.J., Lugaz, N.: 2015, Comparing generic models for interplanetary shocks and magnetic clouds axis configurations at 1 AU. *J. Geophys. Res.(Space Physics)* **120**(5), 3328. DOI. ADS.
- Janvier, M., Winslow, R.M., Good, S., Bonhomme, E., Démoulin, P., Dasso, S., Möstl, C., Lugaz, N., Amerstorfer, T., Soubrié, E., *et al.*: 2019, Generic Magnetic Field Intensity Profiles of Interplanetary Coronal Mass Ejections at Mercury, Venus, and Earth From Superposed Epoch Analyses. *J. Geophys. Res.(Space Physics)* **124**(2), 812. DOI. ADS.
- Jian, L.K., Russell, C.T., Luhmann, J.G., Galvin, A.B.: 2018, STEREO Observations of Interplanetary Coronal Mass Ejections in 2007-2016. *Astrophys. J.* **855**(2), 114. DOI. ADS.

- Joshi, B., Kushwaha, U., Veronig, A.M., Dhara, S.K., Shanmugaraju, A., Moon, Y.-J.: 2017, Formation and Eruption of a Flux Rope from the Sigmoid Active Region NOAA 11719 and Associated M6.5 Flare: A Multi-wavelength Study. *Astrophys. J.* **834**(1), 42. DOI. ADS.
- Kahler, S.W.: 1992, Solar flares and coronal mass ejections. *Annu. Rev. Astron. Astr.* **30**, 113. DOI. ADS.
- Kahler, S.W., Krucker, S., Szabo, A.: 2011, Solar energetic electron probes of magnetic cloud field line lengths. *J. Geophys. Res.(Space Physics)* **116**(A1), A01104. DOI. ADS.
- Kaiser, M.L., Kucera, T.A., Davila, J.M., St. Cyr, O.C., Guhathakurta, M., Christian, E.: 2008, The STEREO Mission: An Introduction. *Space Sci. Rev.* **136**(1-4), 5. DOI. ADS.
- Kallenrode, M.-B.: 2004, *Space physics: An introduction to plasmas and particles in the heliosphere and magnetospheres*, Springer, Berlin.
- Kilpua, E., Koskinen, H.E.J., Pulkkinen, T.I.: 2017, Coronal mass ejections and their sheath regions in interplanetary space. *Living Rev. Sol. Phys.* **14**(1), 5. DOI. ADS.
- Kilpua, E.K.J., Jian, L.K., Li, Y., Luhmann, J.G., Russell, C.T.: 2011, Multipoint ICME encounters: Pre-STEREO and STEREO observations. *J. Atmos. Solar-Terr. Phys.* **73**(10), 1228. DOI. ADS.
- Kilpua, E.K.J., Isavnin, A., Vourlidas, A., Koskinen, H.E.J., Rodriguez, L.: 2013, On the relationship between interplanetary coronal mass ejections and magnetic clouds. *Annales Geophysicae* **31**(7), 1251. DOI. ADS.
- Kilpua, E.K.J., Mierla, M., Zhukov, A.N., Rodriguez, L., Vourlidas, A., Wood, B.: 2014, Solar Sources of Interplanetary Coronal Mass Ejections During the Solar Cycle 23/24 Minimum. *Solar Phys.* **289**(10), 3773. DOI. ADS.
- Kilpua, E.K.J., Lumme, E., Andreeva, K., Isavnin, A., Koskinen, H.E.J.: 2015, Properties and drivers of fast interplanetary shocks near the orbit of the Earth (1995-2013). *J. Geophys. Res.(Space Physics)* **120**(6), 4112. DOI. ADS.

- Kilpua, E.K.J., Balogh, A., von Steiger, R., Liu, Y.D.: 2017, Geoeffective Properties of Solar Transients and Stream Interaction Regions. *Space Sci. Rev.* **212**(3-4), 1271. DOI. ADS.
- Kilpua, E.K.J., Good, S.W., Palmerio, E., Asvestari, E., Lumme, E., Ala-Lahti, M., Kalliokoski, M.M.H., Morosan, D.E., Pomoell, J., Price, D.J., *et al.*: 2019, Multipoint Observations of the June 2012 Interacting Interplanetary Flux Ropes. *Front. Astron. Space Sci.* **6**, 50. DOI. ADS.
- Kilpua, E.K.J., Good, S.W., Dresing, N., Vainio, R., Davies, E.E., Forsyth, R.J., Gieseler, J., Lavraud, B., Asvestari, E., Morosan, D.E., *et al.*: 2021, Multi-spacecraft observations of the structure of the sheath of an interplanetary coronal mass ejection and related energetic ion enhancement. *Astron. Astrophys.*. DOI.
- Klein, L.W., Burlaga, L.F.: 1982, Interplanetary magnetic clouds at 1 AU. *J. Geophys. Res.* **87**(A2), 613. DOI. ADS.
- Krieger, A.S., Timothy, A.F., Roelof, E.C.: 1973, A Coronal Hole and Its Identification as the Source of a High Velocity Solar Wind Stream. *Solar Phys.* **29**(2), 505. DOI. ADS.
- Lario, D., Raouafi, N.E., Kwon, R.-Y., Zhang, J., Gómez-Herrero, R., Dresing, N., Riley, P.: 2014, The Solar Energetic Particle Event on 2013 April 11: An Investigation of its Solar Origin and Longitudinal Spread. *Astrophys. J.* **797**(1), 8. DOI. ADS.
- Lee, M.A., Fahr, H.J., Kucharek, H., Moebius, E., Prested, C., Schwadron, N.A., Wu, P.: 2009, Physical Processes in the Outer Heliosphere. *Space Sci. Rev.* **146**(1-4), 275. DOI. ADS.
- Leighton, R.B.: 1969, A Magneto-Kinematic Model of the Solar Cycle. *Astrophys. J.* **156**, 1. DOI. ADS.
- Leitner, M., Farrugia, C.J., Möstl, C., Ogilvie, K.W., Galvin, A.B., Schwenn, R., Biernat, H.K.: 2007, Consequences of the force-free model of magnetic clouds for their heliospheric evolution. *J. Geophys. Res.(Space Physics)* **112**(A6), A06113. DOI. ADS.
- Lemen, J.R., Title, A.M., Akin, D.J., Boerner, P.F., Chou, C., Drake, J.F., Duncan, D.W., Edwards, C.G., Friedlaender, F.M., Heyman, G.F., *et al.*: 2012, The Atmo-

- spheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO). *Solar Phys.* **275**(1-2), 17. DOI. ADS.
- Lepping, R.P., Berdichevsky, D.B., Ferguson, T.J.: 2003, Estimated errors in magnetic cloud model fit parameters with force-free cylindrically symmetric assumptions. *J. Geophys. Res.(Space Physics)* **108**(A10), 1356. DOI. ADS.
- Lepping, R.P., Jones, J.A., Burlaga, L.F.: 1990, Magnetic field structure of interplanetary magnetic clouds at 1 AU. *J. Geophys. Res.* **95**(A8), 11957. DOI. ADS.
- Lepping, R.P., Acuña, M.H., Burlaga, L.F., Farrell, W.M., Slavin, J.A., Schatten, K.H., Mariani, F., Ness, N.F., Neubauer, F.M., Whang, Y.C., *et al.*: 1995, The Wind Magnetic Field Investigation. *Space Sci. Rev.* **71**, 207. DOI. ADS.
- Lepping, R.P., Wu, C.-C., Berdichevsky, D.B., Szabo, A.: 2015, Wind Magnetic Clouds for 2010 - 2012: Model Parameter Fittings, Associated Shock Waves, and Comparisons to Earlier Periods. *Solar Phys.* **290**(8), 2265. DOI. ADS.
- Lepping, R.P., Wu, C.-C., Berdichevsky, D.B., Szabo, A.: 2018, Wind Magnetic Clouds for the Period 2013 - 2015: Model Fitting, Types, Associated Shock Waves, and Comparisons to Other Periods. *Solar Phys.* **293**(4), 65. DOI. ADS.
- Liu, Y., Richardson, J.D., Belcher, J.W.: 2005, A statistical study of the properties of interplanetary coronal mass ejections from 0.3 to 5.4 AU. *Planet. Space Sci.* **53**(1-3), 3. DOI. ADS.
- Liu, Y.D., Luhmann, J.G., Kajdič, P., Kilpua, E.K.J., Lugaz, N., Nitta, N.V., Möstl, C., Lavraud, B., Bale, S.D., *et al.*: 2014, Observations of an extreme storm in interplanetary space caused by successive coronal mass ejections. *Nat. Commun.* **5**, 3481. DOI. ADS.
- Liu, Y., Luhmann, J.G., Huttunen, K.E.J., Lin, R.P., Bale, S.D., Russell, C.T., Galvin, A.B.: 2008, Reconstruction of the 2007 May 22 Magnetic Cloud: How Much Can We Trust the Flux-Rope Geometry of CMEs? *Astrophys. J. Lett.* **677**(2), L133. DOI. ADS.
- Liu, Y., Thernisien, A., Luhmann, J.G., Vourlidas, A., Davies, J.A., Lin, R.P., Bale, S.D.: 2010, Reconstructing Coronal Mass Ejections with Coordinated Imaging and in

- Situ Observations: Global Structure, Kinematics, and Implications for Space Weather Forecasting. *Astrophys. J.* **722**(2), 1762. DOI. ADS.
- Lugaz, N., Winslow, R.M., Farrugia, C.J.: 2020, Evolution of a Long-Duration Coronal Mass Ejection and Its Sheath Region Between Mercury and Earth on 9-14 July 2013. *J. Geophys. Res.(Space Physics)* **125**(1), e27213. DOI. ADS.
- Lugaz, N., Farrugia, C.J., Winslow, R.M., Small, C.R., Manion, T., Savani, N.P.: 2017a, Importance of CME Radial Expansion on the Ability of Slow CMEs to Drive Shocks. *Astrophys. J.* **848**(2), 75. DOI. ADS.
- Lugaz, N., Temmer, M., Wang, Y., Farrugia, C.J.: 2017b, The Interaction of Successive Coronal Mass Ejections: A Review. *Solar Phys.* **292**(4), 64. DOI. ADS.
- Lugaz, N., Farrugia, C.J., Winslow, R.M., Al-Haddad, N., Galvin, A.B., Nieves-Chinchilla, T., Lee, C.O., Janvier, M.: 2018, On the Spatial Coherence of Magnetic Ejecta: Measurements of Coronal Mass Ejections by Multiple Spacecraft Longitudinally Separated by 0.01 au. *Astrophys. J. Lett.* **864**(1), L7. DOI. ADS.
- Lugaz, N., Salman, T.M., Winslow, R.M., Al-Haddad, N., Farrugia, C.J., Zhuang, B., Galvin, A.B.: 2020, Inconsistencies Between Local and Global Measures of CME Radial Expansion as Revealed by Spacecraft Conjunctions. *Astrophys. J.* **899**(2), 119. DOI. ADS.
- Luhmann, J.G., Gosling, J.T., Hoeksema, J.T., Zhao, X.: 1998, The relationship between large-scale solar magnetic field evolution and coronal mass ejections. *J. Geophys. Res.* **103**(A4), 6585. DOI. ADS.
- Lundquist, S.: 1950, Magneto-hydrostatic fields. *Ark. Fys.* **2**, 361.
- Magara, T., Mineshige, S., Yokoyama, T., Shibata, K.: 1996, Numerical Simulation of Magnetic Reconnection in Eruptive Flares. *Astrophys. J.* **466**, 1054. DOI. ADS.
- Manchester, W., Kilpua, E.K.J., Liu, Y.D., Lugaz, N., Riley, P., Török, T., Vršnak, B.: 2017, The Physical Processes of CME/ICME Evolution. *Space Sci. Rev.* **212**(3-4), 1159. DOI. ADS.
- Marubashi, K.: 1986, Structure of the interplanetary magnetic clouds and their solar origins. *Advances in Space Research* **6**(6), 335. DOI. ADS.

- Marubashi, K., Akiyama, S., Yashiro, S., Gopalswamy, N., Cho, K.-S., Park, Y.-D.: 2015, Geometrical Relationship Between Interplanetary Flux Ropes and Their Solar Sources. *Solar Phys.* **290**(5), 1371. DOI. ADS.
- Masías-Meza, J.J., Dasso, S., Démoulin, P., Rodriguez, L., Janvier, M.: 2016, Superposed epoch study of ICME sub-structures near Earth and their effects on Galactic cosmic rays. *Astron. Astrophys.* **592**, A118. DOI. ADS.
- McComas, D.J., Bame, S.J., Barker, P., Feldman, W.C., Phillips, J.L., Riley, P., Griffee, J.W.: 1998a, Solar Wind Electron Proton Alpha Monitor (SWEPAM) for the Advanced Composition Explorer. *Space Sci. Rev.* **86**, 563. DOI. ADS.
- McComas, D.J., Bame, S.J., Barraclough, B.L., Feldman, W.C., Funsten, H.O., Gosling, J.T., Riley, P., Skoug, R., Balogh, A., Forsyth, R., *et al.*: 1998b, Ulysses' return to the slow solar wind. *Geophys. Res. Lett.* **25**(1), 1. DOI.
- McComas, D.J., Barraclough, B.L., Funsten, H.O., Gosling, J.T., Santiago-Muñoz, E., Skoug, R.M., Goldstein, B.E., Neugebauer, M., Riley, P., Balogh, A.: 2000, Solar wind observations over Ulysses' first full polar orbit. *J. Geophys. Res.* **105**(A5), 10419. DOI.
- McComas, D.J., Elliott, H.A., Schwadron, N.A., Gosling, J.T., Skoug, R.M., Goldstein, B.E.: 2003, The three-dimensional solar wind around solar maximum. *Geophys. Res. Lett.* **30**(10), 1517. DOI.
- McComas, D.J., Angold, N., Elliott, H.A., Livadiotis, G., Schwadron, N.A., Skoug, R.M., Smith, C.W.: 2013, Weakest Solar Wind of the Space Age and the Current "Mini" Solar Maximum. *Astrophys. J.* **779**(1), 2. DOI. ADS.
- McComas, D.J., Alexander, N., Allegrini, F., Bagenal, F., Beebe, C., Clark, G., Crary, F., Desai, M.I., De Los Santos, A., Demkee, D., *et al.*: 2017, The Jovian Auroral Distributions Experiment (JADE) on the Juno Mission to Jupiter. *Space Sci. Rev.* **213**(1-4), 547. DOI. ADS.
- McFadden, J.P., Carlson, C.W., Larson, D., Ludlam, M., Abiad, R., Elliott, B., Turin, P., Marckwordt, M., Angelopoulos, V.: 2008, The THEMIS ESA Plasma Instrument and In-flight Calibration. *Space Sci. Rev.* **141**(1-4), 277. DOI. ADS.

- Moore, R.L., Roumeliotis, G.: 1992, In: Svestka, Z., Jackson, B.V., Machado, M.E. (eds.) *Triggering of Eruptive Flares - Destabilization of the Preflare Magnetic Field Configuration* **399**, 69. DOI. ADS.
- Möstl, C., Farrugia, C.J., Temmer, M., Miklenic, C., Veronig, A.M., Galvin, A.B., Leitner, M., Biernat, H.K.: 2009a, Linking Remote Imagery of a Coronal Mass Ejection to Its In Situ Signatures at 1 AU. *Astrophys. J. Lett.* **705**(2), L180. DOI. ADS.
- Möstl, C., Farrugia, C.J., Biernat, H.K., Leitner, M., Kilpua, E.K.J., Galvin, A.B., Luhmann, J.G.: 2009b, Optimized Grad - Shafranov Reconstruction of a Magnetic Cloud Using STEREO- Wind Observations. *Solar Phys.* **256**(1-2), 427. DOI. ADS.
- Möstl, C., Farrugia, C.J., Kilpua, E.K.J., Jian, L.K., Liu, Y., Eastwood, J.P., Harrison, R.A., Webb, D.F., Temmer, M., Odstroil, D., *et al.*: 2012, Multi-point Shock and Flux Rope Analysis of Multiple Interplanetary Coronal Mass Ejections around 2010 August 1 in the Inner Heliosphere. *Astrophys. J.* **758**(1), 10. DOI. ADS.
- Müller, D., Marsden, R.G., St. Cyr, O.C., Gilbert, H.R.: 2013, Solar Orbiter . Exploring the Sun-Heliosphere Connection. *Solar Phys.* **285**(1-2), 25. DOI. ADS.
- Müller, D., St. Cyr, O.C., Zouganelis, I., Gilbert, H.R., Marsden, R., Nieves-Chinchilla, T., Antonucci, E., Auchère, F., Berghmans, D., Horbury, T.S., *et al.*: 2020, The Solar Orbiter mission. Science overview. *Astron. Astrophys.* **642**, A1. DOI. ADS.
- Mulligan, T., Russell, C.T., Luhmann, J.G.: 1998, Solar cycle evolution of the structure of magnetic clouds in the inner heliosphere. *Geophys. Res. Lett.* **25**(15), 2959. DOI. ADS.
- Mulligan, T., Russell, C.T., Anderson, B.J., Lohr, D.A., Rust, D., Toth, B.A., Zanetti, L.J., Acuna, M.H., Lepping, R.P., Gosling, J.T.: 1999, Intercomparison of NEAR and Wind interplanetary coronal mass ejection observations. *J. Geophys. Res.* **104**(A12), 28217. DOI. ADS.
- Nakagawa, T., Nishida, A., Saito, T.: 1989, Planar magnetic structures in the solar wind. *J. Geophys. Res.* **94**(A9), 11761. DOI. ADS.
- Nakwacki, M.S., Dasso, S., Démoulin, P., Mandrini, C.H., Gulisano, A.M.: 2011, Dynamical evolution of a magnetic cloud from the Sun to 5.4 AU. *Astron. Astrophys.* **535**, A52. DOI. ADS.

- Neugebauer, M., Snyder, C.W.: 1962, Solar Plasma Experiment. *Science* **138**(3545), 1095. DOI. ADS.
- Neugebauer, M., Clay, D.R., Gosling, J.T.: 1993, The origins of planar magnetic structures in the solar wind. *J. Geophys. Res.* **98**(A6), 9383. DOI. ADS.
- Nieves-Chinchilla, T., Colaninno, R., Vourlidas, A., Szabo, A., Lepping, R.P., Boardman, S.A., Anderson, B.J., Korth, H.: 2012, Remote and in situ observations of an unusual Earth-directed coronal mass ejection from multiple viewpoints. *J. Geophys. Res.(Space Physics)* **117**(A6), A06106. DOI. ADS.
- Nieves-Chinchilla, T., Vourlidas, A., Stenborg, G., Savani, N.P., Koval, A., Szabo, A., Jian, L.K.: 2013, Inner Heliospheric Evolution of a “Stealth” CME Derived from Multi-view Imaging and Multipoint in Situ observations. I. Propagation to 1 AU. *Astrophys. J.* **779**(1), 55. DOI. ADS.
- Nieves-Chinchilla, T., Vourlidas, A., Raymond, J.C., Linton, M.G., Al-haddad, N., Savani, N.P., Szabo, A., Hidalgo, M.A.: 2018, Understanding the Internal Magnetic Field Configurations of ICMEs Using More than 20 Years of Wind Observations. *Solar Phys.* **293**(2), 25. DOI. ADS.
- Nieves-Chinchilla, T., Jian, L.K., Balmaceda, L., Vourlidas, A., dos Santos, L.F.G., Szabo, A.: 2019, Unraveling the Internal Magnetic Field Structure of the Earth-directed Interplanetary Coronal Mass Ejections During 1995 - 2015. *Solar Phys.* **294**(7), 89. DOI. ADS.
- Nitta, N.V., Mulligan, T.: 2017, Earth-Affecting Coronal Mass Ejections Without Obvious Low Coronal Signatures. *Solar Phys.* **292**(9), 125. DOI. ADS.
- Odstrcil, D., Pizzo, V.J.: 1999, Distortion of the interplanetary magnetic field by three-dimensional propagation of coronal mass ejections in a structured solar wind. *J. Geophys. Res.* **104**(A12), 28225. DOI. ADS.
- Ogilvie, K.W., Coplan, M.A.: 1995, Solar wind composition. *Reviews of Geophysics* **33**(S1), 615. DOI. ADS.
- Ogilvie, K.W., Desch, M.D.: 1997, The wind spacecraft and its early scientific results. *Advances in Space Research* **20**(4-5), 559. DOI. ADS.

- Ogilvie, K.W., Chornay, D.J., Fritzenreiter, R.J., Hunsaker, F., Keller, J., Lobell, J., Miller, G., Scudder, J.D., Sittler, E.C. Jr., Torbert, R.B., *et al.*: 1995, SWE, A Comprehensive Plasma Instrument for the Wind Spacecraft. *Space Sci. Rev.* **71**, 55. DOI. ADS.
- O’Kane, J., Green, L.M., Davies, E.E., Möstl, C., Hinterreiter, J., Freiherr von Forstner, J.L., Weiss, A.J., Long, D.M., Amerstorfer, T.: 2021a, Solar origins of a strong stealth CME detected by Solar Orbiter. *Astron. Astrophys.* DOI.
- O’Kane, J., Mac Cormack, C., Mandrini, C.H., Démoulin, P., Green, L.M., Long, D.M., Valori, G.: 2021b, The Magnetic Environment of a Stealth Coronal Mass Ejection. *Astrophys. J.* **908**(1), 89. DOI. ADS.
- Owen, C.J., Bruno, R., Livi, S., Louarn, P., Al Janabi, K., Allegrini, F., Amoros, C., Baruah, R., Barthe, A., Berthomier, M., *et al.*: 2020, The Solar Orbiter Solar Wind Analyser (SWA) suite. *Astron. Astrophys.* **642**, A16. DOI. ADS.
- Owens, M.J.: 2006, Magnetic cloud distortion resulting from propagation through a structured solar wind: Models and observations. *J. Geophys. Res.(Space Physics)* **111**(A12), A12109. DOI. ADS.
- Owens, M.J.: 2009, The Formation of Large-Scale Current Sheets within Magnetic Clouds. *Solar Phys.* **260**(1), 207. DOI. ADS.
- Owens, M.J.: 2016, Do the Legs of Magnetic Clouds Contain Twisted Flux-rope Magnetic Fields? *Astrophys. J.* **818**(2), 197. DOI. ADS.
- Owens, M.J., Forsyth, R.J.: 2013, The Heliospheric Magnetic Field. *Living Rev. Sol. Phys.* **10**(1), 5. DOI. ADS.
- Owens, M.J., Lockwood, M., Barnard, L.A.: 2017, Coronal mass ejections are not coherent magnetohydrodynamic structures. *Nature Scientific Reports* **7**, 4152. DOI. ADS.
- Owens, M.J., Cargill, P.J., Pagel, C., Siscoe, G.L., Crooker, N.U.: 2005, Characteristic magnetic field and speed properties of interplanetary coronal mass ejections and their sheath regions. *J. Geophys. Res.(Space Physics)* **110**(A1), A01105. DOI. ADS.

- Palmerio, E., Kilpua, E.K.J., Savani, N.P.: 2016, Planar magnetic structures in coronal mass ejection-driven sheath regions. *Ann. Geophys.* **34**(2), 313. DOI. ADS.
- Palmerio, E., Kilpua, E.K.J., James, A.W., Green, L.M., Pomoell, J., Isavnin, A., Valori, G.: 2017, Determining the Intrinsic CME Flux Rope Type Using Remote-sensing Solar Disk Observations. *Solar Phys.* **292**(2), 39. DOI. ADS.
- Palmerio, E., Kilpua, E.K.J., Möstl, C., Bothmer, V., James, A.W., Green, L.M., Isavnin, A., Davies, J.A., Harrison, R.A.: 2018, Coronal Magnetic Structure of Earth-bound CMEs and In Situ Comparison. *Space Weather* **16**(5), 442. DOI. ADS.
- Parker, E.N.: 1958, Dynamics of the Interplanetary Gas and Magnetic Fields. *Astrophys. J.* **128**, 664. DOI. ADS.
- Paschmann, G., Daly, P.W.: 1998, *Analysis Methods for Multi-Spacecraft Data*. **1**, ESA Publications Division, Noordwijk, The Netherlands. ADS.
- Paschmann, G., Fazakerley, A.N., Schwartz, S.J.: 1998, Moments of Plasma Velocity Distributions. *ISSI Scientific Reports Series* **1**, 125. ADS.
- Patsourakos, S., Vourlidas, A., Török, T., Kliem, B., Antiochos, S.K., Archontis, V., Aulanier, G., Cheng, X., Chintzoglou, G., Georgoulis, M.K., *et al.*: 2020, Decoding the Pre-Eruptive Magnetic Field Configurations of Coronal Mass Ejections. *Space Sci. Rev.* **216**(8), 131. DOI. ADS.
- Pevtsov, A.A., Canfield, R.C., McClymont, A.N.: 1997, On the Subphotospheric Origin of Coronal Electric Currents. *Astrophys. J.* **481**(2), 973. DOI. ADS.
- Phillips, J.L., Bame, S.J., Barnes, A., Barraclough, B.L., Feldman, W.C., Goldstein, B.E., Gosling, J.T., Hoogeveen, G.W., McComas, D.J., Neugebauer, M., *et al.*: 1995, Ulysses solar wind plasma observations from pole to pole. *Geophys. Res. Lett.* **22**(23), 3301. DOI. ADS.
- Plunkett, S.P., Thompson, B.J., St. Cyr, O.C., Howard, R.A.: 2001, Solar source regions of coronal mass ejections and their geomagnetic effects. *J. Atmos. Solar-Terr. Phys.* **63**(5), 389. DOI. ADS.
- Pneuman, G.W., Kopp, R.A.: 1971, Gas-Magnetic Field Interactions in the Solar Corona. *Solar Phys.* **18**(2), 258. DOI. ADS.

- Ratkiewicz, R.: 1992, An analytical solution for the heliopause boundary and its comparison with numerical solutions. *Astron. Astrophys.* **255**(1-2), 383. ADS.
- Reiss, M.A., MacNeice, P.J., Mays, L.M., Arge, C.N., Möstl, C., Nikolic, L., Amerstorfer, T.: 2019, Forecasting the Ambient Solar Wind with Numerical Models. I. On the Implementation of an Operational Framework. *Astrophys. J. Suppl. S.* **240**(2), 35. DOI. ADS.
- Reiss, M.A., MacNeice, P.J., Muglach, K., Arge, C.N., Möstl, C., Riley, P., Hinterreiter, J., Bailey, R.L., Weiss, A.J., Owens, M.J., *et al.*: 2020, Forecasting the Ambient Solar Wind with Numerical Models. II. An Adaptive Prediction System for Specifying Solar Wind Speed near the Sun. *Astrophys. J.* **891**(2), 165. DOI. ADS.
- Richardson, I.G.: 2014, Identification of Interplanetary Coronal Mass Ejections at Ulysses Using Multiple Solar Wind Signatures. *Solar Phys.* **289**(10), 3843. DOI. ADS.
- Richardson, I.G., Cane, H.V.: 1995, Regions of abnormally low proton temperature in the solar wind (1965-1991) and their association with ejecta. *J. Geophys. Res.* **100**(A12), 23397. DOI. ADS.
- Richardson, I.G., Cane, H.V.: 2010, Near-Earth Interplanetary Coronal Mass Ejections During Solar Cycle 23 (1996 - 2009): Catalog and Summary of Properties. *Solar Phys.* **264**(1), 189. DOI. ADS.
- Richardson, J.D., Kasper, J.C., Wang, C., Belcher, J.W., Lazarus, A.J.: 2008a, Cool heliosheath plasma and deceleration of the upstream solar wind at the termination shock. *Nature* **454**(7200), 63. DOI. ADS.
- Richardson, J.D., Liu, Y., Wang, C., McComas, D.J.: 2008b, Determining the LIC H density from the solar wind slowdown. *Astron. Astrophys.* **491**(1), 1. DOI. ADS.
- Richardson, J.D., Belcher, J.W., Garcia-Galindo, P., Burlaga, L.F.: 2019, Voyager 2 plasma observations of the heliopause and interstellar medium. *Nature Astronomy* **3**, 1019. DOI. ADS.
- Riley, P., Crooker, N.U.: 2004, Kinematic Treatment of Coronal Mass Ejection Evolution in the Solar Wind. *Astrophys. J.* **600**(2), 1035. DOI. ADS.

- Riley, P., Linker, J.A., Lionello, R., Mikić, Z., Odstreil, D., Hidalgo, M.A., Cid, C., Hu, Q., Lepping, R.P., *et al.*: 2004, Fitting flux ropes to a global MHD solution: a comparison of techniques. *J. Atmos. Solar-Terr. Phys.* **66**(15-16), 1321. DOI. ADS.
- Robbrecht, E., Patsourakos, S., Vourlidas, A.: 2009, No Trace Left Behind: STEREO Observation of a Coronal Mass Ejection Without Low Coronal Signatures. *Astrophys. J.* **701**(1), 283. DOI. ADS.
- Rouillard, A.P., Lavraud, B., Sheeley, N.R., Davies, J.A., Burlaga, L.F., Savani, N.P., Jacquey, C., Forsyth, R.J.: 2010, White Light and In Situ Comparison of a Forming Merged Interaction Region. *Astrophys. J.* **719**(2), 1385. DOI. ADS.
- Rouillard, A.P., Lavraud, B., Génot, V., Bouchemit, M., Dufourg, N., Plotnikov, I., Pinto, R.F., Sanchez-Diaz, E., Lavarra, M., Penou, M., *et al.*: 2017, A propagation tool to connect remote-sensing observations with in-situ measurements of heliospheric structures. *Planet. Space Sci.* **147**, 61. DOI. ADS.
- Ruffenach, A., Lavraud, B., Owens, M.J., Sauvaud, J.-A., Savani, N.P., Rouillard, A.P., Démoulin, P., Foullon, C., Opitz, A., Fedorov, A., *et al.*: 2012, Multispacecraft observation of magnetic cloud erosion by magnetic reconnection during propagation. *J. Geophys. Res.(Space Physics)* **117**(A9), A09101. DOI. ADS.
- Ruffenach, A., Lavraud, B., Farrugia, C.J., Démoulin, P., Dasso, S., Owens, M.J., Sauvaud, J.-A., Rouillard, A.P., Lynnyk, A., Foullon, C., *et al.*: 2015, Statistical study of magnetic cloud erosion by magnetic reconnection. *J. Geophys. Res.(Space Physics)* **120**(1), 43. DOI. ADS.
- Russell, C.T., Shinde, A.A., Jian, L.: 2005, A new parameter to define interplanetary coronal mass ejections. *Adv. Space Res.* **35**(12), 2178. DOI. ADS.
- Russell, C.T., Gosling, J.T., Zwickl, R.D., Smith, E.J.: 1983, Multiple spacecraft observations of interplanetary shocks: ISEE 3-D plasma measurements. *J. Geophys. Res.* **88**(A12), 9941. DOI. ADS.
- Rust, D.M.: 1994, Spawning and Shedding Helical Magnetic Fields in the Solar Atmosphere. *Geophys. Res. Lett.* **21**(4), 241. DOI. ADS.

- Salman, T.M., Winslow, R.M., Lugaz, N.: 2020, Radial Evolution of Coronal Mass Ejections Between MESSENGER, Venus Express, STEREO, and L1: Catalog and Analysis. *J. Geophys. Res.(Space Physics)* **125**(1), e27084. DOI. ADS.
- Sarkar, R., Gopalswamy, N., Srivastava, N.: 2020, An Observationally Constrained Analytical Model for Predicting the Magnetic Field Vectors of Interplanetary Coronal Mass Ejections at 1 au. *Astrophys. J.* **888**(2), 121. DOI. ADS.
- Savani, N.P., Owens, M.J., Rouillard, A.P., Forsyth, R.J., Davies, J.A.: 2010, Observational Evidence of a Coronal Mass Ejection Distortion Directly Attributable to a Structured Solar Wind. *Astrophys. J. Lett.* **714**(1), L128. DOI. ADS.
- Schatten, K.H., Wilcox, J.M., Ness, N.F.: 1969, A model of interplanetary and coronal magnetic fields. *Solar Phys.* **6**(3), 442. DOI. ADS.
- Schou, J., Antia, H.M., Basu, S., Bogart, R.S., Bush, R.I., Chitre, S.M., Christensen-Dalsgaard, J., Di Mauro, M.P., Dziembowski, W.A., Eff-Darwich, A., *et al.*: 1998, Helioseismic Studies of Differential Rotation in the Solar Envelope by the Solar Oscillations Investigation Using the Michelson Doppler Imager. *Astrophys. J.* **505**(1), 390. DOI. ADS.
- Schwadron, N.A., Bzowski, M.: 2018, The Heliosphere Is Not Round. *Astrophys. J.* **862**(1), 11. DOI. ADS.
- Schwartz, S.J.: 1998, Shock and Discontinuity Normals, Mach Numbers, and Related Parameters. *ISSI Scientific Reports Series* **1**, 249. ADS.
- Schwenn, R.: 1990, In: Schwenn, R., Marsch, E. (eds.) *Large-Scale Structure of the Interplanetary Medium*, 99. ADS.
- Siscoe, G.L., Suey, R.W.: 1972, Significance criteria for variance matrix applications. *J. Geophys. Res.* **77**(7), 1321. DOI. ADS.
- Smith, C.W., L’Heureux, J., Ness, N.F., Acuña, M.H., Burlaga, L.F., Scheifele, J.: 1998, The ACE Magnetic Fields Experiment. *Space Sci. Rev.* **86**, 613. DOI. ADS.
- Smith, E.J.: 2001, The heliospheric current sheet. *J. Geophys. Res.* **106**(A8), 15819. DOI. ADS.

- Spiegel, E.A., Zahn, J.-P.: 1992, The solar tachocline. *Astron. Astrophys.* **265**, 106. ADS.
- Steed, K., Owen, C.J., Démoulin, P., Dasso, S.: 2011, Investigating the observational signatures of magnetic cloud substructure. *J. Geophys. Res.(Space Physics)* **116**(A1), A01106. DOI. ADS.
- Stone, E.C., Cummings, A.C.: 2001, Estimate of the Location of the Solar Wind Termination Shock. In: *International Cosmic Ray Conference* **10**, 4263. ADS.
- Stone, E.C., Frandsen, A.M., Mewaldt, R.A., Christian, E.R., Margolies, D., Ormes, J.F., Snow, F.: 1998, The Advanced Composition Explorer. *Space Sci. Rev.* **86**, 1. DOI. ADS.
- Stone, E.C., Cummings, A.C., McDonald, F.B., Heikkila, B.C., Lal, N., Webber, W.R.: 2005, Voyager 1 Explores the Termination Shock Region and the Heliosheath Beyond. *Science* **309**(5743), 2017. DOI. ADS.
- Stone, E.C., Cummings, A.C., McDonald, F.B., Heikkila, B.C., Lal, N., Webber, W.R.: 2008, An asymmetric solar wind termination shock. *Nature* **454**(7200), 71. DOI. ADS.
- Stone, E.C., Cummings, A.C., Heikkila, B.C., Lal, N.: 2019, Cosmic ray measurements from Voyager 2 as it crossed into interstellar space. *Nature Astronomy* **3**, 1013. DOI. ADS.
- Tayler, R.J.: 1997, *The sun as a star*, Cambridge University Press, Cambridge.
- Thompson, M.J.: 2004, Solar interior: Helioseismology and the Sun's interior. *Astron. Geophys.* **45**(4), 4.21. DOI. ADS.
- Thompson, M.J., Christensen-Dalsgaard, J., Miesch, M.S., Toomre, J.: 2003, The Internal Rotation of the Sun. *Annu. Rev. Astron. Astr.* **41**, 599. DOI. ADS.
- Titov, D.V., Svedhem, H., McCoy, D., Lebreton, J.-P., Barabash, S., Bertaux, J.-L., Drossart, P., Formisano, V., Haeusler, B., Korabely, O.I., *et al.*: 2006, Venus Express: Scientific goals, instrumentation, and scenario of the mission. *Cosmic Research* **44**(4), 334. DOI. ADS.

- Török, T., Kliem, B.: 2005, Confined and Ejective Eruptions of Kink-unstable Flux Ropes. *Astrophys. J. Lett.* **630**(1), L97. DOI. ADS.
- Tousey, R.: 1973, The solar corona. In: *Space Research Conference* **2**, 713. ADS.
- van Ballegooijen, A.A., Martens, P.C.H.: 1989, Formation and Eruption of Solar Prominences. *Astrophys. J.* **343**, 971. DOI. ADS.
- Velli, M.: 1994, From Supersonic Winds to Accretion: Comments on the Stability of Stellar Winds and Related Flows. *Astrophys. J. Lett.* **432**, L55. DOI. ADS.
- Vemareddy, P., Mishra, W.: 2015, A Full Study on the Sun-Earth Connection of an Earth-directed CME Magnetic Flux Rope. *Astrophys. J.* **814**(1), 59. DOI. ADS.
- von Forstner, J.L.F., M., D., Möstl, C., Guo, J., Papaioannou, A., Elftmann, R., Xu, Z., Terasa, J.C., Kollhoff, A., Wimmer-Schweingruber, R.F., et al.: 2021, Radial Evolution of the April 2020 Stealth Coronal Mass Ejection between 0.8 and 1 AU: A Comparison of Forbush Decreases at Solar Orbiter and Earth. *Astron. Astrophys.* DOI.
- Vourlidas, A.: 2014, The flux rope nature of coronal mass ejections. *Plasma Physics and Controlled Fusion* **56**(6), 064001. DOI. ADS.
- Vourlidas, A., Sanchez Andrade-Nuño, B., Landi, E., Patsourakos, S., Teriaca, L., Schühle, U., Korendyke, C.M., Nestoras, I.: 2010, The Structure and Dynamics of the Upper Chromosphere and Lower Transition Region as Revealed by the Subarcsecond VAULT Observations. *Solar Phys.* **261**(1), 53. DOI. ADS.
- Vourlidas, A., Lynch, B.J., Howard, R.A., Li, Y.: 2013, How Many CMEs Have Flux Ropes? Deciphering the Signatures of Shocks, Flux Ropes, and Prominences in Coronagraph Observations of CMEs. *Solar Phys.* **284**(1), 179. DOI. ADS.
- Vršnak, B., Amerstorfer, T., Dumbović, M., Leitner, M., Veronig, A.M., Temmer, M., Möstl, C., Amerstorfer, U.V., Farrugia, C.J., Galvin, A.B.: 2019, Heliospheric Evolution of Magnetic Clouds. *Astrophys. J.* **877**(2), 77. DOI. ADS.
- Wang, C., Du, D., Richardson, J.D.: 2005, Characteristics of the interplanetary coronal mass ejections in the heliosphere between 0.3 and 5.4 AU. *J. Geophys. Res.(Space Physics)* **110**(A10), A10107. DOI. ADS.

- Wang, Y., Chen, C., Gui, B., Shen, C., Ye, P., Wang, S.: 2011, Statistical study of coronal mass ejection source locations: Understanding CMEs viewed in coronagraphs. *Journal of Geophysical Research (Space Physics)* **116**(A4), A04104. DOI. ADS.
- Wang, Y., Zhuang, B., Hu, Q., Liu, R., Shen, C., Chi, Y.: 2016, On the twists of interplanetary magnetic flux ropes observed at 1 AU. *J. Geophys. Res.(Space Physics)* **121**(10), 9316. DOI. ADS.
- Wang, Y., Shen, C., Liu, R., Liu, J., Guo, J., Li, X., Xu, M., Hu, Q., Zhang, T.: 2018, Understanding the Twist Distribution Inside Magnetic Flux Ropes by Anatomizing an Interplanetary Magnetic Cloud. *J. Geophys. Res.(Space Physics)* **123**(5), 3238. DOI. ADS.
- Webb, D.F., Howard, T.A.: 2012, Coronal Mass Ejections: Observations. *Living Rev. Sol. Phys.* **9**(1), 3. DOI. ADS.
- Webber, W.R., McDonald, F.B.: 2013, Recent Voyager 1 data indicate that on 25 August 2012 at a distance of 121.7 AU from the Sun, sudden and unprecedented intensity changes were observed in anomalous and galactic cosmic rays. *Geophys. Res. Lett.* **40**(9), 1665. DOI. ADS.
- Wei, F., Liu, R., Fan, Q., Feng, X.: 2003, Identification of the magnetic cloud boundary layers. *J. Geophys. Res.(Space Physics)* **108**(A6), 1263. DOI. ADS.
- Wenzel, K.P., Marsden, R.G., Page, D.E., Smith, E.J.: 1992, The ULYSSES Mission. *Astron. Astrophys. Suppl.* **92**, 207. ADS.
- Wilcox, J.M., Ness, N.F.: 1965, Quasi-Stationary Corotating Structure in the Interplanetary Medium. *J. Geophys. Res.* **70**(23), 5793. DOI. ADS.
- Winslow, R.M., Lugaz, N., Philpott, L.C., Schwadron, N.A., Farrugia, C.J., Anderson, B.J., Smith, C.W.: 2015, Interplanetary coronal mass ejections from MESSENGER orbital observations at Mercury. *J. Geophys. Res.(Space Physics)* **120**(8), 6101. DOI. ADS.
- Winslow, R.M., Lugaz, N., Schwadron, N.A., Farrugia, C.J., Yu, W., Raines, J.M., Mays, M.L., Galvin, A.B., Zurbuchen, T.H.: 2016, Longitudinal conjunction between MESSENGER and STEREO A: Development of ICME complexity through stream interactions. *J. Geophys. Res.(Space Physics)* **121**(7), 6092. DOI. ADS.

- Wood, B.E., Howard, R.A.: 2009, An Empirical Reconstruction of the 2008 April 26 Coronal Mass Ejection. *Astrophys. J.* **702**(2), 901. DOI. ADS.
- Wood, B.E., Karovska, M., Chen, J., Brueckner, G.E., Cook, J.W., Howard, R.A.: 1999, Comparison of Two Coronal Mass Ejections Observed by EIT and LASCO with a Model of an Erupting Magnetic Flux Rope. *Astrophys. J.* **512**(1), 484. DOI. ADS.
- Wood, B.E., Wu, C.-C., Lepping, R.P., Nieves-Chinchilla, T., Howard, R.A., Linton, M.G., Socker, D.G.: 2017, A STEREO Survey of Magnetic Cloud Coronal Mass Ejections Observed at Earth in 2008-2012. *Astrophys. J. Suppl. S.* **229**(2), 29. DOI. ADS.
- Xiao, C.J., Pu, Z.Y., Ma, Z.W., Fu, S.Y., Huang, Z.Y., Zong, Q.G.: 2004, Inferring of flux rope orientation with the minimum variance analysis technique. *J. Geophys. Res.(Space Physics)* **109**(A11), A11218. DOI. ADS.
- Yurchyshyn, V.: 2008, Relationship between EIT Posteruption Arcades, Coronal Mass Ejections, the Coronal Neutral Line, and Magnetic Clouds. *Astrophys. J. Lett.* **675**(1), L49. DOI. ADS.
- Zhang, J., Cheng, X., Ding, M.-D.: 2012, Observation of an evolving magnetic flux rope before and during a solar eruption. *Nat. Commun.* **3**, 747. DOI. ADS.
- Zhang, T.L., Berghofer, G., Magnes, W., Delva, M., Baumjohann, W., Biernat, H., Lichtenegger, H., Nakamura, R., Schwingenschuh, K., Auster, H.-U., et al.: 2007, MAG: the fluxgate magnetometer of Venus express. *ESA Special Publication* **1295**(10).
- Zhang, Y., Sun, W., Feng, X.S., Deehr, C.S., Fry, C.D., Dryer, M.: 2008, Statistical analysis of corotating interaction regions and their geoeffectiveness during solar cycle 23. *J. Geophys. Res.(Space Physics)* **113**(A8), A08106. DOI. ADS.
- Zurbuchen, T.H., Richardson, I.G.: 2006, In-Situ Solar Wind and Magnetic Field Signatures of Interplanetary Coronal Mass Ejections. *Space Sci. Rev.* **123**(1-3), 31. DOI. ADS.

Appendix

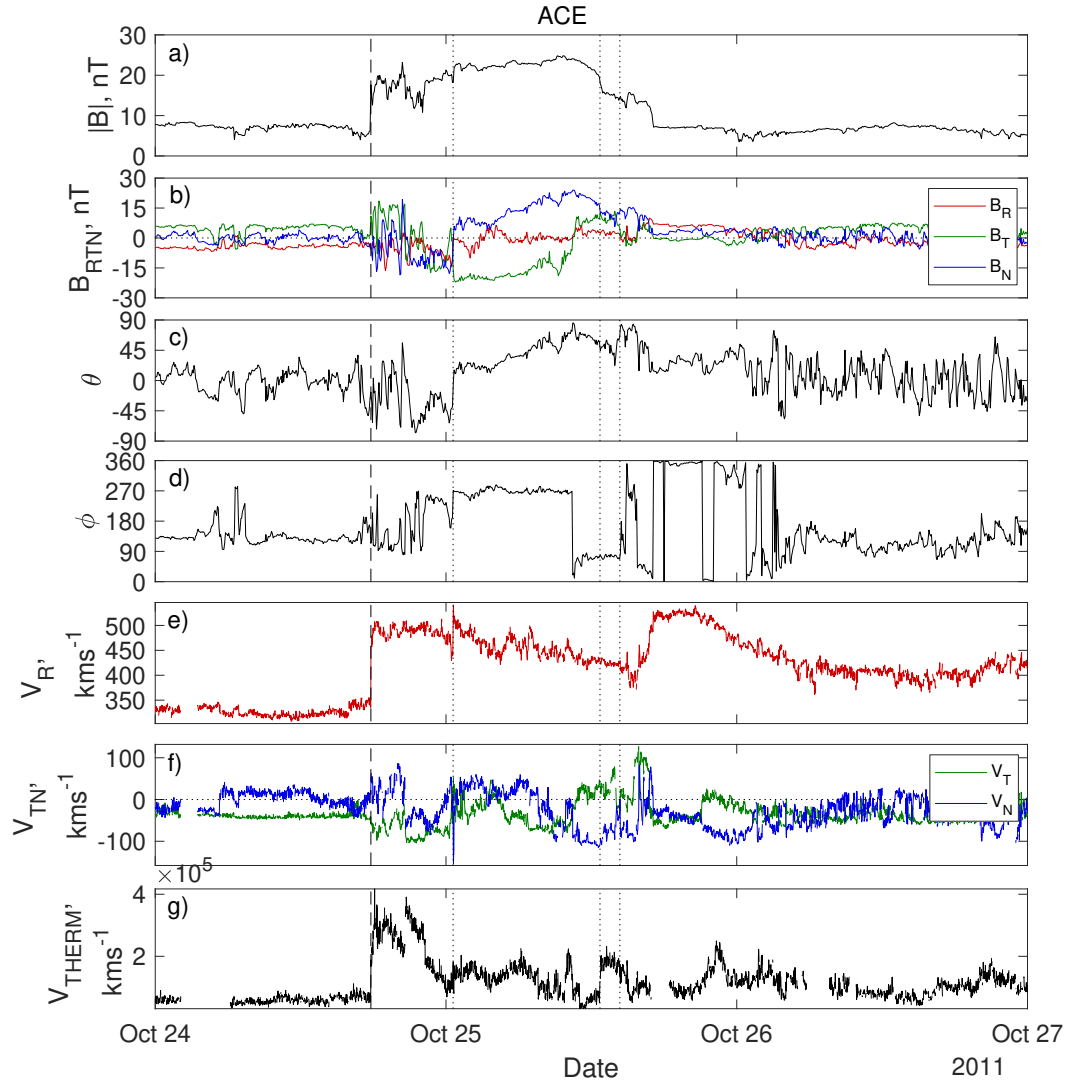


Figure 6.1: In situ magnetic field (1 minute resolution) signatures observed by ACE displayed in the same format as Figure 4.2.

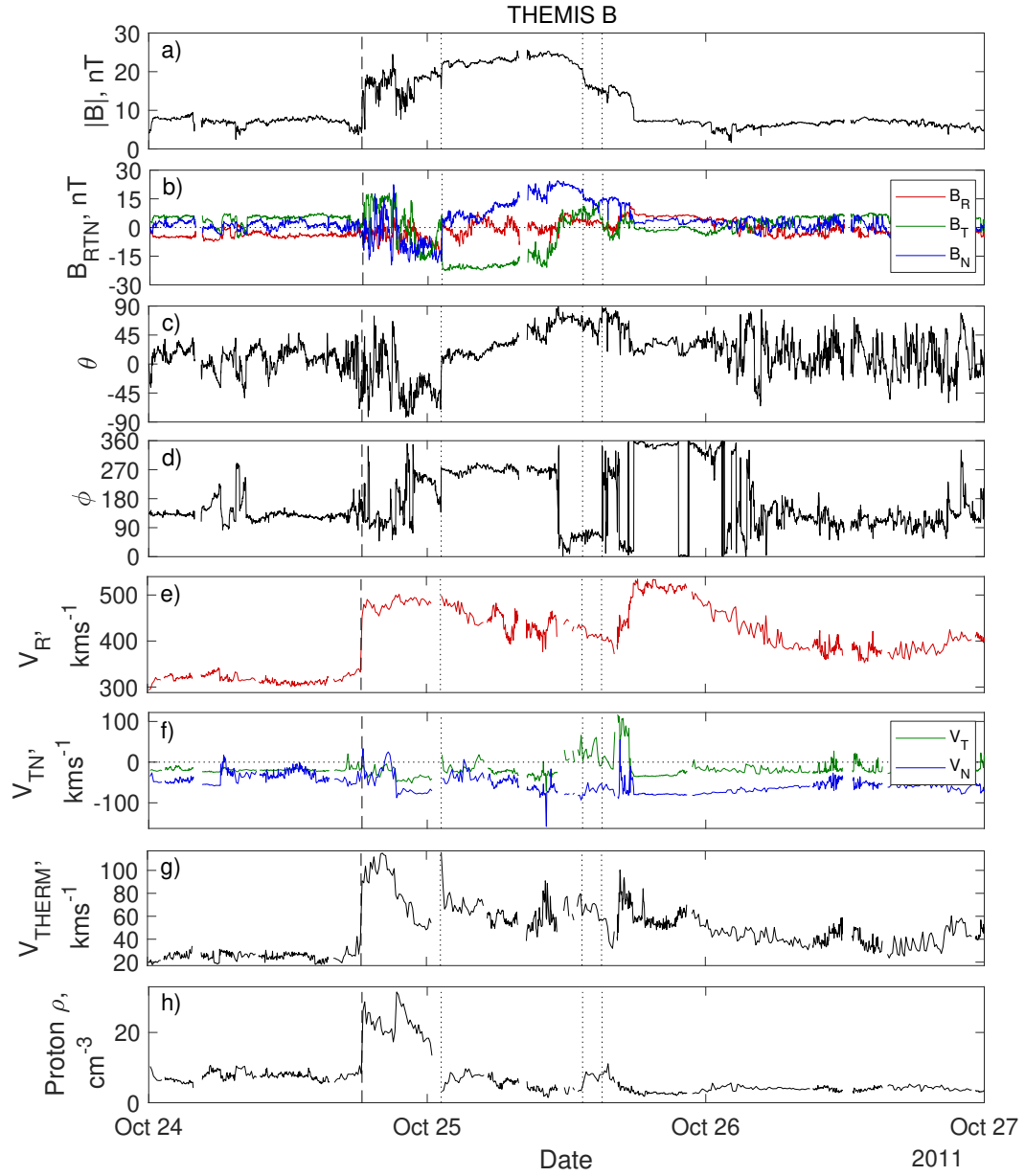


Figure 6.2: In situ magnetic field (1 minute resolution) signatures observed by THEMIS B displayed in the same format as Figure 4.2.

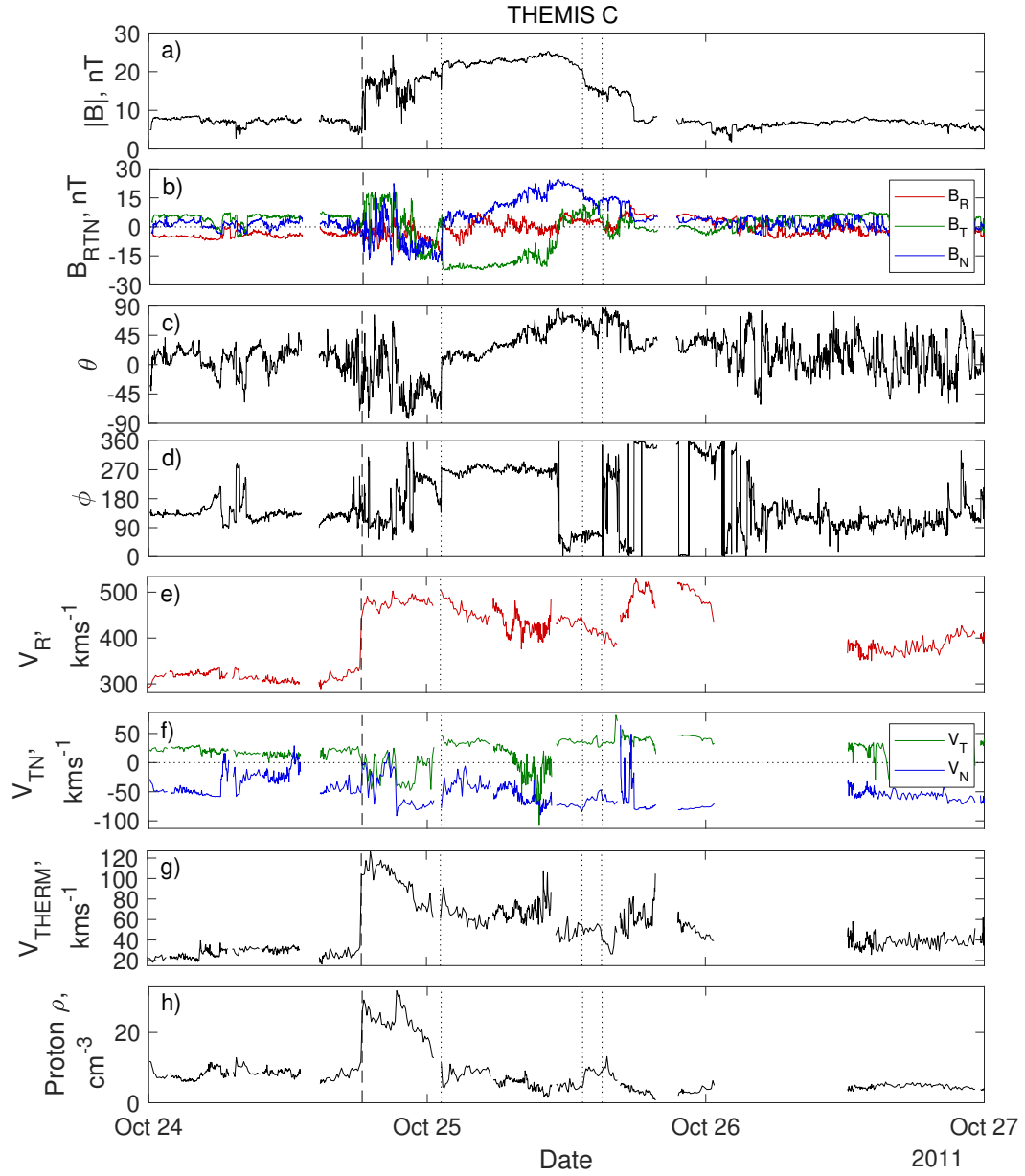


Figure 6.3: In situ magnetic field (1 minute resolution) signatures observed by THEMIS C displayed in the same format as Figure 4.2.

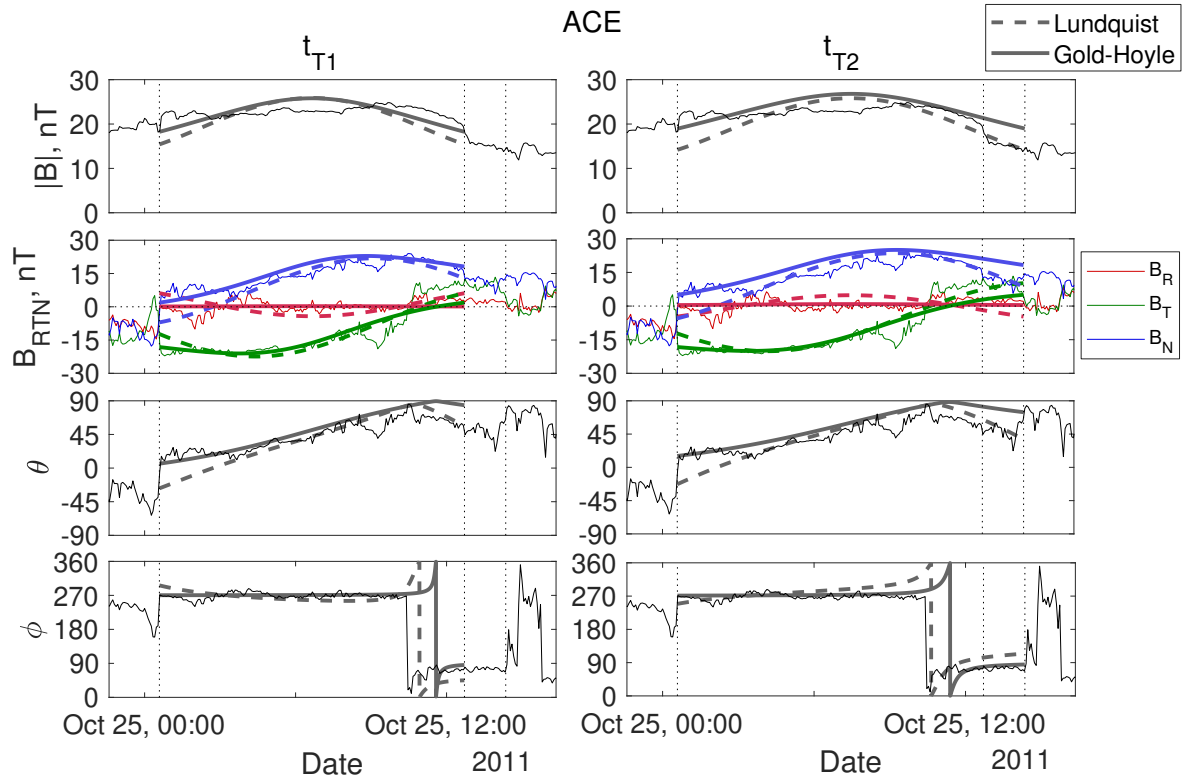


Figure 6.4: Force-free flux rope models fitted to the in situ magnetic field signatures observed by ACE, displayed in the same format as Figure 4.4.

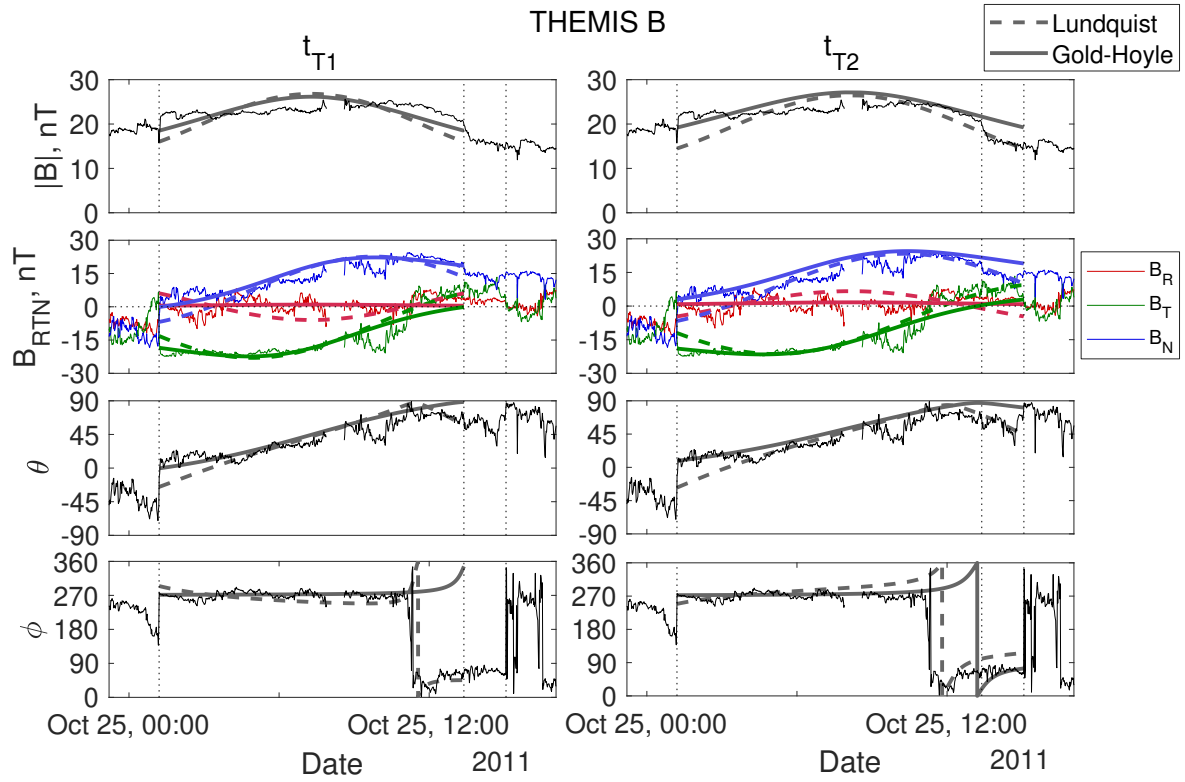


Figure 6.5: Force-free flux rope models fitted to the in situ magnetic field signatures observed by THEMIS B, displayed in the same format as Figure 4.4.

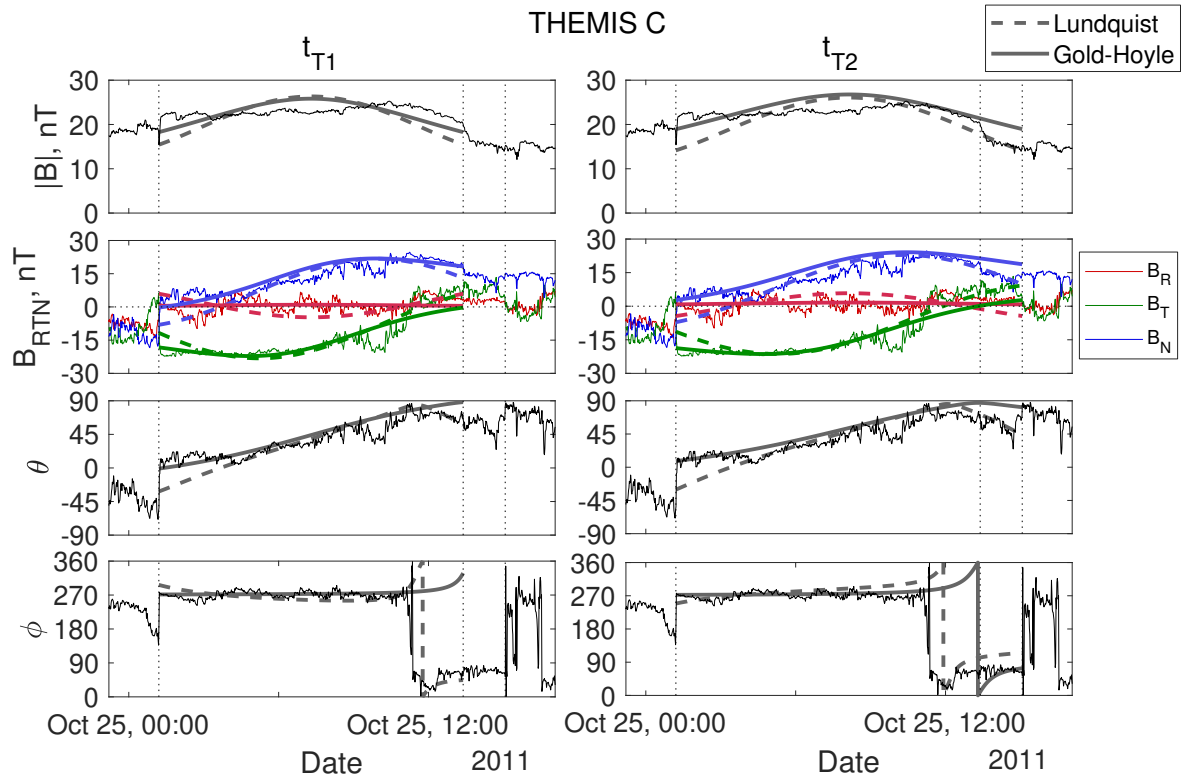


Figure 6.6: Force-free flux rope models fitted to the in situ magnetic field signatures observed by THEMIS C, displayed in the same format as Figure 4.4.