Statistical Study of Interplanetary Coronal Mass Ejections with Strong Magnetic Fields

Matthew E. Murphy

Follow this and additional works at: https://scholarworks.rit.edu/theses

Recommended Citation

This Thesis is brought to you for free and open access by RIT Scholar Works. It has been accepted for inclusion in Theses by an authorized administrator of RIT Scholar Works. For more information, please contact ritscholarworks@rit.edu.
Statistical Study of Interplanetary Coronal Mass Ejections with Strong Magnetic Fields

by

Matthew E. Murphy

B.S., Seattle University, 2010

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the Chester F. Carlson Center for Imaging Science College of Science Rochester Institute of Technology

August 13, 2015

Signature of the Author

Accepted by

Coordinator, M.S. Degree Program Date
The M.S. Degree Thesis of Matthew E. Murphy has been examined and approved by the thesis committee as satisfactory for the thesis required for the M.S. degree in Imaging Science.

Dr. Roger Dube, Thesis Advisor
Date

Dr. Joel Kastner, Committee Member
Date

Dr. Anthony Vodacek, Committee Member
Date
Contents

List of Figures 7

Acronyms 12

Abstract 15

1 Introduction 21

2 Background and Motivation 27

2.1 Space Weather .................. 27

2.1.1 Effects of Space Weather .... 27

2.1.2 CMEs, SEPs, Solar Flares and Sources . . . . 31
2.1.3 Coordinate System ................. 33
2.2 Space Weather Prediction Center ........ 34
  2.2.1 Initial parameters ................. 35
2.3 Space Weather Research Center and CCMC .... 38
2.4 Spacecraft and Instrumentation Overview .... 39
  2.4.1 STEREOs A and B ................. 41
  2.4.2 Earth directed events ............... 47
2.5 Empirical Relationships .................. 50
  2.5.1 Travel time and Initial Speed Literature Review 50
  2.5.2 In Situ Magnetic field and Speed Literature Review ............... 56
2.6 Problem Statement ....................... 60

3 Theory ........................................ 62
  3.1 Relationships between solar storm parameters .... 62
    3.1.1 Speed and Magnetic field ............... 63
    3.1.2 Distance, Time, velocity and acceleration .... 63
3.1.3 SHARP Solar source Magnetic field ....... 64

3.2 Geoeffectiveness (and magnetic field Bz) ....... 65

3.3 CME Groups ........................................... 66

3.4 Summary ................................................ 72

4 Method .................................................... 74

4.1 Plan of Study Overview and Eureqa ............. 74

4.2 Data Collection ......................................... 80

4.2.1 Matching ICMEs to Strong IMFs and Data Sources ...................................... 80

4.3 Analysis ................................................... 83

4.3.1 Groupings and the Magnetic Cloud Relationship 83

4.3.2 Validation of Eureqa ................................. 84

4.3.3 Multi-dimensional analysis and trends using Eureqa ................................... 86

5 Results and Discussion ................................. 87
5.1 Collection and Preparation of Data ............... 87
5.1.1 Collected Data Summary and Discussion . . . 91
5.2 Analysis results ........................................ 92
5.2.1 Groupings and the Magnetic Cloud Relationship 92
5.2.2 Validation of Eureqa ................................. 97
5.2.3 Multi-Dimensional analysis: Initial CME Speed
and SHARP parameters using Eureqa ........... 101

6 Summary and Suggested Further Study .......... 107

7 Bibliography ................................................. 110
List of Figures

1.1 CME carrying the Sun’s magnetic field. This figure from a space physics article by Zhou et al. (2012) . . 22

2.1 Space Weather effects. Figure is courtesy of NASA . 29

2.2 Effects of Space Weather on Satellites. Figure from a report by D. Baker et al. (2006) [1] . . . . . . . . . . 30

2.3 Stonyhurst Heliographic longitude and latitude orientation on the Sun. Figure is from a paper by W. Thompson [2]. . . . . . . . . . . . . . . . . . . . . . 33

2.4 Coronagraph image observed from STEREO B. Figure courtesy of NASA. . . . . . . . . . . . . . . . . . . . . . 36
2.5 Positions of SOHO (and ACE) and STEREO A and B on November 24, 2009. Figure from the *The Sun Today* website [3].

2.6 STEREO A and B spacecraft and instrumentation. Figure is from a user manual by A. Davis [4].

2.7 Positions STEREO A and B on August 1, 2010. Figure courtesy of NASA [5].

2.8 Positions STEREO A and B on July 1, 2012. Figure courtesy of NASA [5].

2.9 Positions STEREO A and B on July 1, 2014. Figure courtesy of NASA [5].

2.10 Positions STEREO A and B on February 18, 2015. Figure courtesy of NASA [5].

2.11 HARP regions on SDO/HMI imagery. From a paper by M. G. Bobra et al. (2014) [6].
2.12 In situ Max Magnetic Field and Speed. From a paper by Cane and Richardson [7].

3.1 Group 1 CME example. From paper by Jian et al. (2006) [8].

3.2 Group 2 CME example. From paper by Jian et al. (2006) [8].

3.3 Group 3 CME example. From paper by Jian et al. (2006) [8].

3.4 Interpretive sketch of all groups. From paper by Jian et al. (2006) [8].

4.1 Eureqa enter data window. Screen shot from Eureqa software [9].

4.2 Eureqa prepare data window. Screen shot from Eureqa software [9].

4.3 Eureqa prepare data window. Screen shot from Eureqa software [9].
4.4 Eureqa results window. Screen shot from Eureqa software [9].

5.1 Relative Locations on Sun for each event. The blue markers are STEREO B, the orange are ACE and the red are STEREO A.

5.2 Group 1 in 2013 max CME speed and magnetic field at 1 AU. The line is \( y = 0.0362x - 1.495 \) with an \( R^2 = 0.696 \).

5.3 Group 2 in 2013 max CME speed and magnetic field at 1 AU. The line is \( y = 0.0375x - 3.486 \) with an \( R^2 = 0.209 \).

5.4 Group 3 in 2013 max CME speed and magnetic field at 1 AU. With a line of \( y = 0.0264x + 1.134 \) and an \( R^2 = 0.165 \).

5.5 Group 1 CMEs over the years 2010 to 2013. With a line of \( y = 0.0326x - 0.4253 \) and a \( R^2 = 0.452 \).
5.6 The blue unfilled circles represent the Gopalswamy ESA approximation for events with $V > 500 km/s$ [10]. The red filled squares are the new model found using Eureqa. Both use the speed and travel time data seen in subsection 5.1.1. ......... 100

5.7 The predicted magnetic field at ACE versus the actual measured magnetic field. ............... 103

5.8 The predicted magnetic field at ACE versus the actual measured magnetic field. ............... 105
Acronyms

**ACE** Advanced Composition Explorer. 23

**ADAPT** Air Force data assimilative photospheric flux transport.

  108

**AU** astronomical unit. 24

**B** magnetic field. 16

**B_z** Z component of the magnetic field \(B\). 23

**CAT** CME Analysis Tool. 81

**CCMC** Community Coordinated Modeling Center. 38

12
CME  Coronal Mass Ejection. 16

DONKI  Database Of Notifications, Knowledge, Information. 81

ECA  Estimated CME Arrival. 52

ESA  Estimated Shock Arrival. 52

EUVI  extreme ultraviolet. 39

GOES  Geostationary Operational Environmental Satellites. 25

HMI  Helioseismic and Magnetic Imager. 25

IMF  Interplanetary Magnetic Field. 41

IMPACT  In situ Measurements of Particles and CME Transients. 24

IPS  interplanetary shocks. 54

L1  first Lagrangian point. 23
nT nanoteslas. 16

**PLASTIC** Plasma and Suprathermal Ion Composition. 82

**SDO** Solar Dynamics Observatory. 25

**SECCHI** Sun Earth Connection Coronal and Heliospheric Investigation. 24

**SEP** Solar Energetic Particle. 16

**SHARP** Space-Weather HMI Active Region Patches. 48

**SOHO** Solar and Heliospheric Observatory. 23

**STEREO A and B** Solar TErestrial RElations Observatory Ahead and Behind. 23

**SWPC** Space Weather Prediction Center. 34

**SWRC** Space Weather Research Center. 38
WSA-Enlil Wang, Sheeley, and Arge-Sumerian god of storms and wind. 36
Statistical Study of Interplanetary Coronal Mass Ejections with Strong Magnetic Fields

by
Matthew E. Murphy

Submitted to the
Chester F. Carlson Center for Imaging Science
in partial fulfillment of the requirements
for the Master of Science Degree
at the Rochester Institute of Technology

Abstract

Coronal Mass Ejections (CMEs) with strong magnetic fields \((B)\) are typically associated with significant Solar Energetic Particle (SEP) events, high solar wind speed and solar flare events. Successful prediction of the arrival time of a CME at Earth is required to maximize the time available for satellite, infrastructure, and space travel programs to take protective action against the coming flux of high-energy particles. It is known that the magnetic field strength of a CME is linked to the strength of a geomagnetic storm on Earth. Unfortunately, the correlations between strong magnetic field CMEs from the entire sun (especially from the far side or non-Earth facing side of the sun) to SEP and flare events, solar source regions and other relevant solar variables are not well known. New correlation studies using an artificial intelligence engine (Eureqa) were performed to study CME events with magnetic field strength readings over 30 nanoteslas (nT) from January 2010 to October 17, 2014. This thesis presents the results of this study, validates Eureqa to obtain previously published results, and presents previously unknown functional relationships between solar source magnetic field data, CME initial speed and the CME magnetic field. These new results
enable the development of more accurate CME magnetic field predictions and should help scientists develop better forecasts thereby helping to prevent damage to humanity’s space and Earth assets.

Disclaimer: the views expressed herein are those of the author and do not reflect the official policy or position of the U.S. Air Force, Department of Defense, or the U.S. Government.
Acknowledgements

I would like to acknowledge my adviser Dr. Roger Dube who first introduced me to this fascinating topic at a presentation on the 1859 Carrington event and solar storms. He also introduced me to the software analysis tool Eureqa which was a huge part of this research. He also provided great guidance during my studies. I’d also like to acknowledge my committee members Dr. Joel Kastner and Dr. Tony Vodacek. Also my contact at NASA/SWRC Dr. Yihua Zheng was very helpful in my research and gave me the idea to study strong magnetic field CMEs from all around the Sun. She also provided guidance and information during weekly phone calls and emails.

Attending the Space Weather Workshop in Boulder, CO was very helpful. While there, Captain William Frey, Captain Paul Domm, other attendees and presenters provided lots of insight. Captain Frey also gave me a tour of the SWPC which was very educational, interesting and insightful. At SWPC I was able to meet with operational space weather analysts. These space weather analysts also provided
a lot of insight (so thanks also to SWPC). Also thanks to all the members of the space weather community that helped me along the way.

I would also like to acknowledge all the folks (faculty, colleagues and staff) at RIT Chester F. Carlson Center for Imaging Science that were helpful such as Cindy Schultz, Beth Lockwood and Sue Chan. I would like to thank the US Air Force and my AF RIT colleagues such as Captain Doug Macdonald and our AFIT CIP Liaison Officer Major Oesa Weaver. Big thanks to Sara Smith and her Yorkshire Terrier Kenzie. Also big thanks to my mother Teresa, father John and brother William. Thanks to all my other family and friends that helped make all this possible!
I would like to especially dedicate this work to my mother Teresa, the best mom ever! And also to the best dad and bro, to my father John and my brother William. Thank you so much for always being there for me family!
Chapter 1

Introduction

CMEs are massive solar storms that are difficult to predict. When a CME occurs it carries with it the magnetic field of the Sun as can be seen in figure 1.1 [11]
Earth directed CMEs and related events (SEPs and flares) can cause severe issues to power grids on Earth, and adverse effects on spacecraft and astronauts. Power grid issues on Earth happen when the CME storm is geoeffective. The more geoeffective the CME, the greater the geomagnetic storm on Earth. Storms tend to be geoeffec-
tive particularly when the magnetic field is oriented predominantly southward (negative $B_z$)[12]. CMEs with southward pointing magnetic fields are further attracted to the Earth as they encounter the Earth’s northward pointing magnetic field, so the effect of the storm is not mitigated in any way as they are for CMEs with northward-oriented magnetic fields.

Data related to CME events can be obtained from a variety of sources. Remote sensing is used on coronagraphic images to get parameters such as speed, width and direction of these large plasma clouds when they first emerge from the sun. A coronagraph image can be seen in section 2.2.1 in figure 2.4. In situ measurements can also be made at spacecraft in the path of the CMEs. The Solar TERrestriAL RELations Observatory Ahead and Behind (STEREO A and B) spacecraft [13] combined with the Advanced Composition Explorer (ACE) [14] and Solar and Heliospheric Observatory (SOHO) [15] spacecraft positioned near the first Lagrangian point (L1) pro-
vide a 360° view of the sun. A Lagrangian point (as applied in this study) is a gravitational point in interplanetary space in which a spacecraft can orbit around. L1 is at a point between the Sun and the Earth (at approximately 0.1 astronomical unit (AU) away from the Earth) where the Sun’s and Earth’s gravity is balanced by the centripetal force of the spacecraft. One AU is the distance between the Sun and Earth.

The magnetic field strength measurements originate from magnetometer sensors on the ACE and STEREO spacecraft. On STEREO A and B (described later in this thesis), the instrument is known as the In situ Measurements of Particles and CME Transients (IMPACT) [13]. This IMPACT instrument also monitors SEP levels [13]. Also on-board the STEREO spacecraft is the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) instrumentation. SECCHI has coronagraph cameras and extreme ultraviolet light cameras. These cameras give the ability to monitor CMEs
from the solar source. This imagery was studied to provide the aforementioned information about the CME source region, speed, direction and etc. The combined capabilities of the ACE and SOHO spacecraft at L1 can match the aforementioned capabilities of the STEREO A and B spacecraft. Additional spacecraft and capabilities for Earth directed events include the Geostationary Operational Environmental Satellites (GOES) which can give a measure of solar flare strength and the Solar Dynamics Observatory (SDO) spacecraft which has the Helioseismic and Magnetic Imager (HMI) instrument on board. The HMI instrument can give measurements of the solar source magnetic field.

More research is needed to analyze past solar storm event parameters from the aforementioned spacecraft in order to better predict and understand future solar storm events. Better prediction allows for preventative safeguarding with minimal mission interruption of space assets. Further, it will allow for the prevention of disastrous
power outages on Earth. Additionally, better forecasting of these events will reduce solar storm related health and safety hazard risks to astronauts and Mars colonists.
Chapter 2

Background and Motivation

2.1 Space Weather

2.1.1 Effects of Space Weather

CMEs with strong magnetic fields are typically associated with SEP and solar flare events. Space weather (CMEs, SEPs and solar flares)
can damage spacecraft, cause geomagnetic storms that can knock out power grids on Earth, cause radio blackouts, and threaten the health and safety of astronauts [16]. This is especially true of CMEs with strong magnetic fields. The magnetic field strength of a CME is linked to the strength of a geomagnetic storm on Earth, particularly (as previously explained) when the magnetic field is predominantly southward [12] Some of the effects of space weather can be seen in figure 2.1 [17]
Space weather storms can cause multiple problems on Earth as can be seen in figure 2.1. Spacecraft can be affected as seen in figure 2.2 [1]
There have been a number of storms that have hit earth. One storm in 1989 caused radio interference, power blackouts in Quebec,
power issues in North America, satellites lost control and experienced anomalies [18]. The Halloween storms of 2003 caused a power outage in Sweden and interfered with satellite communications [19]. A stronger storm (which have occurred in recent history such as the Carrington event in 1859) could cause much more damage and chaos. If a Carrington sized event happened today, widespread power outages and damage to satellites could occur, GPS could be interrupted, the damages could cost 1 to 2 trillion dollars and the effects could be felt for years [19].

2.1.2 CMEs, SEPs, Solar Flares and Sources

CMEs are large bursts of solar plasma from the Sun’s corona [20]. CMEs can be described by a number of parameters such as magnetic (B) field, speed, direction, width and others. CMEs are associated with SEPs, solar flares, and the history of their solar source regions. CMEs speeds can travel as fast as 3000 km/s [21]. In a solar flare,
the Sun sends out bursts of X-rays, gamma rays and etc. SEPs are radiation events. Charged particles from the Sun travel on the Sun’s magnetic field lines. There are three main kinds of solar sources: filaments, active regions, and coronal holes.
2.1.3 Coordinate System

Stonyhurst Heliographic coordinate system

The coordinate system used in this paper is the Stonyhurst Heliographic coordinate system. Figure 2.3 [2] gives the positive orientation of the latitude and longitude used in this coordinate system.

Figure 2.3: Stonyhurst Heliographic longitude and latitude orientation on the Sun. Figure is from a paper by W. Thompson [2].
The solar equator and the Earth’s central meridian are at the origin [2]. Thus, it remains fixed with respect to the Earth while the sun rotates underneath [2]. One thing to note is that different latitudes on the Sun rotate at different rates. This differential rotation of the Sun as a function of latitude complicates the development of models and the analysis of CME data.

2.2 Space Weather Prediction Center

The Space Weather Prediction Center (SWPC) is a 24/7 manned operational center that monitors the sun. SWPC will send out warnings when a severe Space Weather event is predicted. In order to make these predictions, observations and measurements are taken of solar events such as CMEs.
2.2.1 Initial parameters

As soon as a CME becomes visible on a coronagraph the analysts at SWPC (and other solar observatory stations) can measure the speed, direction and width of a CME using a CME analysis tool. The STEREO and SOHO spacecraft have coronagraph instruments on board. A coronagraph is a telescope that has an occulting disk in it that blocks out the bright sun (making an artificial eclipse) to make coronal mass ejections visible. The STEREO spacecraft use white-light coronagraphs. See figure 2.4 [22].
Once the observations are made, these initial parameters are entered into (usually) a physics based model such as the WSA-Enlil model. The WSA-Enlil model is named after three space weather sci-
entists Wang-Sheeley-Arge (WSA) and the Sumerian god of storms and wind (Enlil) [23] The model consists of two parts. The first part uses observations of the solar surface magnetic field to make an approximation of the ambient solar wind [24]. The second part consists of inputting the initial CME parameters (speed, size, and direction) [24].

The CME parameters are input into the existing solar wind approximation to give an estimate of the CME’s arrival time, duration and intensity [24]. An accurate magnetic field intensity prediction for 1 AU is not known at this time as magnetic field relationships are an active area of research. The magnetic field of the CME is not known until the CME passes through the ACE spacecraft at 0.1 AU away from the Earth. This distance provides only a 30 minute warning. An example of the in situ magnetic field measurements of a CME as it passes ACE can be seen in section 3.3 in figures 3.1 thru 3.3. Any correlation that can be made between the magnetic
field of a CME and the initial parameters (speed, width, direction etc.) would provide a considerably larger amount of lead-time to space weather forecasters (and provide an additional input into the WSA-ENLIL model).

2.3 Space Weather Research Center and CCMC

The Space Weather Research Center (SWRC) is part of NASA and is dedicated to improving our understanding of space weather events. One important aspect of this center is to improve forecasting abilities. SWRC is a sub-team of the Community Coordinated Modeling Center (CCMC) and provides space weather services to NASA and prototypes new models, procedures and forecasting techniques [25][26].
2.4 Spacecraft and Instrumentation Overview

There are a number of spacecraft whose data are considered in this study. Each spacecraft has a suite of instrumentation on board. The following sensors (used in this study) measure in situ parameters as the CME passes the spacecraft: magnetic field sensors, SEP particle flux sensors and solar wind velocity sensors. The following are imaging instruments that observe the CME or the CME’s solar source region: white-light coronagraph cameras (observe CMEs), and extreme ultraviolet (EUVI) light cameras of multiple wavelengths (observe CME source regions). Wavelengths used in this study to observe the CME solar source regions are: 193/195 Å (Fe XII), 304 Å (He II), and 6173 Å (Fe I). The 193/195 Å (Fe XII) wavelength observes the Sun’s corona. The 304 Å (He II) wavelength observes the light that is emitted from the chromosphere and transition region on the Sun. The 6173 Å (Fe I) wavelength observes the photosphere and the solar source vector magnetic field.
The spacecraft that provide the data used in this paper are at various positions orbiting the sun. Figure 2.5 [3] summarizes most of the spacecraft considered in this work.

Figure 2.5: Positions of SOHO (and ACE) and STEREO A and B on November 24, 2009. Figure from the *The Sun Today* website [3].

SOHO and ACE are at L1. The positions of STEREO A and B change relative to the Earth throughout this study. Figures 2.6 thru 2.10 show positions of STEREO A and B relative to Earth at some various points throughout the study.
2.4.1 STEREOs A and B

The STEREO spacecraft can be seen in figure 2.6 [4]

Figure 2.6: STEREO A and B spacecraft and instrumentation. Figure is from a user manual by A. Davis [4].

The MAG instrument as seen on figure 2.6 is what detects the Interplanetary Magnetic Field (IMF) events. STEREO A and B are almost identical and have the same capabilities. The main purpose of the STEREO spacecraft is to understand the three-dimensional nature of the Sun’s corona and in particular the eruptions of the Sun’s corona (CMEs) [13]. STEREO A and B provide data from the
far-side of the Sun (from such instruments as IMPACT as previously described in chapter 1) and views of the far-side Sun (from SECCHI also as previously described in chapter 1) previously only taken from the Earth’s (near-side) perspective

![Figure 2.7: Positions STEREO A and B on August 1, 2010. Figure courtesy of NASA [5].](image-url)
Figure 2.7 [5] is the position of the spacecraft at the first (greater than 30 nT) event of this study. On August 3, 2010, a greater than 30nT interplanetary magnetic field event measured at STEREO B was also seen at the ACE spacecraft. It is interesting to note that the ACE spacecraft did not observe a magnetic field greater than 30nT.
Figure 2.8: Positions STEREO A and B on July 1, 2012. Figure courtesy of NASA [5].

Figure 2.8 [5] shows the positions of the spacecraft at roughly the midpoint of the study. STEREO B would measure a greater than 30nT event in roughly this position. Approximately 20 days after this point, STEREO A observed the largest magnetic field event of this study (109nT).
Figure 2.9: Positions STEREO A and B on July 1, 2014. Figure courtesy of NASA [5].

This figure shows the positions of the spacecraft STEREO A and B during observable events near the end of the time covered in this study. A few months after the date of this figure, STEREO B observed a $> 30nT$ event. In October 2014, contact was lost with STEREO B and the last $> 30nT$ event at STEREO A was observed. The STEREO A data at that point had become sporadic.
due to interference because STEREO A had moved to a position in which the Sun was near the line of sight between STEREO A and Earth.

Figure 2.10: Positions STEREO A and B on February 18, 2015. Figure courtesy of NASA [5].

Figure 2.10 [5] shows the positions of the spacecraft near the
writing of this thesis paper. STEREO A at this point was in safe mode and STEREO B has been (and still is at this point) out of contact.

2.4.2 Earth directed events

One limitation to this study is that the STEREO A and B do not have all the capabilities of their counterparts observing the nearside (Earth-side) of the sun. In particular, STEREO A and B do not have HMI or flare sensors (which are described in the next sections).

ACE

ACE is situated at L1 (see figure 2.5). It contains the magnetometer sensor data that measures in situ interplanetary magnetic fields (IMF). This sensor is essentially the same as those on STEREO A and B.
GOES

GOES are a number of weather spacecraft orbiting earth at geostationary orbits. These spacecraft provide in situ information on solar flare intensities by measuring the flare’s X-ray flux.

SOHO

The SOHO spacecraft is at L1 (see figure 2.5). SOHO has white-light coronagraph cameras on board which are used in conjunction with STEREO A’s and B’s white-light coronagraph cameras to get the initial parameters (speed, width, and etc.) of CMEs.

SDO and SHARP

SDO is at geostationary orbit. SDO has the HMI instrument on board. Space-Weather HMI Active Region Patches (SHARPs) are calculated from the HMI data. [6]. The SHARPs are used to measure magnetic field solar source information such as the horizontal field.
gradient, free energy proxy, unsigned flux and others [6]. See figure 2.11 [6].

Figure 2.11: HARP regions on SDO/HMI imagery. From a paper by M. G. Bobra et al. (2014) [6].
These parameters have been used for determining the possibility of a flare or CME occurring [6] but not used in conjunction with coronagraphic parameters to predict B field strength at 1 AU.

2.5 Empirical Relationships

2.5.1 Travel time and Initial Speed Literature Review

For fast CMEs (which are what are studied in this paper) the relationship found by Vandas et al. (1996) [27] was

\[ T_{\text{shock}}(h) = 43 - 0.006V_i \] (2.1)

where \( V_i \) is the initial CME speed and \( T_{\text{shock}} \) is the shock travel time.
Gopalswamy [28], [29] included a relationship that involved the effective acceleration which includes the speed at 1 AU:

\[ a = \alpha - \beta u, \quad S = ut + 0.5at^2 \]  \hspace{1cm} (2.2)

where \( S \) is the distance traveled, \( u \) is initial CME speed near the Sun, \( t \) is travel time, \( a \) is acceleration, and \( \alpha \) and \( \beta \) are constants.

The acceleration of CMEs can be described by

\[ a = -0.0054(u - u_c) \]  \hspace{1cm} (2.3)

where \( u_c = 406\text{km/s} \) is the average solar wind speed and \( u \) is the initial speed of the CME in the coronagraph images. This is a simple means to get the acceleration using basic kinematic relationships [29]. This acceleration can be positive or negative depending on the initial speed. When the CME speed is slower than the ambient solar wind the CME gets pushed faster (positive acceleration). Negative
acceleration occurs when the CME is faster than the solar wind and the CME is slowed due to drag. For the purposes of this study, all accelerations are negative due to the high speeds of the studied CMEs. Equation 2.4 is the Estimated CME Arrival (ECA) model and is given as

\[
t_1 = \frac{-u + \sqrt{u^2 + 2ad_1}}{a}, \quad t_2 = \frac{d_2}{\sqrt{u^2 + 2ad_1}}
\]  

(2.4)

where \( t \) is travel time, \( u \) is initial speed of a CME, \( a \) is acceleration of the CME and \( d \) is distance. Usually (for slower CMEs) the CME will slow to the speed of the solar wind at some distance \( d_1 \) [30]. However, the CMEs in this study are assumed to continue to decelerate through 1 AU due to their high initial speeds. For the Estimated Shock Arrival (ESA) Gopalswamy developed a relationship for estimating speeds at 1 AU for the associated CME interplanetary shocks [31]. For both ESA and ECA the inputs are initial speed [30].
The ESA relationship is approximated as [10]

\[ T = AB^u + C \]  \hspace{1cm} (2.5)

where \( T \) is travel time, \( u \) is initial speed, \( A = 151.002 \), \( B = 0.998623 \) and \( C = 11.598 \). This model is for CME speeds greater than 450\( km/s \).

Wang et al. (2002) found [32]

\[ T = 27.98 + \frac{2.11 \times 10^4}{V} \]  \hspace{1cm} (2.6)

Zhang et al. (2003) found [33]

\[ T = 96 - \frac{V}{21} \]  \hspace{1cm} (2.7)

where \( T \) is travel time and \( V \) is the initial speed of the CME. According to Zhang et al. (2003), equation 2.7 works best for CMEs with a speed greater than 500\( km/s \).
Srivastava et al. (2004) found [34]

\[ T = 86.9 - 0.026V \]  \hspace{1cm} (2.8)

Manoharan et al. (2004) made a polynomial fit between travel time in days between start time and the arrival of the interplanetary shocks (IPS) and the initial coronagraph speed of the associated CME. There were 91 IPS utilized in this study. Manoharan et al. (2004) found that

\[ t_{\text{shock}} = 3.9 - 2 \times 10^{-3}V_{CME} + 3.6 \times 10^{-7}V_{CME}^2 \]  \hspace{1cm} (2.9)

where \( t \) is travel time and \( V \) is the initial speed of the CME.
In a similar study by Kim et al. (2007) a linear relationship was found [35] to be

\[ T = 78.86 - 0.02V_{CME} \]  \hspace{1cm} (2.10)

where travel time \((T)\) is given in hours.

How the in situ CME shock (or magnetosheath) speed and in situ CME magnetic obstacle speed relate varies depending on the CME. Also, the speeds vary as the CME passes the spacecraft solar wind speed sensors. In section 3.3 in figures 3.1 thru 3.3 on pages 68 thru 70 the chart \(V_p\) on each figure shows the in situ solar wind speeds for three types of CMEs. On each of the figures, the points from \(a\) to \(b\) show the CME shock (or magnetosheath). The points \(b\) to \(c\) show the CME magnetic obstacle.
2.5.2 In Situ Magnetic field and Speed Literature Review

In a current status of CME/shocks, Zhao and Dryer do not provide an overview of the research of interplanetary magnetic field predictions (especially their north or south polarity) due to how uncertain they are [30]. This is one indication that more research into IMF predictably is required. The geoeffectiveness of a CME is largely determined by the magnetic polarity of the CME so more information on this is of great value to space forecasters (see section 3.2).

Gonzalez et al. (1998) found that magnetic cloud CMEs in situ magnetic field correlated to the in situ CME max speed and is given as

\[ |B|_{max}(nT) = 0.047V_{max}(km/s) - 1.1 \]  

Equation 2.11 uses data from events directed only at Earth. A magnetic cloud is a name for a CME that has lower than normal temper-
ature, has increased magnetic field, and has a smooth and rotating magnetic field direction as observed by in situ spacecraft. [36]. A non-cloud CME is one that does not have all these attributes.
Considering a number of CME events directed only at the ACE spacecraft (and Earth) Owens and Cargill developed an empirical relationship which is described by

\[ |B|_{max}(nT) = 0.047V_{max}(km/s) + 0.0644 \quad (2.12) \]

where \( V \) is the initial maximum speed of the CME and \( B \) is the maximum observed in situ magnetic field. No consideration was made for magnetic cloud and non-cloud events. Events were included that had a greater than 18nT magnetic field at ACE for 3 hours or more.
Cane and Richardson compared max magnetic fields and speeds from 1996 to 2009 as can be seen in figure 2.12 [7].

![Figure 2.12: In situ Max Magnetic Field and Speed. From a paper by Cane and Richardson [7].](image)

The equation of the magnetic cloud line is

\[ B_{\text{max}}(nT) = 0.0439V - 1.8019 \]  \hspace{1cm} (2.13)

The equation of the non-cloud line is

\[ B_{\text{max}}(nT) = 0.0206V + 3.7477 \]  \hspace{1cm} (2.14)
From figure 2.12, the correlation coefficient found for magnetic field \((cc = 0.600)\) correlated to the in situ max speed much better for cloud than for non-cloud CMEs \((cc = 0.277)\). The Eureqa program (which is explained in section 4.1) will be used to fit a linear trend to the same data found in figure 2.12. Eureqa is validated by comparing the correlation coefficients found by Eureqa to the correlation coefficients found by Cane and Richardson.

2.6 Problem Statement

The arrival time and strength of strong B field CME events are difficult to predict; this prediction is critical in preventing possible damage to people, infrastructure, and technological instrumentation. The current correlations between strong B field events and other solar parameters are not well understood. This work will lead to a better understanding of the correlations between solar storm parameters and will improve forecasting of strong B field events. Furthermore, it
would be very useful to space weather forecasters if a correlation can be made between $B_z$ and any of the other solar storm parameters (geoeffectiveness and $B_z$ are described in section 3.2)
Chapter 3

Theory

3.1 Relationships between solar storm parameters

The size of the in situ magnetic field strength should be related to the other parameters of a particular CME. In situ magnetic field strength is the B field measured by magnetometer instruments on the ACE and STEREO spacecraft. An example of a B field measurement can
be seen in figure 3.1 in section 3.3.

3.1.1 Speed and Magnetic field

As shown in section 2.5.2, there is a relationship between the in situ speed of the CME and the in situ magnetic field.

3.1.2 Distance, Time, velocity and acceleration

As seen in equation 2.2 in chapter 2 the kinematic equation (reproduced here again as equation 3.1 for readability) is given as

\[ S = ut + 0.5at^2 \]  

(3.1)

where the distance \( S \) is approximately 1 AU for all three spacecraft (ACE and STEREOS A and B), \( t \) is travel time, \( u \) is initial speed of the CME, and \( a \) is acceleration.

This kinematic relationship (equation 3.1) is utilized to validate
a software data analysis tool (Eureqa) used in this study which is further explained in section 4.3.2. Using Eureqa, a relationship is found using data for CME coronagraph initial speed and CME travel time. As seen in chapter 5, Eureqa is able to find the acceleration relationship as seen in equation 3.1. Eureqa is described in section 4.1

3.1.3 SHARP Solar source Magnetic field

Unsigned flux

Bobra et al. (2014) provide a definition for a parameter known as unsigned flux in units of Maxwells (Mx) [6] and is given as

\[ \Phi = \Sigma |B_z| dA \]  

(3.2)

It makes intuitive sense that the \( B_z \) at the CME solar source should be related to the CME \( B_z \) in situ.
Another parameter from Bobra et al. (2014) is known as the horizontal gradient of the horizontal field and is units of Gauss per mega-meter (\(GMm^{-1}\)) [6] and is given as

\[
|B_h| = \frac{1}{N} \sum \sqrt{\left(\frac{\partial B_h}{\partial x}\right)^2 + \left(\frac{\partial B_h}{\partial y}\right)^2}
\]  

(3.3)

This parameter is related to total magnetic field in chapter 5.

3.2 Geoeffectiveness (and magnetic field \(B_z\))

The main driver of the geoeffectiveness of the CME storm on Earth is negative \(B_z\), although high solar wind speed can also be a factor [12]. A CME with a negative (or southward) \(B_z\) is more geoeffective because the southward \(B_z\) couples with Earth’s northward pointing magnetosphere. The strength of the negative \(B_z\) is not known until the CME passes ACE. ACE is only 0.1 AU away from Earth so
this does not bring much lead time (only about 30 minutes). If a correlation can be made between $B_z$ and any of the other solar parameters that would be very useful to space weather forecasters.

### 3.3 CME Groups

Jian et al. (2006) describe three different types of CME groups [8]. These groups are based on the in situ measurements of pressure versus time. Group 1 CMEs are classified as CMEs in which the pressure in the magnetosheath of the CME increases gradually, Group 2 remain at a relatively stable value, and Group 3 increase quickly and then fall off. Each group can be seen in figures 3.1, 3.2 and 3.3 for group 1,2 and 3 respectively [8]. The bottom chart of each figure shows pressure versus time ($P_t$). Also included are $B_x/B$, $B_y/B$, and $B_z/B$ which are the x, y and z magnetic field with total magnetic field ratios. Additionally on the chart there is (in order from $|B|$ to $\beta$) total magnetic field, solar wind speed, density, temperature, and
beta. Group 1 CMEs are usually associated with magnetic clouds and tend to have similar traits [8]. Utilizing the Jian et al. (2006) group identification is superior to using the cloud and non-cloud identification in that group identification has a geometric physical meaning and is also easier to work with (since only one type of in situ observation is considered instead of three). Furthermore, the group identification is less ambiguous.
Figure 3.1: Group 1 CME example. From paper by Jian et al. (2006) [8]
Figure 3.2: Group 2 CME example. From paper by Jian et al. (2006) [8]
Figure 3.3: Group 3 CME example. From paper by Jian et al. (2006) [8]
Figure 3.4 shows an interpretive sketch of the geometry of the groups [8].

![Figure 3.4: Interpretive sketch of all groups. From paper by Jian et al. (2006) [8]](image-url)
As shown in chapter 2 in situ magnetic field and in situ speed have been related based on whether the CME exhibited traits of a magnetic cloud. Using STEREO data organized into groups from Jian et al. (2013) [37] over the years of 2010 to 2013, the in situ speed and magnetic field relationship based on these groups was explored as shown in chapter 5.

### 3.4 Summary

It has been shown in subsection 2.5.1 on page 50 that the initial CME speed can be correlated to the in situ CME speed due to acceleration. Furthermore, it has been shown in subsection 2.5.2 on page 56 that the in situ speed at 1 AU can be related to the in situ magnetic field. The speed at 1 AU is related to the initial (coronagraphic) speed (by acceleration), thus the in situ magnetic field and initial speed are related. Additionally, it makes intuitive sense that the magnetic field of the solar source region and the in situ magnetic field should
be related in some way. By matching a CME’s source magnetic field information, speed (from coronagraphic observations) and the in situ magnetic field observations of those same CMEs one should be able to correlate to make a prediction of the 1 AU magnetic field. Using a multidimensional analysis software (Eureqa) a prediction model for in situ magnetic field of CMEs using solar source magnetic field and initial CME speed has been made and is shown in chapter 5.
Chapter 4

Method

4.1 Plan of Study Overview and Eureqa

Eureqa is a sophisticated analysis tool that can find previously unknown correlations and relationships between various data variables. This tool is potentially very valuable in developing empirical relationships between solar storm CME variables.
The first step in using Eureqa is to enter tabulated data into the program with each variable as a single column and provide a name for each variable. See figure 4.1

Figure 4.1: Eureqa enter data window. Screen shot from Eureqa software [9].
The data can then be prepared before analysis by removing outliers or missing values. See figure 4.2

Figure 4.2: Eureqa prepare data window. Screen shot from Eureqa software [9].
Next, a model target is set by describing which variables are independent or dependent. Additionally, a relationship between the variables can be entered into the model target. See figure 4.3

Figure 4.3: Eureqa prepare data window. Screen shot from Eureqa software [9].

Next the program is started by the user and Eureqa then automatically discovers models from the given data using algorithms that are evolutionary and sophisticated [38]. Eureqa uses symbolic regression and computation that evolves with minimal error while
finding equations to fit to the given data [39].

Once the Eureqa program has been run, different models found by the program can be viewed and the user can select the best model/s for the specific application. See figure 4.4
Figure 4.4: Eureqa results window. Screen shot from Eureqa software [9].

In order to validate Eureqa’s use for solar storm CME empirical relationship research, previously known CME relationships from
literature were found using Eureqa and CME data. Once Eureqa was shown to reproduce relationships found in literature, other new relationships were explored.

4.2 Data Collection

4.2.1 Matching ICMEs to Strong IMFs and Data Sources

The CME data collection began by first finding in situ magnetic fields above the 30 nT threshold from the ACE and STEREO spacecraft. For comparison the Earth’s magnetic field is about 1000 times stronger than this threshold. Magnetometer instruments on each spacecraft provided this data. This study was done from 2010 to October 2014 (until the STEREO data became unreliable or unavailable, see chapter 2). On the STEREO spacecraft this instrument is known as IMPACT. Once these events were found the CME that
was most likely the cause of these events was found; this data can be seen in chapter 5 in table 5.1. The CME list from the NASA Space Weather Database Of Notifications, Knowledge, Information (DONKI) site [40] was used for this. This site provided a speed, time, width and sometimes a solar source location.

The speed, width and etc. were found by space weather forecasters using the STEREO SOHO CME Analysis Tool (CAT) [41]. This tool uses three dimensional projection (from the three spacecraft) to get accurate speeds, widths and etc. The speed, width and direction of each CME is shown on table 5.2. Additionally, information regarding an accompanying solar flare was sometimes provided. In addition to the information about the magnetic field the strength of any SEP event was also collected (from the IMPACT instrument). The source location of the CME was found by forecasters (and by the author if not available) by using the extreme ultraviolet light cameras on the three spacecraft. A map of the CME source loca-
tions on the Sun can be seen in chapter 5 in figure 5.1. In addition to the speed near the Sun (within 30 Solar Radii) the solar wind speed at (or near) 1 AU was also gathered using the Plasma and Suprathermal Ion Composition (PLASTIC) instrument [42].

A table used for reference and comparison to the NASA CCMC DONKI site is updated on another NASA site [43]. The full catalog is described by Gopalswamy et al (2009).[21]. This site provided information on a subset CMEs and is useful because it also includes backside CMEs (not just those directed at Earth) many of which are those that were selected as mentioned previously. This table includes CME coronagraph and solar source location information among other things.

Another table used for reference is found online at a Caltech website [44]. This catalog only includes ACE in situ measurements but is useful in that in provides information as to whether the CME event was a magnetic cloud or not. This table is described by Cane
and Richardson [7].

A table that was used for a separate analysis and reference is updated on a UCLA website [45]. This table is discussed by Jian et al. (2013)[37]. This table has STEREO CME event in situ measurements from 2006 to December 2013 for Behind and to June 2014 for Ahead. It includes what group each event belongs to as described in section 3.3. It also has max in situ magnetic field, in situ pressure, in situ solar wind speed measurements and some other CME parameters.

4.3 Analysis

4.3.1 Groupings and the Magnetic Cloud Relationship

Jian et al. (2006) pointed out that group 1 CMEs as compared to group 2 and 3 CMEs (groups are described in section 3.3) share the
most features with magnetic cloud CMEs [8]. The data catalog as
described by Jian et al. (2013) with in situ STEREO event informa-
tion was used to compare max magnetic field and max solar wind
speed of the CME events from 2010 to 2013 (same time period has
the selected CME events) [37]. The magnetic field and speed rela-
tionship is described in subsection 2.5.2 and is supported by Owens
et al. (2002) [46], [47] and others. It will be investigated to see how
Group 1, 2 and 3 max speed at 1 AU compares to the magnetic field
at 1 AU measurements.

4.3.2 Validation of Eureqa

As described in section 4.1, Eureqa is a useful data analysis tool.
However, it is important to first validate Eureqa to see if it can find
the relationships already described in literature. The data from the
figures 2.12 in subsection 2.5.2 was run using Eureqa to verify that
the program would get the same approximate trend. Additionally,
the trend found using Eureqa for this paper’s data set for velocity and travel time is compared to the ESA shock model described by Gopalswamy et al. (2005) [10]. The trend to be used is similar to equation 3.1 and is known as the kinematic relationship. Rewriting equation 3.1 from page 63 in preparation for use in the Eureqa program:

\[
\frac{a}{t} = u + bu^c t \tag{4.1}
\]

where \(u\) is initial speed of the CME, \(t\) is travel time of the CME, \(a\), \(b\) and \(c\) are constants to be found using Eureqa. This equation relates distance, time, speed and acceleration. The variables \(u\) and \(t\) are from STEREO and ACE data over 2010 to 2014 as described in this paper and as shown in chapter 5.
4.3.3 Multi-dimensional analysis and trends using Eureqa

The validation of Eureqa’s capabilities is presented in section 5.2.2. Once the Eureqa software [9] had been validated, three dimensional relationships were explored. Variables such as magnetic field at the solar source, speed near the sun and in situ magnetic field were combined into one empirical relationship.
Chapter 5

Results and Discussion

5.1 Collection and Preparation of Data

Tables 5.1 and 5.2, show the CME data collected for this thesis. Table 5.1 shows which CME was matched to each in situ CME magnetic field measurement. Table 5.2 shows the details of the CMEs from table 5.1.

The relative locations on the Sun for each of the greater than 30nT events are shown in figure 5.1. The background image of the
Table 5.1: IMF max in situ measurement with corresponding identified CMEs

<table>
<thead>
<tr>
<th>IMF Date</th>
<th>IMF Time, UT</th>
<th>Spacecraft</th>
<th>Max B(nT)</th>
<th>CME date</th>
<th>CME time</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/3/10</td>
<td>4:59</td>
<td>Behind</td>
<td>33.9</td>
<td>8/1/10</td>
<td>8:20</td>
</tr>
<tr>
<td>2/17/11</td>
<td>23:53</td>
<td>ACE</td>
<td>31.6</td>
<td>2/15/11</td>
<td>1:56</td>
</tr>
<tr>
<td>8/5/11</td>
<td>17:06</td>
<td>ACE</td>
<td>36.1</td>
<td>8/2/11</td>
<td>5:19</td>
</tr>
<tr>
<td>9/24/11</td>
<td>9:03</td>
<td>Behind</td>
<td>34.3</td>
<td>9/22/11</td>
<td>11:24</td>
</tr>
<tr>
<td>9/26/11</td>
<td>11:50</td>
<td>ACE</td>
<td>34.6</td>
<td>9/24/11</td>
<td>12:33</td>
</tr>
<tr>
<td>10/3/11</td>
<td>22:23</td>
<td>Behind</td>
<td>35.1</td>
<td>10/1/11</td>
<td>20:48</td>
</tr>
<tr>
<td>1/22/12</td>
<td>5:14</td>
<td>ACE</td>
<td>31.1</td>
<td>1/19/12</td>
<td>15:10</td>
</tr>
<tr>
<td>1/24/12</td>
<td>14:21</td>
<td>ACE</td>
<td>36.3</td>
<td>1/23/12</td>
<td>4:00</td>
</tr>
<tr>
<td>1/29/12</td>
<td>13:04</td>
<td>Ahead</td>
<td>49.6</td>
<td>1/27/12</td>
<td>16:39</td>
</tr>
<tr>
<td>3/8/12</td>
<td>10:42</td>
<td>ACE</td>
<td>40.6</td>
<td>3/7/12</td>
<td>0:36</td>
</tr>
<tr>
<td>3/19/12</td>
<td>23:37</td>
<td>Ahead</td>
<td>35.3</td>
<td>3/18/12</td>
<td>0:39</td>
</tr>
<tr>
<td>3/28/12</td>
<td>21:37</td>
<td>Behind</td>
<td>37.3</td>
<td>3/26/12</td>
<td>23:12</td>
</tr>
<tr>
<td>5/28/12</td>
<td>2:48</td>
<td>Ahead</td>
<td>45.4</td>
<td>5/26/12</td>
<td>22:54</td>
</tr>
<tr>
<td>6/16/12</td>
<td>8:56</td>
<td>ACE</td>
<td>41.6</td>
<td>6/14/12</td>
<td>12:52</td>
</tr>
<tr>
<td>7/4/12</td>
<td>6:56</td>
<td>Behind</td>
<td>40.5</td>
<td>7/2/12</td>
<td>8:36</td>
</tr>
<tr>
<td>7/23/12</td>
<td>21:00</td>
<td>Ahead</td>
<td>109.4</td>
<td>7/23/12</td>
<td>2:36</td>
</tr>
<tr>
<td>9/23/12</td>
<td>9:20</td>
<td>Behind</td>
<td>30.6</td>
<td>9/20/12</td>
<td>15:24</td>
</tr>
<tr>
<td>5/16/13</td>
<td>9:42</td>
<td>Ahead</td>
<td>30.3</td>
<td>5/13/13</td>
<td>17:24</td>
</tr>
<tr>
<td>7/25/13</td>
<td>6:28</td>
<td>Ahead</td>
<td>41.8</td>
<td>7/22/13</td>
<td>6:24</td>
</tr>
<tr>
<td>10/2/13</td>
<td>1:17</td>
<td>ACE</td>
<td>32.7</td>
<td>9/29/13</td>
<td>20:39</td>
</tr>
<tr>
<td>10/8/13</td>
<td>19:37</td>
<td>ACE</td>
<td>35.8</td>
<td>10/6/13</td>
<td>14:39</td>
</tr>
<tr>
<td>11/6/13</td>
<td>1:52</td>
<td>Behind</td>
<td>31.3</td>
<td>11/4/13</td>
<td>5:09</td>
</tr>
<tr>
<td>3/14/14</td>
<td>23:00</td>
<td>Behind</td>
<td>29.3</td>
<td>3/12/14</td>
<td>14:39</td>
</tr>
<tr>
<td>7/1/14</td>
<td>11:20</td>
<td>Behind</td>
<td>33.3</td>
<td>6/29/14</td>
<td>12:39</td>
</tr>
<tr>
<td>9/12/14</td>
<td>15:21</td>
<td>ACE</td>
<td>31.7</td>
<td>9/10/14</td>
<td>18:18</td>
</tr>
<tr>
<td>9/25/14</td>
<td>14:09</td>
<td>Behind</td>
<td>68.9</td>
<td>9/22/14</td>
<td>9:12</td>
</tr>
<tr>
<td>10/17/14</td>
<td>20:00</td>
<td>Ahead</td>
<td>35.0</td>
<td>10/14/14</td>
<td>19:00</td>
</tr>
</tbody>
</table>
Table 5.2: Initial parameters of CMEs identified as seen in table 5.1

<table>
<thead>
<tr>
<th>CME date</th>
<th>CME time</th>
<th>CME Speed (km/s)</th>
<th>Direction (LON/LAT)</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/1/10</td>
<td>8:20</td>
<td>1000</td>
<td>-34/24</td>
<td>96</td>
</tr>
<tr>
<td>2/15/11</td>
<td>1:56</td>
<td>900</td>
<td>0/-20</td>
<td>70</td>
</tr>
<tr>
<td>8/2/11</td>
<td>5:19</td>
<td>900</td>
<td>15/4</td>
<td>35</td>
</tr>
<tr>
<td>09/22/11</td>
<td>11:24</td>
<td>1000</td>
<td>-90/10</td>
<td>140</td>
</tr>
<tr>
<td>9/24/11</td>
<td>12:33</td>
<td>1507</td>
<td>-45/12</td>
<td>100</td>
</tr>
<tr>
<td>10/1/11</td>
<td>20:48</td>
<td>1500</td>
<td>-120/20</td>
<td>90</td>
</tr>
<tr>
<td>1/19/12</td>
<td>15:10</td>
<td>1020</td>
<td>-21/46</td>
<td>138</td>
</tr>
<tr>
<td>1/23/12</td>
<td>4:00</td>
<td>2211</td>
<td>26/41</td>
<td>62</td>
</tr>
<tr>
<td>1/27/12</td>
<td>16:39</td>
<td>2200</td>
<td>75/40</td>
<td>110</td>
</tr>
<tr>
<td>3/7/12</td>
<td>0:36</td>
<td>2200</td>
<td>-60/30</td>
<td>100</td>
</tr>
<tr>
<td>3/18/12</td>
<td>0:39</td>
<td>1450</td>
<td>105/25</td>
<td>120</td>
</tr>
<tr>
<td>3/26/12</td>
<td>23:12</td>
<td>1450</td>
<td>-105/15</td>
<td>100</td>
</tr>
<tr>
<td>5/26/12</td>
<td>22:54</td>
<td>1650</td>
<td>-110/5</td>
<td>70</td>
</tr>
<tr>
<td>6/14/12</td>
<td>12:52</td>
<td>1364</td>
<td>-9/-20</td>
<td>100</td>
</tr>
<tr>
<td>7/2/12</td>
<td>8:36</td>
<td>1100</td>
<td>-130/-10</td>
<td>70</td>
</tr>
<tr>
<td>7/23/12</td>
<td>2:36</td>
<td>3400</td>
<td>138/-10</td>
<td>160</td>
</tr>
<tr>
<td>9/20/12</td>
<td>15:24</td>
<td>2319</td>
<td>-138/-28</td>
<td>112</td>
</tr>
<tr>
<td>5/13/13</td>
<td>17:24</td>
<td>1050</td>
<td>80/10</td>
<td>72</td>
</tr>
<tr>
<td>7/22/13</td>
<td>6:24</td>
<td>1000</td>
<td>157/30</td>
<td>70</td>
</tr>
<tr>
<td>9/29/13</td>
<td>20:39</td>
<td>1100</td>
<td>8/26</td>
<td>70</td>
</tr>
<tr>
<td>10/6/13</td>
<td>14:39</td>
<td>790</td>
<td>6/-15</td>
<td>50</td>
</tr>
<tr>
<td>3/12/14</td>
<td>14:39</td>
<td>1150</td>
<td>-154/30</td>
<td>120</td>
</tr>
<tr>
<td>6/29/14</td>
<td>12:39</td>
<td>750</td>
<td>138/-10</td>
<td>60</td>
</tr>
<tr>
<td>9/10/14</td>
<td>18:18</td>
<td>1400</td>
<td>10/15</td>
<td>45</td>
</tr>
<tr>
<td>9/22/14</td>
<td>9:12</td>
<td>795</td>
<td>-165/13</td>
<td>92</td>
</tr>
<tr>
<td>10/14/14</td>
<td>19:00</td>
<td>950</td>
<td>-109/-16</td>
<td>120</td>
</tr>
</tbody>
</table>
Sun is for illustrative purposes only. It is a 360° Stonyhurst composite map of EUVI/AIA 304 Å images taken from STEREO A, STEREO B and ACE on November 14, 2013.

Figure 5.1: Relative Locations on Sun for each event. The blue markers are STEREO B, the orange are ACE and the red are STEREO A.

On figure 5.1 it is important to note that the STEREO A events get progressively further west (positive HEEQ) and the STEREO B events get progressively east (negative HEEQ) as the study pro-
gressives. Also note that all the source locations are within +/- 30° latitude from the solar equator.

5.1.1 Collected Data Summary and Discussion

All CME events in this study had initial speeds above 750\textit{km/s}. Additionally, 88\% of the events studied had associated SEP events. One event that stands out as being odd is the 68.9 nT at STEREO B which occurred on September 25, 2014. This event had one of the slowest CME speeds for this data group (795\textit{km/s}) and yet the second highest magnetic field measurement. It may be that measurement took into account multiple CMEs and not just the one it was correlated to.
5.2 Analysis results

5.2.1 Groupings and the Magnetic Cloud Relationship

Groups 1, 2 and Group 3 CMEs during 2013 were compared using the max CME magnetic field and max in situ CME speed from the database from Jian et al. (2013) [37]. Figures 5.2 thru 5.4 show CME groups 1 thru 3 respectively.
Figure 5.2: Group 1 in 2013 max CME speed and magnetic field at 1 AU. The line is $y = 0.0362x - 1.495$ with an $R^2 = 0.696$
Figure 5.3: Group 2 in 2013 max CME speed and magnetic field at 1 AU. The line is $y = 0.0375x - 3.486$ with an $R^2 = 0.209$
Figure 5.4: Group 3 in 2013 max CME speed and magnetic field at 1 AU. With a line of $y = 0.0264x + 1.134$ and an $R^2 = 0.165$
Equation 5.1 below shows the magnetic cloud trend found by Cane and Richardson [7] (on the left) and that found using group 1 data (on the right). These equations show that the magnetic cloud relationship with speed is very similar to the group 1 relationship.
These groups proposed by Jian et al. (2006) [8] could prove useful for 1 AU magnetic field prediction. The two equations are given as

\[
B_{\text{max,MC}}(nT) = 0.0439V - 1.8019, B_{\text{max,1}}(nT) = 0.0326V - 0.4253 \quad (5.1)
\]

The Group 1 correlation coefficient of the best fit trend (\(cc = 0.672\)) is better than correlation coefficient found by Richardson et al. (2010) (\(cc = 0.600\)) [7].

### 5.2.2 Validation of Eureqa

**Validation of Magnetic fields and speed**

Eureqa was validated using the method described in chapter 4 and equations 5.2 and 5.3 are what were produced [9].
The cloud CME equation was found to be

\[ B = 0.0403V - 0.903 \]  (5.2)

where \( B \) is magnetic field and \( V \) is in situ speed of the CME. The Eureqa program found a correlation coefficient of \( cc = 0.638 \) which is better than that found by Richardson et al. (2010) \( (cc = 0.600) \)[7].

The non-cloud CME equation was found to be

\[ B = 0.0187V + 3.184 \]  (5.3)

The Eureqa program found a correlation coefficient of \( cc = 0.332 \) which is actually again better than that found by Richardson et al. (2010) \( (cc = 0.277) \)[7].

98
Validation of Travel time and speed model

The new speed and travel time model found using the Eureqa tool [9] is

\[
\frac{31997.7}{T} = V - 7.79 \times 10^{-6}TV^{1.997} \tag{5.4}
\]

where \(T\) is CME travel time and \(V\) is initial speed.

Solving equation 5.4 for \(T\) we have

\[
T = 6.418 \times 10^{-4} \frac{1.000 \times 10^8V - 6324\sqrt{2.500 \times 10^8V^2 - 2.492 \times 10^8V^{1.997}}}{V^{1.997}} \tag{5.5}
\]

The new speed and time model found using Eureqa and the data as found in subsection 5.1.1 is compared to the Gopalswamy ESA model [10] as seen in figure 5.6.
Figure 5.6: The blue unfilled circles represent the Gopalswamy ESA approximation for events with $V > 500 \text{km/s}$ [10]. The red filled squares are the new model found using Eureqa. Both use the speed and travel time data seen in subsection 5.1.1.

As can be seen by figure 5.6 the two models are very similar. The empirical Eureqa model however is more easily explained physically than the Gopalswamy ESA approximation model because the Eureqa equation came directly from the kinematic relationship as shown in chapter 3 in equation 3.1. In contrast, the Gopalswamy ESA approximation model is purely empirical. The Eureqa tool has
proven it can be given a set of CME data and find the physical relationship that relates the CME data parameters.

5.2.3 Multi-Dimensional analysis: Initial CME Speed and SHARP parameters using Eureqa

Using the freshly validated tool, Eureqa was then applied to study various solar source SHARP magnetic field parameters for possible correlation use in 1 AU (at ACE) magnetic field prediction. Two parameters that stood out as possible predictors were (1) the unsigned flux ($\Phi$) for the $B_z$ 1 AU prediction and (2) the mean magnetic field horizontal gradient ($|B_h|$) for the 1 AU total magnetic field ($B$) prediction. These parameters stood out due to their high correlation to the parameters of interest. These parameters were combined with the initial speed of the CME to create models to predict magnetic field.
The empirical model found to predict total magnetic field \( B \) is

\[
B = 28.51 + 0.00389V + \frac{1.79}{|B_h| - 56.56} \quad (5.6)
\]

where \( V \) is the initial speed of the CME and \(|B_h|\) is mean magnetic field horizontal gradient. This equation is compared to the actual \( B \) and this comparison is shown in figure 5.7. Eureqa’s ability to predict observables (“predicted”) should appear as a straight line with reasonable correlation coefficients when compared to the actual data (“actual”).
Figure 5.7: The predicted magnetic field at ACE versus the actual measured magnetic field.

The fit of the line in figure 5.7 is

\[ y = 0.324x + 22.77 \] (5.7)

this trend line has a \( R^2 = 0.406 \). The mean of the differences between actual and predicted from figure 5.7 is -1.04 and the standard
The empirical model found to predict minimum $B_z$ is

$$B_z = 0.00764V - 20.58 - 1.97 \times 10^{-22} \Phi$$  \hspace{1cm} (5.8)$$

where $V$ is the initial speed of the CME and $\Phi$ is the unsigned flux. This equation is compared to the actual predicted $B_z$ and this comparison is shown in figure 5.8.
Figure 5.8: The predicted magnetic field at ACE versus the actual measured magnetic field.

The fit of the line in figure 5.8 is

\[ y = 0.5664x - 7.1073 \] \hspace{1cm} (5.9)

This line has an \( R^2 = 0.60606 \). The mean of the differences between actual and predicted in figure 5.8 is 1.43 and the standard
deviation is 3.36.

Relationships 5.8 and 5.6 can be understood from a physics perspective in that the magnetic field source information describes how much potential energy is on the sun. Additionally, the speed represents how much of that energy escapes the sun. When these parameters are combined as done in this work, the CME magnetic field strength can be predicted. This can dramatically increase the lead time (from approximately 30 minutes to approximately a day or more) for CME magnetic field prediction; in other words instead of waiting for the CME to get close to Earth a prediction can be made close to the Sun.

Other parameters were investigated but not included in this thesis due to the complexity required in the interpretation, or the usefulness and low-impact of these other parameters. Such parameters were the SEP proton flux, the solar flare flux, the area of the NOAA active region on the solar source, and the CME direction and width.
Chapter 6

Summary and Suggested Further Study

The groups proposed by Jian et al. (2006) [8] have been shown in this paper that they can be used in relating in situ magnetic field and in situ speed as done with magnetic clouds as seen in papers by
Owens et al. (2002) [46], [7].

Using Eureqa, previously unknown functional relationships between solar storm parameters were found by relating SHARP solar source magnetic field parameters and coronagraph CME speed to CME 1 AU magnetic field data. Up to now (as shown in chapter 2) SHARP data has only been used for the prediction of the probability of a flare or CME event occurring on a certain part of the Sun. Now, SHARP data has been shown that it can be used for 1 AU CME magnetic field prediction. The relationships found using Eureqa were given to the SWRC and could potentially be very useful to the SWPC and other space weather forecasters.

For this study it was unfortunate that HMI/SDO SHARP data was only available for Earth facing events. Future study could involve the Air Force data assimilative photospheric flux transport (ADAPT) model [48]. ADAPT provides far side magnetic field estimation maps. These maps would then be analyzed with an al-
teration to the SHARP code in order to calculate far-side HARP regions from these maps. From this, far side magnetic field parameters would be generated. These parameters (with the knowledge of CME STEREO source locations) could then be correlated to the STEREO CME parameters to see if the relationships found at ACE still hold true (as seen in chapter 5). Additionally, other solar storm parameters could be investigated. For instance, instead of predicting the CME magnetic field, the amount of X-ray flux from solar flares could be investigated.
Chapter 7

Bibliography


thesuntoday.org/tag/cor1/.


