UNDERSTANDING THE EVOLUTION AND PROPAGATION OF CORONAL MASS EJECTIONS AND ASSOCIATED PLASMA SHEATHS IN INTERPLANETARY SPACE

by

Phillip Hess A Dissertation Submitted to the Graduate Faculty of George Mason University In Partial fulfillment of The Requirements for the Degree of Doctor of Philosophy Computational Sciences and Informatics

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Dedication

I dedicate this dissertation to my parents, who have always given me immense support

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I would like to thank many people, without whom this would not have been possible. First and foremost, my parents, Piper and David, have done more to support me than I could ever possibly list. I am also grateful to my sister Pier, who has always been there for me and with whom I am lucky to have a very close relationship. All the members of my committee have given me great guidance and support, both in the process of writing this dissertation and in the classes they taught me. Specifically, my graduate advisor, Dr. Jie Zhang, was always a wonderful advisor who helped guide me to this point. I surely would not be here were it not for his tutelage and support. To the many people I have worked with in the Space Weather Lab, it has been a great five years and I look forward to working with all of you as we continue on in the field. And all the friends who have been there along the way and are too many to include, I thank you all for being there for me and helping reach this point.

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Abstract

UNDERSTANDING THE EVOLUTION AND PROPAGATION OF CORONAL MASS EJECTIONS AND ASSOCIATED PLASMA SHEATHS IN INTERPLANETARY SPACE Phillip Hess, PhD

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Dissertation Director: Dr. Jie Zhang

A Coronal Mass Ejection (CME) is an eruption of magnetized plasma from the Corona of the Sun. Understanding the physical process of CMEs is a fundamental challenge in solarphysics, and is also of increasing importance for our technological society. CMEs are known the main driver of space weather that has adverse effects on satellites, power grids, com-munication and navigation systems and astronauts. Understanding and predicting CMEs is still in the early stage of research. In this dissertation, improved observational methods and advanced theoretical analysis are used to study CMEs. Unlike many studies in the past that treat CMEs as a single object, this study divides a CME into two separate components: the ejecta from the corona and the sheath region that is the ambient plasma compressed by the shock/wave running ahead of the ejecta; both structures are geoeffective but evolve differently. Stereoscopic observations from multiplespacecraft, including STEREO and SOHO, are combined to provide a three-dimensional geometric reconstruction of the structures studied. True distances and velocities of CMEs are accurately determined, free of projection effects, and with continuous tracking from the low corona to 1 AU.To understand the kinematic evolution of CMEs, an advanced drag-based model (DBM) is proposed, with several improvements to the original DBM model. The new model varies the drag parameter with distance; the variation is constrained by thenecessary conservation of physical parameters. Second, the deviation of CME-nose from the Sun-Earth-line is taken into account. Third, the geometric correction of the shape of the ejecta front is considered, based on the assumption that the true front is a flattened croissant-shaped flux rope front. These improvements of the DBM model provide a framework for using measurement data to make accurate prediction of the arrival times of CME ejecta and sheaths. Using a set of seven events to test the model, it is found that the evolution of the ejecta front can be accurately predicted, with a slightly poorer performance on the sheath front. To improve the sheath prediction, the standoff-distance between the ejecta and the sheath front is used to model the evolution. The predicted arrivals of both the sheath and ejecta fronts at Earth are determined to within an average 3.5 hours and 1.5 hours of observed arrivals, respectively. These prediction errors show a significant improvement over predictions made by other researches. The results of this dissertation study demonstrate that accurate space weather prediction is possible, and also reveals what observations are needed in the future for realistic operational space weather prediction.

Chapter 1: Introduction

1.1 Coronal Mass Ejections and Space Weather Impacts

Coronal mass ejections (CMEs) are among the most powerful phenomena in the solar system. At Earth these solar eruptions can have a number of negative consequences, including damage to satellites and power grids as well as interfering with communication systems (Schwenn, 2006; Pulkkinen, 2007). The potential damage of severe space weather caused by a CME interacting with the magnetosphere of the Earth can be mitigated by predicting when the CME will arrive at the Earth. To accurately predict this arrival, it is necessary to develop a comprehensive physical understanding of how a CME evolves between the Sun and the Earth.

The focus of this dissertation will be to address Coronal Mass Ejections in the heliosphere. Specifically I study how the CME eruptive ejecta and the sheath region of accumulated solar wind plasma/possible shock wave evolve separately. This is important as both features have their own unique space weather effects, and to properly understand both they must be studied as related but separate structures propagating in the heliosphere. This can lead to a better scientific understanding of the forces acting on the entire CME structure, as well as improving the potential for space weather forecasting.

The next sections will highlight the importance of studying Coronal Mass Ejections and the work that has already been done on the subject. Chapter 2 will detail the various observational data sets I have used, as well as the techniques used to determine CME heights in the heliosphere. The primary new aspect of this chapter is the separate stereoscopic tracking both the CME and the plasma sheath/shock wave that the CME can drive, rather than simply tracking both of these together in the heliosphere. This is important to allow for the study of each feature and understanding the separate physics in each, and studies not considering each front will be missing a key piece of the overall CME dynamics and limiting the accuracy of measurement. As all forecasting techniques require measurements as input, making these measurements as accurate as possible is vital to all forecasting efforts.

Chapter 3 presents the analytical modeling techniques that have been used to extract kinematic information from the height measurements in Chapter 2. Again this work is improved by applying the model to each front separately, so that it can be seen the ways in which the propagation of each front is similar and how it is different. The same chapter will then detail some of the extra considerations I have made to try and improve the model and better constrain the parameters to work towards making it more predictive. Chapter 4 contains the results of how all of these considerations have been combined to establish an effective proof of concept of a method that could lead to improved better forecasting results, albeit on an admittedly limited sample of events. Chapter 5 will present the work I have done to compare both my observational measurements and analytical work with data from numerical simulations of CMEs. Finally, Chapter 6 will summarize the dissertation as well as discussing future studies that can improve this work as well as the implications of this work towards determining what future observing missions would be the most beneficial to space weather forecasters.

1.1.1 Space Weather: Background and Consequences

To understand why Coronal Mass Ejections are an important area of study, it is first necessary to understand space weather and how it works. This means it is important to establish how the Sun interacts with the magnetic field of the Earth under typical conditions, and how a CME can cause the equilibrium between the solar wind and the Earth to be disrupted.

There is a constant flow of plasma from the Sun called the solar wind. This plasma, generally moving radially between 300-500 km/s comes into contact with the Earth. Under most conditions, the Earth is protected from the solar wind because of its strong internal magnetic field. When the Earth encounters a strong, locally closed magnetic field in the



Figure 1.1: An artist's rendition of the Sun-Earth Connection. Image courtesy NASA http://sec.gsfc.nasa.gov/popscise.jpg

solar wind, it is possible for the solar wind energy to enter the magnetosphere and affect the Earth (Gosling et al., 1990). A (not nearly to scale) schematic of this Sun-Earth ' connection showing the solar wind is shown in Figure 1.1.

Among the most powerful drivers of space weather, A CME is a large eruption of magnetized plasma from the Sun. CMEs are often, but not always related to solar flares and/or prominences. While a flare/CME combination is the classical picture, there does not seem to be any indication that geoeffective CMEs are more or less likely to be flare related (Zhang et al., 2003).

CMEs can have very real and very tangible impacts at the Earth. Due to their high energies and strong magnetic fields, CMEs are capable of causing sever space weather effects. Among the systems that can be affected by large space weather events are communications, aviation, navigation and ground power stations.

Satellites, used for a variety of communication and navigation processes, such as GPS,

can suffer a number of negative effects due to space weather. Radiation can cause bits of memory to be switched affecting internal satellite software. In extreme events, the orbits of spacecraft can be degraded, leaving the satellite susceptible to collision or crashing (Pulkkinen, 2007). According to a 2003 House Committee investigating space weather effects, a geomagnetic storm caused the loss of the \$640 million ADEOS-2 satellite (Council, 2008).

Ground based communications can also be disrupted because of space weather. Radio waves in the ionosphere can be distorted through a process called scintillation. This can disrupt radio communications and seriously impact airplanes. The Wide Area Augmentation System (WAAS) is an improvement over GPS used by commercial flights to aid in navigation and aiding the ability of a plane to land in inclimate weather conditions. WAAS can be rendered ineffective by space weather, endangering flights and forcing planes to be grounded. Aviation is further impacted by the build up of energy at the poles in response to a geomagnetic storm. An increasing amount of long range flight routes are becoming polar as it can be a more efficient way to travel. During a geomagnetic storm, the ionospheric response at the poles will leave ground stations unable to communicate with planes going near the poles, forcing the flights to be canceled or rerouted to less efficient paths. Successfully predicting space weather events can allow for these planes to be rerouted in advance and reduce the effect on individual passengers and saving airlines millions of dollars (Council, 2008).

Another significant space weather effect will disrupt ground based power stations. Ground induced currents, electrical currents caused by the magnetospheric response to solar events in the magnetosphere, can disturb ground based power distribution systems. In 1989, a geomagnetic storm caused a total blackout in Quebec, and damaged equipment all throughout North America, with a map of the effects shown in Figure 1.2. In addition to large scale blackouts, there are more localized transistor blowouts that can occur. It can be difficult to know exactly how transistors will respond to the most severe space weather events, so an ability to predict their arrival to shift the load off these transistors and reduce the current flowing through the most sensitive parts of the grid is vital (Gaunt, 2015).



Figure 1.2: A map of the effects of the 1989 geomagnetic storm on ground based power systems in North America, from solarweek.org

These issues and more mean that a powerful geomagnetic storm can cause millions of dollars in damage to technological systems. By studying the Coronal Mass Ejections that can drive these geomagnetic storms, it is possible for the operators of these systems to employ preventive measures. This is why the work in this dissertation is of great benefit to not only the heliospheric research community, but society at large.

1.1.2 Introduction to Coronal Mass Ejections

There are a few different ways for an interplanetary field capable of generating a geomagnetic storm to reach the Earth. Among the most common and most powerful interplanetary transient is a Coronal Mass Ejection. A CME is an eruption of a highly magnetized plasma from the low corona and can have prolonged magnetic fields of 20-30 nT for a period of many hours (Echer et al., 2008).

After the initial eruption, a CME will propagate outward in a roughly radial direction,



Figure 1.3: A comparison of the SEEDS detection rate, normalized by the number of images used (because the LASCO C2 image cadence changed in 2010 and more observations will cause more detections) compared to the monthly sunspot number (Source: WDC-SILSO, Royal Observatory of Belgium, Brussels).

though deflection in the corona is possible if the CME interacts with a strong magnetic structure near the Sun (Kay et al., 2015). Powerful CMEs have demonstrated velocities over 3000 km/s and can carry as much as 10^{32} ergs of energy (Howard et al., 1985).

CMEs can be directed towards the Earth and occur at rates corresponding to solar activity (Wang & Colaninno, 2014). The number of CMEs will correspond to the solar cycle, and there will be many more CMEs during solar maximum, The CME rate corresponds to the sunspot number, as seen in Figure 1.3, which compares the sunspot number to the number of CMEs detected by the Solar Eruptive Event Detection System (SEEDS), an automatic detection algorithm developed at GMU (Olmedo et al., 2008). During the maximum phase of the 11 year solar cycle, there will be multiple CMEs every day. During solar minimum, CMEs will still occur though with far less frequency. There have been examples of strong CMEs occurring during minimum, but strong geomagnetic storms are more likely during solar maximum.



Figure 1.4: A cartoon of the theoretical flux rope geometry showing the twisted magnetic field lines of the CME flux rope ejecta and their connectivity to the Sun, as will as how the ambient solar wind plasma is compressed by the CME into a sheath running ahead of the flux rope, with a possible shock wave at the front of the sheath. Figure taken from (Zurbuchen & Richardson, 2006)

As observations have improved, so has the understanding of the complete CME structure as it propagates. The eruptive material itself, which hereafter will be referred to as the ejecta, is widely considered to be a flux rope in the heliosphere (Zhang et al., 2013; Vourlidas et al., 2013). The legs or flanks of a CME will remain connected to the Sun and the internal flux rope structure contains both toroidal magnetic field aligned with the CME central axis and poloidal magnetic field helically wrapped around the central axis (Chen & Garren, 1993). A cartoon illustration of a flux rope in the heliosphere from Zurbuchen & Richardson (2006) is shown in Figure 1.4.

Figure 1.4 shows the CME ejecta, from the main body of twisted field lines about the central axis to the legs connecting back to the sun. The complex field lines in front of the

ejecta in the sheath can also be seen. These are field lines that connect back to the Sun like typical interplanetary field lines but are pushed and compressed by the ejecta. If the CME is traveling faster than the local Alfvén speed relative to the solar wind, the outer boundary of this sheath will be a fast mode shock wave. Even if a CME is not fast enough to generate a shock, if it is moving faster than the solar wind it will still accumulate solar wind plasma and generate a sheath.

While it is generally well agreed that most, if not all, CMEs in the heliosphere are flux ropes, there still exists some debate as to when the flux rope forms and the role the flux rope may play in CME initiation. One proposed mechanism, known as tether cutting reconnection, has a filament above a sheared magnetic arcade. The shear increases, causing reconnection beneath the filament, pushing it outward and eventually causing an eruption (Moore et al., 2001). Another theory, the breakout model (Antiochos et al., 1999), features a quadrapolar magnetic configuration which causes reconnection between the flux system that will become the CME and the strapping field which holds it in place. This opens the overlying field and weakens it allowing the CME to erupt (Lynch et al., 2008). Neither of these models has a flux rope prior to the eruption, but rather the flux rope is formed by the initiation mechanism. The flux injection model (Chen, 1996) proposes that a stable flux rope exists in the filament channel, and as extra magnetic flux is added into the flux rope, it eventually becomes energized and destabilized. MHD instabilities such as the Kink and Torus Instability acting on a flux rope in the corona have also been proposed (Kliem & Török, 2006). The nature of initiation and when and where the flux rope is formed is still a hotly debated topic in solar physics. However, the focus of this dissertation is post-eruption propagation, so these processes will not have an impact on the results.

Near the Sun, the CME flux rope has a high density, a high temperature and strong magnetic field. As the CME propagates, it expands causing the density and temperature to decrease because the mass of the ejecta will largely be conserved as the structure expands. The CME at 1 AU, hereafter an Interplanetary CME or ICME, is usually defined as a structure with a low density, temperature and rotating magnetic field (Illing & Hundhausen, 1985). The rotating magnetic field is one of the key components in determining the geoeffectiveness of a CME.

1.1.3 Magnetospheric Response to CMEs

The magnetic field of the Earth is a dipole field, but with the night side being carried out by the solar wind to form a "tail". This field is important for protecting the Earth from the solar wind, as Mars for instance does not have a strong magnetic field and the solar wind interacts directly with its ionosphere stripping away plasma and atmospheric material (Ma et al., 2014). Without the magnetic field to protect the Earth, enough atmospheric oxygen may be lost to significantly affect the habitability of th Earth (Wei et al., 2014). While a CME will not open the field enough to cause this drastic a consequence, its still one of the strongest drivers of geomagnetic enhancement.

Obviously, a CME must be directed towards the Earth in order to be geoeffective but there must also be a strong magnetic field in the southward direction, as viewed from the Earth. (Gosling et al., 1991; Zhang et al., 2007). This is due to the geomagnetic field, which protects the Earth from most of the solar wind. The region inside the Earth's magnetic field, the magnetosphere, forms a pressure balance with the incoming solar wind. The solar wind, which has a comparatively weak magnetic field, has a much a higher thermal pressure than magnetic pressure. The magnetosphere, due to the strong geomagnetic field, is dominated by magnetic pressure. The point where the mostly thermal pressure of the solar wind and the magnetic pressure of the Earth balance is called the magnetopause. Currently, the magnetic north pole of the Earth is at the geometric north pole, meaning the magnetic field of the Earth is aligned such that the field is pointing in the northward direction.

A CME with a parallel or mostly parallel magnetic field with that of the Earth will be harmlessly deflected around the magnetopause and will cause little in the way of observable space weather effects. However, a magnetic field that is anti-parallel with the geomagnetic field will cause magnetic reconnection along the magnetopause. Magnetic reconnection is the process through which two oppositely point magnetic fields are forced together, creating two new fields perpendicular to the original fields. The plasma along these fields will flow out from the original reconnection site.

When reconnection happens at the front end of the magnetosphere, this will "open" the magnetosphere and allow energy from the CME inside. This will create open field lines, which will be pushed towards the geomagnetic tail. This will cause reconnection in the tail, sending energy back towards the Earth (Dungey, 1961). This energy can cause observational phenomena such as aurora and harmful space weather effects at the Earth. An illustration of this process can be seen in Figure 1.5. The direction of the internal magnetic field of the CME will determine whether or not it is geoeffective, the strength of the storm will be influenced by other factors like the the magnetic field magnitude, the duration of the cloud through the Earth of the CME and the presence of other heliospheric structures with which the CME has interacted (Lugaz et al., 2015; Chen et al., 1997). Gonzalez et al. (2004) also show a correlation between the speed of the CME and the magnetic field strength of the CME.

It is possible for the sheath plasma to have a southward pointing magnetic field capable of causing geomagnetic storms, it is however more difficult as the sheath is made up of solar wind plasma with a much weaker magnetic field magnitude compared to the CME. Still, Zhang et al. (2008) show that, on average, the shock-sheath region contributes about 30% of energy input into the magnetosphere during a CME event. For some events, this percentage can be more than 80%. Regardless of the role of a sheath in specific geomagnetic storms, the full sheath geometry is still an important area of study, as shock waves are also capable of accelerating energetic particles that have their own space weather impacts.

Shock waves are capable of driving Solar Energetic Particles (SEPs), with energies that reach GeV levels and 80% of the speed of light. SEPs can be driven in two different ways. The short duration, impulsive SEPs are related to powerful solar flares emitting particles from the low corona. Longer lasting SEP events come from CME driven shock waves, which continue to accelerate the particles as wave propagates in the heliosphere. SEPs



Figure 1.5: A cartoon illustration of the magnetic reconnection that occurs when a strong southward magnetic field interacts with the magnetosphere. The grey boxes indicate sites of reconnection. The southern Interplanetary Magnetic Field hits the northward geomagnetic field at the point of the box on the left, which opens the geomagnetic field and deposits energy at the tail, where the second reconnection occurs. The blue lines are solar wind field lines, the green lines are closed geomagnetic field lines and the red lines are open geomagnetic field lines Figure taken from (Nat, 2004).

can be observed in radio observations as Type II radio bursts when related to CME driven shocks. This should not be confused with the impulsive type III radio burst, associated with powerful solar flares (Reames, 1999; Gopalswamy et al., 2002; Kahler & Reames, 2003). SEPs are an important space weather concern because they can electrically charge components of spacecraft and and satellites, degrading circuitry and damaging hard drives. SEPs can also be physically harmful to astronauts.

SEPs are often associated with the passage of a CME driven shock wave through a magnetic field line connected to the Earth (or another observer) (Gopalswamy et al., 2014; Kozarev et al., 2015). To understand SEPs, it is important to understand the exact geometry and location of all parts of the shock front, making a careful study of shock propagation and geometry crucial for understanding SEP events. One of the observational aspects in this dissertation is an attempt to fit the geometry of the shock front in the heliosphere. If this were to be combined with an interplanetary magnetic field model, it could lead to a better understanding of strong SEP events.

Understanding the shock/sheath region is also important observationally. Observations of the CME beyond the low Solar Corona will be essentially proxies for density (explained in detail in the next section) and as the CME flux rope propagates and expands, density drops making it less visible in observations. However, the sheath region traveling in front of the CME will still be visible with the right image processing techniques.

With the wide array of potential damage that can be caused by CMEs, studying their evolution and propagation is vital if we want to predict their arrival at the Earth and minimize the space weather effects. This is the significance of studying CMEs and the next subsection will discuss the roll different types of observations in helping to achieve the goal of understanding CMEs. The purpose of this dissertation will be to study CMEs in the heliosphere with two specific aims. The first, focusing on the space weather aspects, will be to, using a combination of observations and simple analytical models, detail my efforts to develop an accurate but method of predicting CME arrival at the Earth. This is no easy task, and has been attempted for many years. One of the unique aspects of my work is that I attempt the prediction of both the sheath and ejecta fronts at the Earth. While this dissertation did not directly lead to an operational forecasting tool, it did lead to a proof of concept that may provide a path for accurate space weather prediction.

The second aim will focus less on the practical space weather concerns at the Earth and focus more on a scientific study of the physics governing Coronal Mass Ejection propagation and shock/sheath generation. There are obvious areas of overlap between these two goals, as understanding detailed physics will help develop an accurate empirical model, and having an accurate empirical model should help constrain our knowledge of the actual physics occurring in a CME.

Throughout the history of CME research, there has been some dispute in the community over terminology. To avoid confusion, I will follow a convention similar to Rouillard (2011). The entire in situ signature including shock, sheath and ejecta will be referred to as an ICME (Interplanetary Coronal Mass Ejection). Within the ICME, the shock (if the event has one) refers exclusively to the shock wave running in the front of a fast CME. Throughout the rest of this dissertation when discussing events as a general group, I will use sheath front to determine the outer boundary of all sheaths, including shocks. The separate study of the ejecta and sheath is one of the key contributions of my work.

1.2 CME Propagation and Evolution

Recent observational advances have provided much more data to help constrain the understanding of how CMEs propagate in the heliosphere. There are already a number of theoretical and empirical models capable of approximating the kinematics of a CME. Without considering the specific details of any model, there are a few basic properties of CME evolution that are necessary to explain CME observations. It is well established that CMEs have to expand to go from the observed structures near the Sun to the size seen at 1 AU. Fast CMEs have to slow down, as the speeds observed in coronagraphs for many events are much faster than what is observed in situ for most events and would produce arrivals at the Earth well before what is observed. All models will be based on some sort of measurement-based input, to determine the CME speed as the first boundary condition for propagation. Even though many CMEs still have higher speeds than the solar wind as observed in situ, but it has been seen that at 4 to 5 AU, CME speeds will be very similar to the solar wind. (Gosling et al., 1994). Each model then has it's own term that controls the rate at which the CME accelerates. As CMEs are generally seen to have a speed trending towards that of the solar wind, many models will also have a final asymptotic speed.

A number of purely empirical models used for space weather prediction have been developed. Sheeley et al. (1999) used an exponential function to determine the velocity (V) at a point (r) based on the asymptotic height and speed (V_a, r_a) and the initial height (r_i) and the speed at that height $(V(r_i))$.

$$V^{2}(r) = V_{a}^{2} \left[1 - e^{-\left(\frac{r-r_{i}}{r_{a}}\right)}\right]$$
(1.1)

Gopalswamy et al. (2005) found additional empirical relationships, the Empirical CME Arrival (ECA) and Empirical Shock Arrival (ESA) model (Gopalswamy et al., 2005) have been used to predict the arrival times using a large number of CMEs to determine average kinematics. The advantage of an empirical model such as this is the limited input information required to calculate. In the case of the ECA model, the arrival is based only on the near-sun speed of the CME.

$$a = 1.41 - 0.0035u \tag{1.2}$$

where a is the acceleration of the $\text{CME}(m/s^2)$ and u is the CME velocity near the sun (km/s). The empirical model can be calculated instantaneously once the speed is determined. The usefulness is limited by the simplicity of the model, which fails to accurately recreate arrivals and propagation characteristics for many events. On average these empirical models will do well, but for an individual event may struggle if the ejecta and solar wind it encounters differ from typical conditions.

A number of models exist as well (Kim et al., 2010), and most are qualitatively similar. Wood et al. (2012, 2009) assume a three part kinematic evolution with a constant acceleration phase near the Sun as the CME goes from rest to its maximum speed followed by a constant deceleration until the CME reaches its final, constant velocity for the remainder of its propagation. Some models (Reiner et al., 2007) assume a linear change in the velocity and an eventual constant velocity as determined by the in situ solar wind speed. Other models focus farther from the Sun when the CME is moving at a more constant velocity and focuses on an average, constant speed (Tappin & Howard, 2009) or, fit CME height data without assuming a prior function at all using splines and get velocity profiles from those, still producing the same type of kinematic profile as the less flexible models.(Byrne et al., 2013).

After performing analysis using an exponential function based upon that of (Sheeley et al., 1999), I decided that this model, while capable of capturing the basic features of CME propagation, did not sufficiently represent the physics governing CME evolution and it would be difficult to get much physical insight from this model. For this reason, the main model I have used in my work will be the Drag-Based Model (Vršnak et al., 2013) which will be presented in detail as part of Chapter 3. The basic premise of this model is that the CME is done accelerating very close to the Sun. As soon as the CME reaches its maximum velocity it will then start slowing down as it collides with the solar wind, due to aerodynamic drag from the solar wind plasma. As the CME gets slower and slower, the effect of the drag experienced will be lessened as the difference between the solar wind speed and CME speed becomes smaller. Eventually the CME velocity will reach the speed of the ambient solar wind. In theory, slow CMEs will be pushed by the faster solar wind from behind. This may not actually be the case for slower CMEs, as Sachdeva et al. (2015) show that for slower CMEs drag is negligible. For this dissertation, the focus is on events faster than the solar wind, which are shown to be well-explained by the drag model in the same study. These faster events tend to be more energetic and therefore more geoeffective, so focusing on them should keep the focus on the more important events.

The most significant improvement to this drag-based model that I have made is an attempt to use measurement of the CME to constrain the inputs to this drag model, rather than just use empirically derived values for these parameters. This means my model will more accurately describe the specifics of an individual CME, which can both improve prediction and allow for more accurate physical profiles to be obtained. Also, as one of the main focuses is to differentiate CME studies between the sheath and ejecta, I also show that while the drag model can capably recreate sheath evolution, the physics of the drag model are not capable of fully explaining the sheath and therefore the drag model is less useful in a predictive sense and for truly understanding sheath propagation.

Chapter 2: CME Observation and Measurement

Phenomena associated with CMEs were first observed in 1859, with the famous 'Carrington Event', often considered the most powerful solar eruption ever observed. These observations continued and improved in the 20th Century as radio bursts, shocks and energetic particles associated with CMEs have been observed since the 1940s (Wild et al., 1954; Forbush, 1946). The forerunner of modern CME imaging from space was first performed in the 1970s by OSO-7 and Skylab(MacQueen et al., 1980; Tousey et al., 1973), P78-1 (Solwind) (Sheeley et al., 1980) and the Solar Maximum Mission (SMM) (Hundhausen et al., 1994) as well as ground based-coronagraphs (Illing & Hundhausen, 1985; Fisher et al., 1981; Hirayama, 1974; Demastus et al., 1973). A more complete description of the observational history of a CME can be seen in the Webb & Howard (2012) Living Review Paper and the Schwenn et al. (2006) Space Science Review.

In the past these observations were very limited in the spatial range they covered, making a full observational study of a CME in the heliosphere impossible. This lack of observations between the Sun and the Earth made truly understanding CME evolution extremely difficult.Near the Sun CMEs had been observable in coronagraphs, white light observations of the solar corona. A CME is seen through these observations based on Thomson scattering, where photons flowing radially from the Sun are deflected by the electrons in the CME. This makes the white light measurements a proxy for density, as the more electrons there are in a given space the more photons will be scattered. (Howard & Tappin, 2009a).

Each pixel in these images is a column density along the given line of sight. The images are projections onto the plane of the sky of the observer, which can make it difficult to infer three-dimensional structures from a single viewpoint. The scattering process is also more effective near the instrument plane of sky, so if there is more CME material there is perpendicular to the observational line of sight, the scattering will be more efficient relative to the observer. These factors complicate the ability to properly interpret a single CME observation, but if multiple view points are combined over multiple time steps, the CME motion can be easier to establish.

2.1 CMEs In Situ

Besides near sun observations from coronagraphs, CMEs can also be observed near the Earth through in situ measurements. Satellites like the Advanced Composition Explorer (ACE), located at the Lagrangian L1 point between the Sun and the Earth, take measurements of the vector magnetic field and of plasma parameters like density, temperature and velocity (Stone et al., 1998). The various structures can all be identified in the solar wind to identify the arrivals and approximate the size of the structures (Cane & Richardson, 2003).

CMEs can be seen in multiple signatures in these measurements, including a rotating magnetic field, bi-directional electron flows, a low temperature, a low density and a very low plasma β , meaning the magnetic pressure is much stronger than the plasma pressure.

$$\beta = \frac{nKT}{B^2/2\mu_0} \tag{2.1}$$

where n, T, and B, are the density, temperature and magnetic field respectively. K and μ_0 are Boltzmann's constant and the permeability of free space, both constants. In the solar wind, the two pressures are of similar magnitudes and this value is around 1. In the presence of a CME at 1 AU, which has a very strong magnetic field and low density and temperature, $\beta << 1$.

Example solar wind plots showing a shock, sheath and magnetic cloud flux rope from the July 14, 2012 ICME are included in Figures 2.1, 2.2 and 2.3. The red line denotes the onset of the shock wave at approximately 17:00 UT on the 14th, seen in the sudden increase in magnetic field, velocity and temperature. This particular event doesn't show the typical



Figure 2.1: ACE data of the July 14, 2012 CME. The plots show, from top to bottom: the Dst index, indicating the level of geomagnetic activity; the total Magnetic Field and the Magnetic Field in the z (north-south) direction; total velocity, proton number density; proton temperature along with the expected proton temperature based on velocity; and the plasma β , or the ratio between plasma pressure and magnetic pressure. The red line is the shock wave onset, the solid blue line is the approximate flux rope arrival and the dashed line is the approximate end of the ICME. The Dst index is not based on ACE data, but on ground stations on the Earth based on the strength of the ring current in the magnetosphere.



Figure 2.2: ACE magnetic field data of the July 14, 2012 CME. The plots show, from top to bottom: magnetic field strength, magnetic field in the x (Sun-Earth), y (east-west), and z (north-south directions) respectively, the magnetic θ (with respect to the ecliptic plane) and ϕ (with respect to the Sun-Earth line). The red line is the shock wave onset, the solid blue line is the approximate flux rope arrival and the dashed line is the approximate end of the ICME.



Figure 2.3: ACE velocity data of the July 14, 2012 CME. The plots show, from top to bottom: velocity strength, velocity in the x (Sun-Earth), y (east-west), and z (north-south directions) respectively, the velocity, θ (with respect to the z-y plane), the velocity θ (with respect to the cliptic plane) and velocity ϕ (with respect to the Sun-Earth line) and the ram pressure. The red line is the shock wave onset, the solid blue line is the approximate flux rope arrival and the dashed line is the approximate end of the ICME.

jump in density expected in a shock (though there is still a slight increase at the proper time; for this event it appears to be minor compared to a jump in density observed in the middle of the sheath). The blue line is the onset of the ejecta at approximately 07:15 UT on the 15th, evidenced by the slow decline in the strength of the velocity and magnetic field strength and the lowered temperature, density and plasma β .

In situ, these classical flux rope signatures have been known as Magnetic Clouds (Lepping et al., 1990). Many ICME signatures lack all the clear signatures of the magnetic cloud. This is because the spacecraft is sampling a very select region of the passing CME, the further a piece of the CME is from the nose, the weaker these signatures become. Many times the most complex in situ signatures correspond to the CME leg passing through the Earth (Zhang et al., 2013).

The magnetic data in Figure 2.2 shows rotations (changes in polarity) in all three directions. The velocity data seen in Figure 2.3 shows a sharp increase in all three directions at the shock and the flux rope shows little in the y and z directions. Also seen in 2.1 is the Disturbance storm time (Dst) index an indication of the strength of the ring current around the Earth. For this epoch, the Dst has a peak of -127 and is indicative of a fairly strong geomagnetic storm beginning shortly after the shock arrival and lasting for almost three days before activity levels returned to quiet levels. An event causing a Dst below -100 is considered strong, and a Dst below -200 is considered exceptionally strong.

As part of this dissertation a comprehensive list of ICMEs in situ has been generated using data from ACE. The list was created with an automatic detection algorithm that was manually checked and cross-referenced with other lists. This algorithm determined time ranges showing at least a few of the classic magnetic cloud signatures like high magnetic field, low density and low temperature.

After manual determination as to whether each event was a CME and not a false detection (false detections were common, especially for Co-rotating Interaction Regions (CIRs), an interplanetary transient formed by a high-speed solar wind stream colliding with a slower speed stream in front of it.) the events were divided into three groups. The "textbook" events which indicated all or nearly all expected ICME structures, the middle quality events which showed most of the expected signatures and the weakest events, which showed enough to indicate the passing of a CME but were missing many of the key signatures, probably indicating the spacecraft is encountering the CME well away from the nose.

This list, going from 2006 through early 2015, is publicly available as part of the International Study of Earth Affecting Solar Transients (ISEST) Program and contains almost all data associated with each event including flare association, location on the sun, measured velocities, geoeffectiveness, in situ data plots and other data, as well as a discussion board for researches to comment on each event and can provide researchers with a resource of useful events (Shi et al., 2015).

2.2 CME Imaging

ICME identification from in situ data has been important for identifying CMEs near the Earth. The in situ observations are unable to provide any information before the CME reaches the observer. In order to find out information about a CME closer to the sun, it is necessary to use remote sensing data to observe a CME from a distance. The remote sensing data has different types, but is vital. All current CME models, both for real time forecasting and for general study, are based upon measurements obtained from remote sensing observations. The better the quality of observations, and the better the interpretation of the observations, the more accurate the inputs into a forecasting model can be.

Remote sensing observations improved with the launch of the Solar and Heliospheric Observatory (SOHO) in 1996. SOHO is a satellite which, like ACE is at the L1 point and continuously observes the Sun. The most significant instruments on SOHO from a CME perspective is a series of coronagraphs called the Large Angle and Spectrometric Coronagraph (LASCO) with a field of view that extends beyond 30 R_{\odot} (Brueckner et al., 1995). Among many other instruments, SOHO also holds the Extreme ultraviolet Imaging Telescope (EIT) for observing the Sun at four different extreme ultraviolet (EUV) wavelengths, 171 Å, 195 Å, 284 Å, and 304 Å (Delaboudiniere et al., 1995) and the Michelson Doppler Imager (MDI), measuring the line of sight photo spheric magnetic field (Scherrer et al., 1995), though these instruments are no longer operational. With this combination of instruments, it became possible to see the flare or prominence eruption in the EUV wavelengths and track the CME in the white light out to 30 R_{\odot} and also observe the magnetic configuration on the Sun that gave rise to the eruption.

While SOHO greatly improved CME observations near the Sun, the 30 R_{\odot} limit left a large gap in CME observations between the coronagraph field of view and the in situ measurements at L1. This made it difficult for many events to connect the remote sensing observations near the Sun and the in situ signatures. There are other observational data sets such as radio observations from IPS (Manoharan et al., 2001) and white light data from the Solar Mass Ejection Imager (SMEI) (Jackson et al., 2004). However these data sets are limited in cadence and resolution and clearly observing CMEs from these data sets is difficult.

The next significant leap forward in CME observations in the heliosphere came in 2006 with the Solar Terrestrial Relations Observatory (STEREO). The mission comprised of two separate but nearly identical satellites in near Earth Orbits. One satellite, STEREO-A is orbiting ahead of the Earth (relative to the Sun-Earth line) at a distance of slightly less than than 1 AU and STEREO-B is orbiting behind the Earth (again relative to the Sun-Earth line) at a distance of just over 1 AU, so the two satellites are moving about 22.6 $^{\circ}$ per year in opposite directions relative to the Earth (Howard et al., 2008). An example of the configuration of the different observational viewpoints is shown in Figure 2.4.

STEREO was a leap forward for heliospheric imaging that had two distinct advantages. The two satellites, observing with the same instruments at approximately the same time, allows for a three dimensional reconstruction of a CME. This makes it much easier to determine an accurate three dimensional structure and velocity compared to the two dimensional plane-of-sky projections offered with just a single view, a significant improvement for CME tracking (Mishra & Srivastava, 2013; Möstl et al., 2014) By using both STEREO satellites


Figure 2.4: The relative location of STEREO-A, STEREO-B and the Earth (where SOHO, ACE and SDO are approximately located) on July 12, 2012.

(and possibly adding in a third viewpoint from the Earth's point of view with LASCO) it is possible to combine multiple observations to determine a unique three- dimensional geometry (Thernisien et al., 2006). It also makes it easier to observe many CMEs by providing a viewpoint away from the Earth.Thomson scattering, the process through which remote sensing, white-light images are generated, is most effective at an angle of 90° from the observer. (Howard & Tappin, 2009a). This means that when observing an Earth directed CME, SOHO is not at an optimal position to see the the CME-scattered photons. For many events, the side-angle view also provides a perspective in which it is easier to see the CME and separate the ejecta and sheath structures than a CME that is propagating directly at an observer.

The other important advance from the STEREO mission is from the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) suite of instruments, which allow for complete and continuous imaging from the Solar surface to beyond 1 AU. SECCHI contains five separate instruments, the Extreme Ultraviolet Imager (EUVI), similar to SOHO's EIT, two coronagraphs, COR1 and COR2, which observe Thomson scattered light in ranges from about 1.4-4 R_{\odot} and about 2.5-15 R_{\odot} respectively and two heliospheric imagers, HI-1 and HI-2 which have rangers of about 15-84 R_{\odot} and about 66-318 R_{\odot} . These distances will change slightly based on the pointing of the satellite and the angle being observed relative to the plane of the sky. The heliospheric imagers, like the coronagraphs, observe Thomson scattered white light but unlike coronagraphs are not pointed at the Sun, allowing for a higher spatial coverage. By combining observations from each instrument, a CME can be tracked continuously from its onset in the low corona well into the heliosphere (Howard et al., 2008). Images from COR2 in both the A and B satellites, on July 12, 2012 at 17:24 UT showing both the flux rope and shock front are presented in Figure 2.5. Heliospheric imager data is shown in Figures 2.6 and 2.7.

In addition to SOHO EIT and STEREO EUVI, the Solar Dynamics Observatory (SDO), another approximately Earth-based observer, was launched in 2010. Among the instruments on board SDO was the Atmospheric Imaging Assembly (AIA), another ultraviolet imager,



Figure 2.5: STEREO COR2 images from both STEREO-B (left) and STEREO-A (right) from July 12, 2012 at 17:24 UT. The shock front and flux rope are noted in each image.



Figure 2.6: STEREO HI-1 running difference images from both STEREO-B (left) and STEREO-A (right) from July 13, 2012 at 00:49 UT. The bright feature most evident in STEREO-A is interpreted as the sheath region of heightened density between the shock front and the CME ejecta. This means the shock front in considered to be the outermost part of the bright front, and the flux rope is the innermost part of the same feature.



Figure 2.7: STEREO HI-2 running difference images from both STEREO-B (left) and STEREO-A (right) from July 14, 2012 at 06:09 UT. By the time the CME is in the HI-2 field of view, it is very difficult to separate the shock font from the ejecta, especially because the density of the CME has lowered to the point it is almost indistinguishable from the background.

but with unprecedented spatial and temporal resolution that allows for 4096x4096 pixel images with time cadences of 10-12 seconds (Lemen et al., 2012). With this new observational power, capturing eruptive phenomena in the solar corona to use as inputs for CME tracking has become much easier. AIA has provided important images for those studying CME initiation, and SDO also has its own photospheric magnetic field observer, the Helioseismic and Magnetic Imager (HMI). In addition to the improved temporal and spatial resolution, HMI observes not just the line of sight magnetic field, but the full vector field in the photosphere. For the purposes of studying CMEs in the heliosphere, the primary advantage of these instruments is an increased ability to see the source location and initial tilt of the ejecta compared to the polarity inversion line of the associated active region. An example of Active Region 11520 (S17° W08°), the source of the July 14, 2012 ICME as observed by multiple SDO AIA wavelengths and HMI is shown in Figure 2.8.



Figure 2.8: A combination of observations from SDO on July 12, 2012 at 19:40 UT showing AR 11520 (S17° W08°), the source of the July 14, 2012 ICME. The CME was associated with an X1 class flare. The wavelengths shown are (top, left to right): 171 Å, 193 Å, 131 Å, (bottom, left to right): 304 Å, 1600 Å, and the HMI line of sight magnetic field. The different wavelengths observe plasma at different temperatures, allowing for different structures to be highlighted in each

2.3 CME Tracking

The images provided by satellites like STEREO, SOHO and SDO have allowed for detailed observation of the complete evolution of a CME from its eruption until it is well passed the Earth. However, to use these images to determine arrival times and velocity profiles, the question of how to derive true CME heights is an important and complex issue. There have been several models and techniques used to obtain the heights (Liu et al., 2010; Mierla et al., 2010; Tappin & Howard, 2009; Lugaz et al., 2009; Möstl et al., 2009; Thernisien et al., 2009; Byrne et al., 2013; Colaninno et al., 2013; Vršnak et al., 2014; Möstl et al., 2014), and for this study two main methods of deriving heights have been utilized.

The first of these methods is the raytrace method developed by Thernisien et al. (2006, 2009) which uses a Graduated Cylindrical Shell (GCS) or croissant geometry to recreate the full geometric shape of the CME from multiple viewpoints. The GCS geometry is defined by six free parameters. These parameters are the direction of propagation of the CME through the heliosphere (longitude and latitude), the half angle width of legs, the tilt angle with respect to a solar latitude of the shell central axis, the ratio between the major and minor radius of the shell (the aspect ratio) which controls the thickness of a cross-section of the croissant, and the height or distance of the leading edge of the shell from the Sun. By keeping the first five of these parameters fixed and adjusting only the height, images from STEREO-A, STEREO-B and SOHO can be combined (at as common a time as different cadences will allow) to determine the leading edge height of the CME. While keeping these parameters fixed to take the measurements may miss any dynamic changes in the CME from being captured, for many CMEs propagating freely into a simple solar wind, these effects should be minor. This is especially true when the CME is closer to the Sun.

The so-called "croissant" shape of the GCS model works for the ejecta, as it is designed to geometrically model a flux rope. The sheath region has a different structure, that appears more spherical observationally. To geometrically model the sheath, a spheroid bubble is used which has been shown to accurately capture the low corona sheath (Kwon et al., 2014) and continues to be effective into the heliosphere. As part of Hess & Zhang (2014), I applied this geometry to a CME beyond the low corona, out to 80 R_{\odot} . The "bubble" used to model the sheath area also has six free parameters. Some of these, also in the flux rope model, are propagation direction (longitude and latitude), tilt, and height. The other two parameters, control the eccentricity and centroid of the spheroid.

As this work is focusing mostly on the shock and ejecta leading edges, less attention was paid to eccentricity and centroid, which are more important to the detailed 3-dimensional sheath geometry but less important for getting the leading edge height along the nose of the shock. Another assumption I have made in making these measurements is that the CME nose and the shock nose are aligned in the same direction. Both features can be measured in such a way that the heights along the leading edge can be tracked, leading to an understanding of the independent evolution of each front, as well as the size of the sheath region between them. The distance between the CME nose and the shock nose is called the standoff-distance, and is an important parameter for defining the sheath (Maloney & Gallagher, 2011; Bemporad & Mancuso, 2010) and may be able to be used to measure the strength of the coronal magnetic field (Kim et al., 2012).

It has been shown before that in addition to having obvious signatures in in situ data, shocks of sufficient strength can also be seen in white light images (Ontiveros & Vourlidas, 2009; Maloney & Gallagher, 2011; Bemporad & Mancuso, 2010; Vourlidas et al., 2003). Using different image processing techniques, either the sheath front or the flux rope portion of the structure can be highlighted (Hess & Zhang, 2014). For the ejecta, a base or average background is subtracted from the observational image, which brings to focus to core of the CME structure. Using a running difference technique, where the previous image is subtracted from the current image, highlights the outermost structure in each image. This will correspond to the sheath. An example of the different techniques on the same image with each front highlighted is shown in Figure 2.9. Doing this for a number of events, both the ejecta and sheath front can be tracked independently of one another, and also compared to ICME signatures in situ.



Figure 2.9: Tracking CME ejecta using the direct image (left) and the shock front using the difference image (right) Images from STEREO A COR2 at 17:54 UT on July 12, 2012 are used as an example. The image on the left is a base-ratio direct image where the flux rope or ejecta (outlined by the blue line) is better shown. The bright feature at the bottom of the ejecta outside the blue line is believed to be a disturbed streamer. The shock front is better seen in the running difference image in the right (demarcated by the red line).

Using both of these geometries to model each respective front, the entire structure can be reconstructed from multiple viewpoints as long as images are taken at approximately consistent times. Performing measurements over many time steps provides a true, threedimensional height-time profile of each front. Figure 2.10 shows images from the STEREO viewpoints for the July 12, 2012 CME with and without the associated geometries. The LASCO view is not included because SEPs caused a data gap covering most of time of the CME in the LASCO FOV. For most events, two distinct viewpoints are enough to constrain these geometries.

Another method for getting a height time profile for a CME comes from the use of so-called j-maps (Sheeley et al., 1999). A j-map is generated by taking images from a satellite and, at a given latitudinal angle extracting strips with a width of a few pixels (the exact width differs depending on the range of the instrument). A strip at specific latitudinal position angle is taken from the satellite observations for a series of time steps and these strips are then combined together to form an image with time on the x-axis and the elongation angle (a proxy for distance) along the y axis. When using running difference images, these transients appear as bright streaks in the j-map, with the elongation angle increasing with time. Example j-maps from both STEREO-A and STEREO-B from July 2012 are shown in Figure 2.11, along with the measured location of the CME from each j-map.

However, due to observational effects (Howard & Tappin, 2009a; Lugaz et al., 2009; Rollett et al., 2012) obtaining a true height from a j-map is a complicated task, as the elongation angles are measuring projections from the satellite in the plane of the sky. Without knowing the exact shape and angular distance of the observer to the specific feature being observed in the j-map, the elongations cannot be perfectly converted to heights. However, these heights can be estimated through various techniques by making a few geometric assumptions and assuming a known propagation direction.

The simplest method used for getting true heights from j-map elongation angles is called



Figure 2.10: Model fitting of CME ejecta and shock front. Images at 17:54 UT on July 12, 2012 from STEREO A COR2 (Left) and STEREO B COR2 (Right) are shown along without (top) and with (bottom) the model mesh. The green mesh shows the GCS fitting to the CME ejecta, while the red mesh shows the spheroid fitting to the CME shock front.



Figure 2.11: j-maps of the July 12-14, 2012 CME for each STEREO spacecraft along the propagation angle as measured by the Raytrace method. The CME is clearer in STEREO A. The bright density enhancement is considered the sheath region of high density. The edge leading this sheath is considered the shock front. The red crosses show the elongation measurements used for the shock obtained from each j-map.

the fixed- φ and is given by

$$R = D_{obs} \frac{\sin(\varepsilon(t))}{\sin(\varepsilon(t) + \varphi)}$$
(2.2)

where ε is the elongation angle of the object being tracked, as determined from the j-map and φ is the direction of propagation of the CME, relative to the observer and D_{obs} is the distance from the observer to the Sun.

This method is valid in distances close to the Sun but is much less accurate the farther the CME is in the heliosphere. The fixed- φ expressly assumes that the feature being observed in the j-map is the exact leading edge of the CME front. When the angle between the observed feature and the Sun is low, this is a good assumption however, due to the spherical nature of the CME front, as the CME propagates outward fixed- φ will lead to a significant over estimation of the true CME height.

For this reason, at distances farther from the Sun, the harmonic mean method is used, which has a similar formulation to fixed- φ but introduces an extra term to scale back the height. Of all methods utilizing single spacecraft observations, Mishra & Srivastava (2013) found the harmonic mean method to be the most successful. The equation for this method is

$$R = D_{obs} \frac{2sin(\varepsilon(t))}{1 + sin(\varepsilon(t) + \varphi)}$$
(2.3)

This equation represents the harmonic mean between the fixed- ϕ and the Point-P method, given by

$$R = D_{obs} sin(\varepsilon(t)) \tag{2.4}$$

which is the simplest and least accurate method of deriving true heights from singlespacecraft observations. Though flawed, the Point-P method tends to under-estimate the true heights, and helps balance the over-estimation of the fixed- ϕ method accurately, despite being somewhat arbitrary (Lugaz et al., 2009).

For both the harmonic mean and fixed- φ methods, the direction of propagation was taken from the GCS model measurements. While this may introduce a bias as I look to use the two measurement sets for purposes of cross- validation, I am confident that the propagation direction is among the lowest sources of error in the GCS fittings.

Both of these methods of measurements have their own issues and obstacles to overcome. For the GCS Model, with the six different parameters, finding one unique solution that works throughout the propagation of the CME can be difficult, and for some events that are highly dynamic, may not even be possible. It is especially difficult to maintain consistency when the CME passes from one field of view to another, for instance from COR2 into HI-1. This is because of the assumption that goes into trying to use the raytrace method to impose a geometry on the observations, which is that not only does the CME have this GCS flux rope geometry, but that this geometry stays largely static as the CME propagates. Close to the Sun, this may be true. But as the CME propagates, one key assumption of the GCS model, that the ejecta continues to expand self-similarly, will definitely break down in the heliosphere. In addition to changes in the flux rope ejecta itself, the CME will also interact with the highly complex and variable solar wind environment. The GCS model will not take these factors into effect, meaning for some complex events the fittings will not work. However, for more textbook events, the GCS model has been effectively used as a powerful tool for CME reconstruction (Poomvises et al., 2010; Nieves-Chinchilla et al., 2012; Colaninno et al., 2013; Hess & Zhang, 2014; Shen et al., 2014a; Shi et al., 2015).

The GCS model is also limited in its ability to capture the ejecta for basic observational reasons as well. After the CME erupts and the ejecta is a few R_{\odot} and no longer accelerating, its mass will be largely conserved. However, due to the internal magnetic pressure of the ejecta as well as interaction with the solar wind, the CME will expand as it propagates. Therefore, as the CME leaves the Sun, its volume will increase and its mass will say roughly constant, leading to a constant decline in the density. As explained, the remote sensing measurements of the CME beyond the very low corona are taken in white light and are essentially density measurements as the higher the density in a space, the more electrons will be Thomson scattered. This means that, as the ejecta propagates into the heliosphere it is getting progressively more faint and difficult to observe. For most events, this means that somewhere in the STEREO HI-1 FOV, it is essentially impossible to differentiate the ejecta from the background.

Generally, faster CMEs are more energetic and more massive, so these events maintain a visible density farther from the Sun. However, being faster, they also get farther from the Sun more quickly while slow events, which can be more difficult to image, provide the advantage of staying in high visibility ranges for more observational frames. The net result of this effect is that faster ejecta are visible at greater distances from the Sun, but the number of actual observations that can be used to measure an ejecta are often very similar for both fast and slow events.

Because of the inability of the GCS model to properly capture the evolution of the ejecta as it propagates, most ejecta can be fit to somewhere between 30 and 80 R_{\odot} . The sheath can still be observed well beyond the ejecta through running difference images but

will evolve enough that the geometric reconstruction loses validity too far from the Sun.

For the j-maps, in addition to errors introduced by the geometric manipulations to get the true height, there are also errors in the j-map itself. To create the j-maps, a number of smoothings and processing techniques must be employed, introducing more ambiguity into the heights that can be derived from them. Given the high level of noise in the data, it is also challenging to automatically detect the correct heights, so the current elongation selection is done by hand, introducing a potential error of a few pixels, which can represent a vast distance in the larger instrument fields of view. For highly active periods of solar activity, it can also be difficult to separate the multiple streaks to measure the event in question, even if the two CMEs do not physically interact.

The other significant weakness of the j-map, is an inability to measure the two separate CME fronts. In theory, a j-map using just base difference images could be constructed and used to measure the ejecta, but given the faint nature of the ejecta in observations and the heavy data processing necessary to create the j-map, a base difference j-map is of little use for measuring the ejecta. However, using running difference images the sheath appears as a continuous, well observed structure that makes it much easier to utilize the continuous coverage of SECCHI from the Sun to the Earth.

While acknowledging these errors, the multiple data sets allow for comparison and verification for the height data. Using the arrival of signatures in situ and comparing those times to the measurements from remote sensing observations is also useful as the in situ arrival provides a measurement in the heliosphere with a more definitive location. Height time data can also be compared to numerical models, where it is easy to get a true height measurement on a uniform time grid, for a further comparison.

Once the heights are determined, another issue is how to use the height data to get a velocity profile. As shown in Byrne et al. (2013), simply taking a numerical derivative of the measurements is not a reliable way to accurately represent the CME velocity. Typically, to get data that makes sense using a numerical derivative, the data must be manipulated and smoothed and this can introduce excessive levels of error. Error is also introduced by the

non-uniform time cadences of the different instruments and fields of view. Given all this information, it is typically more reliable to choose some sort of functional form to fit the data in height-time space and analytically derive this function to get a velocity and acceleration. The primary model chosen for this work is the previously mentioned drag-based model, and an explanation of how it has been used and what is unique to this dissertation is presented in the next section.

Chapter 3: Theoretical Modeling

3.1 The Aerodynamic-Drag Model: An Analytical Model for CME Propagation

The basic equation of motion for a propagating motion will be a combination of three fundamental forces: the Lorentz force (F_L) , gravitational force (F_G) and drag force (F_D) (Cargill, 2004)

$$M_* \frac{dV}{dt} = F_G + F_L + F_D \tag{3.1}$$

where M_* is the combination of the mass of the CME and virtual mass (M_V) , approximated as $\rho_{sw}V/2$ where V is the CME volume. The virtual mass is essentially the mass of the solar wind interacting with the CME. The gravitational force is significant near the Sun and provides an additional damping force that must be overcome for the CME to erupt. Given the inverse square nature of gravitation, this effect will decline rapidly as the CME propagates away from the Sun and as the CME continues to get deeper into the heliosphere can be neglected (Poomvises, 2010; Chen, 1996).

The CME will have two distinct Lorentz forces. Using the Eruptive Flux Rope (EFR) model (Chen, 1996) as an illustrative example, the CME can be seen as a curved flux rope with a toroidal shape with an overlying magnetic field. As can be seen in Figure 3.1, the flux rope is made of field lines wrapped around a central axis.

The external Lorentz force contribution comes from the interaction of the flux rope current and the overlying strapping field. This is essentially a magnetic drag force from the overlying magnetic field above the ejecta. This is another important force in the initiation of a CME, as the flux rope is in equilibrium with the overlying field initially. Overcoming the strapping force is one of the key processes in launching a CME. By the time the CME is propagating, the CME is no longer interacting with the strong magnetic field of the low solar corona, but instead the weaker field of the solar wind. This means that the magnitude of this force will be small in the heliosphere.

The internal Lorentz force, also called the hoop force, is a positive force on the bulk motion of the CME. As the field lines wrap around the curved central flux rope axis, they are more tightly compressed on the inner axis, causing the magnetic pressure to be higher on the inner axis. This will cause the CME to be pushed outward (there is also an internal hoop force acting on the CME minor axis, but this will affect expansion and have little impact on bulk motion). As the CME propagates and expands, the magnitude of this force will decline.

The fundamental assumption of the Drag-Based Model is that, beyond a few R_{\odot} , the internal Lorentz or hoop force will no longer have a significant influence on the CME. The CME will, rather than gaining any kinetic energy as a result of the Lorentz force, will instead be decelerated by the interaction of the ejecta with the solar wind. The CME will therefore have an initial speed that will gradually decline to the speed of the ambient solar wind. The larger the difference in velocity between the CME and the solar wind, the more of an effect solar wind drag will have on the CME.

Beginning with a hydrodynamic model for drag that has been adapted for CME use (Chen, 1996; Cargill, 2004; Vršnak et al., 2013),the drag-based model assumes that the force acting on the CME, and thus the way in which it decelerates, is governed by the square of the difference between the CME velocity and the ambient solar wind speed. Specifically, the formula governing the acceleration is

$$a = -\Gamma(v - v_{sw})|v - v_{sw}| \tag{3.2}$$

where v is the velocity of the CME (km/s), v_{sw} (km/s) is the ambient solar wind speed and Γ (km⁻¹) is the drag parameter.



Figure 3.1: The side-view geometry of the CME near the Sun from the EFR model. B refers to the magnetic field, J to currents, and F to forces. p,t,r are the poloidal, toroidal and radial directions respectively. Figure from Chen & Krall (2003)

Integrating the acceleration will lead to velocity and height profiles given by

$$v(t) = \frac{v_0 - v_{sw}}{1 + \Gamma(v_0 - v_{sw})t} + v_{sw}$$
(3.3)

$$R(t) = \frac{1}{\Gamma} ln [1 + \Gamma(v_0 - v_{sw})t] + v_{sw}t + r_0$$
(3.4)

It should be noted that these equations are the form for CMEs faster than the solar wind, which is the main focus of this dissertation. For slow CMEs, the basic form of both velocity and distance holds but there are some sign differences to account for the fact that the solar wind is pushing the CME forward rather than decelerating it. Most work using the drag model (Vršnak et al., 2014; Hess & Zhang, 2014) has focused on fast events, and there is some question if the slow CME formulation is actually correct (Sachdeva et al., 2015).

The drag parameter Γ is the term that will determine how quickly the CME will be decelerated, and is a function of the drag coefficient c_d , the CME size and ambient solar wind parameters of the form (Vršnak et al., 2013)

$$\Gamma = \frac{c_d A \rho_{sw}}{M_*} \tag{3.5}$$

where A is the cross-sectional area of the CME, M is the mass of the CME, ρ_{sw} is the ambient solar density and M_v is the CME virtual mass.

3.2 Applying the Drag-Based Model to Measurements of Each Front

An example of the raytrace measurements with the model fittings from each front is shown in Figure 3.2 for the July 14, 2012 ICME. The in situ arrivals are marked on this plot as well. The associated velocity and acceleration profiles are shown in Figure 3.3. The GCS and spheroid parameters of the fitting for the ejecta and sheath respectively are shown in



Figure 3.2: The raytrace measurements (black) for both the shock (stars) and ejecta (crosses) as well the ACE in-situ measurements (gold). The least-squares drag fittings of the data are included as the dashed red (shock) and solid blue (ejecta) lines.

full in columns 1-4 of Table 3.1. The top two rows show the flux rope and sheath parameters respectively for the full fitting with the in-situ data point included. Rows 3 and 4 show the parameters for a fitting without the inclusion of any in situ data (both arrival times and upstream solar wind speeds) to make the model more predictive. Also presented in Table 3.1 are the average in situ velocity of each front (column 5), the velocity of the drag model at the point it reaches 1 AU for each front (column 6) and the difference in time between the actual and modeled in situ arrivals (column 7).

The upstream solar wind speed observed by ACE before the arrival of the ICME signatures on July 14, 2012 averaged over a period of 10 hours is 353.7 km/s. The drag model is able to reproduce the speed of the sheath and the flux rope as observed in situ. At 1 AU both fronts were still in the process of decelerating and neither had reached the speed of the solar wind. The velocities from the model are very similar to what is observed in situ.

	Γ (/km)	V_0 (km/s)	V_f (km/s)	$R_0(R_{\odot})$	In Situ Velocity (km/s)	Drag Model (km/s)	ΔT (hours)
Ejecta	3.09e-8	1316.5	353.7	4.29	487.7	477.9	.69
Sheath	1.47e-8	1259.4	353.7	8.69	608.3	625.5	.89
Ejecta Prediction	6.15e-8	1423.8	500	4.29	487.7	571.5	-3.8
Sheath Prediction	4.77e-8	1548.6	500	8.69	608.3	598.9	4.2

Table 3.1: The drag fitting parameters of the two front and the in situ parameters from ACE. The ACE velocities are the average over the full in-situ time range for both the shock-sheath region and the ejecta.

This is a sign that the drag model is able to, using height-time measurements near the Sun and in situ data at L1, accurately capture both the flux rope and shock propagation. As would be expected, the arrival times and velocities are much more accurate with the in situ data plotted.

The drag parameter values, Γ , for each front, 1.47×10^{-8} and $3.09 \times 10^{-8} km^{-1}$, are similar to those derived theoretically in Vršnak et al. (2013). However, the great difference in the two separate Γ values is an illustration that the two fronts, while following a similar evolution are still separate and independent and that the ejecta undergoes more rapid and severe deceleration than the sheath. This indicates that either the sheath is undergoing less drag than the ejecta, or has energy being added to it as it propagates.

To estimate the error, we assume that the GCS method for the flux rope in COR2 has an error of \pm .5 R_{\odot} , with the total 1 R_{\odot} error representing about 3% of the total field of view of the instrument. This is doubled to \pm 1 R_{\odot} for the sheath, since it is so faint and diffuse near the Sun. For both fronts in HI-1, an error of \pm 2.5 R_{\odot} is used, which is a total error of about 7% of the HI-1 field of view. The increase in error in HI-1 is due to the increase in the ambiguity of the CME fronts at large heliospheric distance, as well as the errors introduced by the more significant image processing techniques needed to see the CME structures in the heliospheric imagers. This may be an underestimation of the error given the difficulty of performing accurate measurements in the HI-1 FOV. For the drag-model fitting of the ejecta, this yielded a χ^2 - value of 12.5. With 23 degrees of freedom



Figure 3.3: The top plot is the velocity profile for the fitted drag model for both shock (red dashed line) and ejecta (blue line). The bottom plot is the acceleration of the model.

in the fit, this gives a p-value for the fit of .96. For the shock, the χ^2 -value was 28.4 with 22 degrees of freedom, for a p-value of just .16. This still indicates a decent but worse fit compared to the ejecta.

There are a number of possible explanations for this difference, with possibilities including that the drag model is more physically descriptive for the flux rope in the solar wind than it is for sheath propagation. Still, the fit is good enough to provide an approximation of the sheath propagation, even if it doesn't physically explain the entire evolution of the sheath.

To confirm the sheath bubble measurements, they can be compared to the j-map data, as seen in Figure 3.4. This comparison cannot be done with the ejecta, as it cannot be observed in the j-map. Both fixed- φ and harmonic mean are included, rather than attempting to determine a point at which the latter begins to out perform the former. The data sets show qualitative agreement, at least before the fixed- φ data begins to blow up. There is no force that far from the Sun that would account for such an increase it height, so clearly the



Figure 3.4: The measured heights from the stereoscopic measurements (crosses) and j-maps, using both fixed- φ (diamonds) and harmonic mean (stars). The j-maps were taken along the CME leading edge, as determined by the GCS parameters. The observer distance used to get the heights was taken from the position of the STEREO spacecraft on July 13, 2012 at 12:00 UT.

fixed- φ method breaks down eventually. The j-map data is frequently under measuring the shock compared to the stereoscopic reconstruction in the low HI-1 FOV (50 R_{\odot}) but then the j-map height catches up and becomes larger than the GCS measurements. The velocity comparison between the raytrace/DBM data and the data obtained from the Harmonic Mean method on the STEREO-A j-map is shown in Figure 3.5.

Closer to the Sun, the j-map and raytrace velocities, as obtained from drag-based model fittings are similar, but grow more different as the CME gets further from the Sun, eventually differing by around 100 km/s. Because the geometric assumptions in the j-map conversions from elongation into height are known to break down as height increases (Rollett et al., 2012), it should be reasonable to blame this disparity on the errors in obtaining the heights from the j-maps. The data shown in Figures 3.4 and 3.5 are clearly different, but show



Figure 3.5: The velocity obtained from the STEREO-A J-Map Harmonic Mean data with both a numerical derivative (crosses) and by fitting the data with the DBM (dashed line). This is compared to the sheath velocity as determined from the DBM fitting to the raytrace measurements (solid line).

enough qualitative agreement to provide confidence in the GCS measurements, which should be more accurate and more able to measure the small scale velocity differences than the j-map methods given the combination of multiple viewpoints.

3.3 Modeling Each Front Without In Situ Data

While these fittings with the drag model are useful for demonstrating the ability of the model to fit the CME ejecta and shock, those fittings are not particularly useful for predictive purposes, because they include the in situ arrival of the fronts in the fitting and in situ solar wind velocities. In order to use the model for prediction, the fittings must contain only information that can be obtained early in CME propagation. To test the ability of the model to work in a predictive sense, the in-situ measurements must be removed to see if these same fittings can be recreated based solely on the height measurements closer to the Sun. Vršnak et al. (2013) show that a good range for Γ is 1×10^{-8} to $1 \times 10^{-7} km^{-1}$ and solar wind speed of 300-500 km/s for a typical solar wind upstream of the CME are useful for prediction. Using these limits on the parameters and fitting the raytrace measurements from eruption until 06:49 UT on July 13th, predicted arrival times can be calculated. The parameters are included in Table 3.1 for comparison with the parameters that were calculated using in situ data.

Both the sheath and ejecta front skew towards the maximum allowed solar wind speed of 500 km/s, a result of fitting data exclusively within 80 R_{\odot} , at which point the CME is still in the process of slowing down and has a speed well over 500 km/s. Without any in situ data for the arrival or solar wind speed, there is nothing in the data that will lead the fitting to a lower speed. Without further constraints, there is no way for the fitting to approach a more realistic final speed. The derived initial speeds are also higher for each front.

Even with these higher initial and final speeds, the model still predicts the shock to arrive later than the actual in situ signatures. This is because of a significant increase in Γ in both the shock and ejecta in the predictive fitting. The CME will experience more drag near the Sun and is consistent with what was found by Poomvises et al. (2010) that the majority of the drag occurs within $50R_{\odot}$. This indicates that rather than using one static Γ value, using a decreasing value with a stronger drag early in the propagation could be more physically accurate, as the solar wind density is higher and the difference in velocities between the CME and solar wind is greater. These fittings show that without improving the constraints on the model parameters, the data alone will not be able to capture all of the physics in the drag model.

While both the initial and final velocities of both structures are higher in the predictive fitting, with the higher amount of drag, the speed declines more quickly and the average speed of the propagation will be closer to the final speed. In the fittings with including the in situ data, the drag is more gradual leading to a higher overall average speed.

The sheath prediction is about 4 hours late, and the ejecta prediction is about 4 hours

early. Accordingly, the predicted shock velocity is lower than what is observed in-situ, and the flux rope velocity is higher. This is encouraging result for space weather prediction. Gopalswamy et al. (2013) show an error of about 18 hours with the ESA empirical model. The prediction also improves upon most of the methods used for this same event in Möstl et al. (2014) for the arrival of the shock, and compares favorably to the most successful prediction therein, the SSEF corrected model.

One of the reasons that this July 2012 CME can be reasonably predicted, is that it is a fast event. For faster events that spend more time well over the solar wind speed, accurate measurement of the event to accurately determine the speed near the Sun will be more important in determining arrival time. For a slower CME, the velocity of the CME will reach the solar wind speed much earlier in its propagation. This makes accurate determination of the solar wind more important for slower events. Because of the high speed of the July 2012 event, the solar wind speed isn't as crucial. Slower events will also have more raw error in prediction because there is more time from eruption to arrival for potential errors to spread through the model.

An example showing this importance of V_0 vs. V_{sw} through a hypothetical parameter space study is shown in Figure 3.6. These plots were created by creating a hypothetical CME propagated through the drag model and holding R_0 and Γ constant and varying one of the two remaining parameters. Altering the initial speed as a larger impact than altering the solar wind. Even though the net arrival time difference between a 1000 and 2000 km/s V_0 than altering the 300-500 km/s V_{sw} . Accurately determining the CME initial speed within 1000 km/s is also much easier than determining the solar wind speed between 300 and 500 km/s, especially given accurate stereoscopic measurement. If the different runs in the two plots are closely examined, it can be seen that when V_{sw} is changed there will be a much larger disparity in the profiles beyond 1 AU. The longer the CME is propagating, the more of an impact V_{sw} will have, reinforcing the notion that V_{sw} will have a larger impact on slower events.



Figure 3.6: Parameter space study with two different hypothetical CMEs. Left: A CME with a known V_{sw} and varied V_0 . Right: A CME with a known V_0 and varied V_{sw} . Both plots have time in hours on the x-axis and distance from the Sun on the y-axis. 1 AU is marked with the horizontal line and the arrivals of the fastest and slowest CMEs are shown in the dashed vertical lines, signifying arrival time at the Earth.

3.4 Improving the Drag-Based Model

3.4.1 Varying the Drag in the Heliosphere

This initial result was an indication that combining height measurements well into the heliosphere with the drag-based model could lead to an improved predictive tool, so long as the measurements were able to sufficiently constrain the model parameters. The results of the fittings without including in situ data indicated that, to turn the drag-based model in a useful tool for prediction, the inputs, especially Γ have to be improved.

The model is a function of four parameters. R_0 and V_0 can both be reliably obtained from the measurements as long as the measurements are accurate. For the solar wind speed, which as has been previously mentioned will have to be eventually modeled to create a truly predictive model, the ACE measurement is used for the sake of trying to improve the way Γ is treated in the model.

Fitting all the measurements to one static set of parameters and determining an average Γ throughout the heliosphere is a useful way for reconstructing CME evolution once the arrival time is already known. However, it is not as good predictively, partially because Γ

is not one constant value as the CME propagates. Instead the CME undergoes more drag closer to the sun and Γ decreases as the distances from the Sun increases (Zic et al., 2015).

Beginning with Equation 3.5, Γ is a function the cross-sectional area (A), the mass of the CME (M), ρ_{sw} is the ambient solar density and the virtual mass M_v , which can be approximated as $\rho_{sw}V/2$ where V is the CME volume (Cargill, 2004) assumptions can be made to the form of Γ to make it easier to restrict its value at any point in the heliosphere. The CME Mass will be roughly constant, but the cross-sectional Area will change with distance, as will the solar wind density. By taking CME mass to be a function of its density and velocity (ρV) and approximating the volume as rA where r is the CME minor radius, the drag parameter can now be approximated as

$$\Gamma = \frac{c_d}{r(\frac{\rho}{\rho_{sw}} + 1/2)} \tag{3.6}$$

To determine the CME density, as it propagates, it is assumed to evolve as $\rho = \rho_0 r_0^3/r^3$. To get Γ to be constant, an assumption that the exponent in the CME density evolution is a two rather than a three must be made (Vršnak et al., 2014). This is for a number of reasons likely to be too low as the CME should undergo a more dramatic density evolution than the solar wind, which follows an inverse square law of the form $\rho_{sw} = \rho_{sw0}R_0^2/R^2$. This assumption is based on the idea that the CME will have a higher density than the ambient near the Sun, while in-situ the CME will usually show a lower density relative to the background (Zurbuchen & Richardson, 2006).

The more significant drop in density also follows from a physical argument. If the CME underwent no internal expansion and was simply pulled out by the solar wind, the CME plasma would be frozen in to the solar wind plasma in a radial direction and the CME would undergo the same $1/r^2$ evolution in density as the solar wind (Riley & Crooker, 2004). However, the CME has significant internal magnetic pressure and will expand as it propagates (Wang et al., 2009). The GCS model assumes that this expansion is self-similar and constant, so the radial expansion of the ejecta will be the same as the radial expansion

in the solar wind, leaving the relative proportions of the GCS shape to be the same at all times. In this case, instead of just the $1/r^2$ solar wind like expansion of the solar wind, there would be the expansion in the radial dimension would cause the overall expansion to follow $1/r^3$.

This may be true in the inner heliosphere, but as the CME travels farther from the Sun this internal expansion, rather than continuing at the same rate, will decrease as the internal magnetic pressure weakens. This could lead to something approximating the $1/r^{2.32}$ shown in Liu et al. (2005). For this work $1/r^3$ is used, but it is possible that the model would be improved from a physical standpoint by assuming less internal CME expansion.

Assuming $\rho = \rho_0 r_0^3 / r^3$ and $\rho_{sw} = \rho_{sw0} R_0^2 / R^2$, and relating the CME minor radius to the height with the aspect ratio from the GCS model (κ), the two density equations can be combined and the density ratio can now be expressed as

$$\frac{\rho}{\rho_{sw}} = \frac{\rho_0 \kappa R_0}{\rho_{sw0} R} \tag{3.7}$$

which then leaves

$$\Gamma(R) = \frac{c_d}{\frac{\rho_0 \kappa R_0}{\rho_{sw0}} + \frac{\kappa R}{2}}$$
(3.8)

the dimensionless drag coefficient c_d is an unknown, but can reasonably be approximated between 1 and 1.5 (Poomvises, 2010; Subramanian et al., 2012). c_d is held constant, so its value will have an impact on the physical meaning of the model and the derived numerical quantities, but not the ability of the model to fit the data. κ is, for every event determined in the measurement and is approximately 0.4. c_d and κ are both dimensionless, so the drag parameter can be seen to still have units of $distance^{-1}$. This leaves the initial density ratio as the only term in the drag model that cannot be observed or easily approximated.

One method to determine Γ is to use a series of fittings of the measurements. This is done by performing the fits and each time including an additional data point (so the first fitting is to the first five measurements, then the first six and so on. These fittings provide a Γ value at each point. This provides a series of values of Γ throughout the heliosphere that can be fit with Equation 3.8 with just the density ratio unknown. Once the drag parameter profile is determined, Equation 3.7 can be used to approximate the evolution of the CME density relative to the ambient.

Once Γ is fit to be a series of values that vary with distance from the Sun, a more detailed drag-based model can be calculated. In studies using the drag-based model with a constant Γ , it is essentially a two point model between the Sun and the Earth. With Γ as a function of distance, the drag model can be used iteratively throughout the heliosphere. At time t=1, R and v are functions of ($\Gamma(R_0)$, v_0 , v_{sw} , R_0). At t=2, R and v are now functions of ($\Gamma(R(1))$, v(1), v_{sw} , R(1)) and so on until the CME reaches L1 (Hess & Zhang, 2015).

3.4.2 Correcting For Angular Distance From the Earth

Another factor to consider is the propagation direction of the CME relative to the Sun-Earth line. There will be a difference between the GCS height measurements along the CME nose and the in situ data points, which are on the Sun-Earth line and can encounter the ejecta well away from the nose. The GCS geometry is curved at the front and distance from the Sun is non uniform. The larger the deviation from the Sun-Earth line to the CME nose, the more this will matter. Using the geometry of the GCS model, the effect of this deviation can be tested.

However, this will not be a perfect comparison, as the GCS model is an idealized geometry assuming a constant self-similar expansion. This is a simplification of a complex, highly variable process. There are a number of factors that will distort the CME structure, including the frozen-in effect of the CME and the solar wind (Riley & Crooker, 2004), the potential for different parts of the CME to interact with different ambient mediums, and of course possible errors in the GCS geometry and fitting, such as the self-similarity assumption.

The detailed definition of the basic geometric terms in the GCS model are taken directly

from Thernisien (2011) and manipulated to return the distance from the base point of the model for any given angular deviation from the nose (θ), for a given set of GCS parameters. Some of these geometric terms can be seen in Figure 3.7. Following these same conventions, the GCS model is defined by two conic legs, of height, h, connected by a central axis which varies in height with the angular distance from the leg (β). At each β angle, there is a circular cross-section that also varies in size. At the leg, this circle is defined by the base of the cone and gets progressively wider as the cross section approaches the CME nose ($\beta = 90^{\circ}$ (Thernisien et al., 2009). Considering just the z=0 plane of the flux rope central axis, the different heights from the center of the Sun (which is the point at which the legs of the model connect) to each point along the shell. The point for a given θ is P.

The distance from the center to P can be determined by four parameters, the CME height, the aspect ratio (κ), the half-angular width (α) and the angular difference between CME nose and the point in question (θ). κ , the relation between width of the CME and the size of the legs, provides a consistent, self-similar ratio between CME size and distance from the origin at each β . Because the GCS model is always self-similar, the height is important for returning the correct value, but the actual calculations can be done to determine the effect of the geometry as a function of θ without knowing the height, which will just provide the magnitude.

To get P, the key terms in the GCS model must be calculated. The central point of the GCS geometry, B, is determined by the CME leg height and width, $B = h/cos\alpha$. The radius of the conic leg height, ρ is also needed $\rho = htan\alpha$. B is essentially the central point of the model around which the shell is constructed.

To get the distance from B to P, the distance to the central axis point and the radius at each β must be calculated. Again from Thernisien (2011), the central axis distance at each β , X_0 is given by

$$X_0 = \frac{\rho + B\kappa^2 \sin\beta}{1 - \kappa^2} \tag{3.9}$$



Figure 3.7: The calculated quantities of the GCS model used to get the height of the CME along the propagation direction of the eruption. The dashed curve represents the ejecta central axis, X_0 . The inputs to this calculation are the GCS parameters, specifically θ , the deviation from the Sun-Earth line. To determine this height, the height at every point along the GCS front is determined by calculating the central axis height and cross-sectional radius at each angle β . This produces the overall GCS front. Figuring which point at the front intersects with the line along θ , the length of P can be calculated with the law of cosines.

As can be seen from this formula, as the angle from the leg changes, this central axis height is not the same distance from B. Instead, B is largest at the CME nose, and smallest at the legs. Each point along this central axis is the center of a circular cross section, defining the overall shape of the geometry. As with the central axis, the radial size of these cross-sections will change with β , again reaching its maximum at the nose.

The radius of each cross section, centered at a point on X_0 and defined in radius by β is given by

$$R^2 = X_0^2 + \frac{B^2 \kappa^2}{1 - \kappa^2}.$$
(3.10)

Detailed formulations of these quantities are presented in (Thernisien, 2011), but conceptually result from the self-similarity relation of the aspect ratio and a coordinate transform along β , requiring the relationship between the major and minor axis to be consistent. The ratio of the distance of any point along the central axis and its radius must be consistent, which keeps the proportional size of all the circular cross sections to be the same as the central axis is increased.

With all of these parameters, the full triangle shown in Figure 3.7 defined by sides, B, $X_0 + R$, P with angles $\beta + \pi/2$ and θ can be used to calculate P, which is the only thing not explicitly determined by the model. This is done using the law of cosines and the known sides and angles of the triangle.

$$P = b^{2} + (X_{0} + R)^{2} - 2b(X_{0} + R)cos(\pi/2 + \beta)$$
(3.11)

These P value calculations a based on β , an angular distance centered on the central point B. From the observation, the θ angle between the Sun-Earth line is centered on the connection of the legs, the center of the Sun. To get the correct β value for the particular GCS model and θ angle, the entire outer shell is calculated and the β angle where a line along θ is intersecting with the shell is found, along the final height, P for the given θ to be known (Hess & Zhang, 2015).

3.4.3 Treating the Sheath Front

Both the Γ correction applied to the drag-based model and the geometric correction due to θ are based on the flux rope. One of the key features of this work is to deal with both the sheath and ejecta fronts separately. Scientifically, this differentiation of the fronts is necessary to truly determine the manner in which the sheath/shock is being generated. For forecasting reasons it is also important. While the majority of geomagnetic storms are driven by the CME ejecta, the sheath itself can also drive activity. For many events, both the sheath and ejecta will contribute the geomagnetic storm.

As explained previously, fitting the sheath measurements with the drag-based model yielded height and velocity profiles that matched observations, but with higher errors than fitting the ejecta. Likewise, attempting to constrain the drag parameter in the same way for the sheath as the flux rope closer to the Sun to create a prediction consistently failed, leading to sheath front arrivals being predicted well behind the observed arrivals. This is likely an indication that the drag-based model is incapable of accurately capturing the full sheath evolution.

To predict the arrival of the sheath front, a new model was used that combined both the ejecta measurements and the sheath front measurements. The basis for this model is that during the propagation, the sheath front will be a combination of two factors. The most significant impact on the propagation of the sheath is the flux rope driver pushing it. Secondly, independent of the driver, the sheath will also have its own momentum, which will cause the standoff-distance to increase as the CME propagates. To put things another way, if the ejecta were somehow removed after the sheath front was generated, the sheath front would continue to propagate as a blast wave. This also means that, if a shock were generated in the low corona in all directions, the sections of the shock that are not being continuously driven by the flux rope propagating behind it, will move through the corona as a more gradually propagating wave, known as an EUV wave (Grechnev et al., 2015; Kwon et al., 2013). Therefore, the sheath will be combination of two components, the velocity of the ejecta pushing it forward and its own independent velocity component. The will



Figure 3.8: The standoff-distance of the July 2012 CME as determined by subtracting the ejecta measurements from the shock measurements. The solid line is the linear fit to the data.

result in the sheath always having a larger velocity than the ejecta, which matches in situ observations.

As observed before in both radio (Corona-Romero et al., 2013) and remote-sensing observations (Hess & Zhang, 2014) there is an independent element to the propagation of the sheath front that provides additional momentum. To determine this term, the standoffdistance between the ejecta and sheath front noses is calculated at each time when both fronts have been measured. For many events, a linear trend in the standoff-distance can be observed. An example of this standoff-distance trend is shown is shown in Figure 3.8. To model the standoff-distance beyond the point where both fronts are visible in the remote sensing data, a linear fit can be performed on these measurements and extrapolated outwards.

Temmer et al. (2013) show that the standoff-distance will increase more significantly

within about 2.5 R_{\odot} but use a linear model throughout the heliosphere, showing an observational agreement with theoretical analysis to demonstrate that it is a useful approximation. Using a linear standoff-distance evolution as well as the propagation profiles determined for the ejecta, it is now possible to combine the two into a model for the sheath front (Hess & Zhang, 2015)

$$R_{SF}(t) = R_{FR}(t) + At + B (3.12)$$

$$V_{SF}(t) = V_{FR}(t) + A$$
 (3.13)

where A and B are the terms of the linear standoff-distance fitting. Physically, the sheath front will almost certainly not continue to propagate linearly. This implies that the independent velocity of the sheath front will be constant and never diminish, which cannot be the case. There is very likely a dissipative force of some kind acting on the sheath front that will eventually slow it down. The assumption in using a linear model for the standoff-distance, and one that is based on observations, is that the drag will not have a significant impact within 1 AU. This is probably an over-simplification, but it does allow for calculations to be made and predictions to be attempted.

Another factor in the handling of the sheath front is the geometric correction factor. The geometry of the sheath front is not the same as that of the flux rope, as the raytrace fitting on the sheath is using a completely different shape. Trying to use the same correction may introduce more error into the process. However, the curvature of the sheath and the ejecta should be similar along the front of the flux rope, as the flux rope will be constantly pushing that part of the sheath. Using the same geometric correction for each front is still an improvement over ignoring geometric effects altogether, though refinement is possible. For this study, the correction is applied to the sheath based on the θ deviation in the same manner as the ejecta.
3.4.4 Applying the Deviation Correction

When predictions were first attempted, it was obvious from linking the remote sensing measurements to the actual in-situ arrivals that the curvature was being greatly over-estimated for CMEs where θ was more than 10°, causing predicted arrivals as much as 25% after the observed arrival. However, ignoring the geometric correction entirely showed a lesser, but still consistent under-estimation of these events by about 10%. Therefore, a weighted average of the GCS corrected height and the uncorrected height, based on these relative errors, is used. The height of the CME where the height is measured at the nose, h_N , combined with the height along θ as calculated from the GCS model, h_G can be combined (Hess & Zhang, 2015)

$$h_f = .65h_N + .35h_G \tag{3.14}$$

to give the final geometric correction used, h_f .

The different front curvatures are shown in Figure 3.9. To use this correction, the measurements taken with the GCS model are considered to be along the CME nose. The geometric correction is applied to the in situ arrival point. For example, according to this formula when a hypothetical CME with a width of 30° , and an aspect ratio of 0.4 with θ between $20 - 30^{\circ}$ reaches the L1 point, the CME nose will be about 5-10% farther into the heliosphere. The correction factor for this hypothetical CME between $0^{\circ} - 35^{\circ}$ is plotted in Figure 3.10.

At first glance, this correction seems relatively minor for CMEs propagating within 35° of the Sun-Earth line, which will cover the large majority of Earth-impacting CMEs (Zhang et al., 2007). Still, for a CME with an average speed of 500 km/s, an extra $15R_{\odot}$ (7% of the distance from the Sun to L1) from the distance correction will cause a difference of about 6 hours in arrival time, which is similar in magnitude to the current error of prediction. Zic et al. (2015) also show that the CME geometry will greatly impact results with the DBM.

This final geometric correction would represent a reduction in curvature of the ejecta



Figure 3.9: The different curvatures of the CME front. The solid black line represents no correction, assuming all points on the CME leading edge are equidistant from the Sun. The solid blue line shows the GCS model geometry. The dashed red line shows the correction as used in this work.



Figure 3.10: The effect of the geometric correction as a function of the θ angle between the CME nose and the Sun- Earth line.

front between the low corona (where the GCS model is most effective) and the arrival of the CME at L1. As explained in Section 3.4.1, the self-similar expansion of the GCS model is an assumption that, while valid near the Sun will break down in the heliosphere, because the internal CME radial expansion will begin to drop in magnitude relative to the lateral expansion of the CME in the solar wind. The legs of the CME will continue to expand at the CME rate as they are being drug by the solar wind, but the expansion along the radial direction will lessen as the internal Lorentz force weakens. Since the GCS model ignores this effect, the longterm evolution of the curvature will be over-estimated. Ignoring the curvature all together is to essentially discount any internal CME expansion and assume that the entire CME front is propagating in the same manner as the solar wind with each point along the front the same radial distance from the Sun. This will cause the CME to flatten as it propagates.

3.5 Event Selection Criteria

With the goal of creating a predictive model, the first step in the process was to perform measurements, for both the ejecta and sheath front, on a number of different events that could be modeled and used as the test set for the creation of a model.

As stated previously as part of the ISEST program, a list of CMEs based on in situ data at the Earth has been generated, which also served as the baseline for this dissertation. This list of events was narrowed down based on a few criteria. I wanted events on which both a sheath and ejecta could be observed in-situ. Events that are particularly weak and slow may not have a sheath. Ejecta that propagate far from the Sun-Earth line may only see a sheath reach the Earth or may just a leg of the flux rope structure, which doesn't always appear as a magnetic cloud (Zhang et al., 2013).

While each STEREO spacecraft has its own in situ measurement where ICME signatures can and have been detected, only events detected at the Earth have been used in this study. This is because of the better quality of observations for Earth directed CMEs. SDO will be able to observe the eruption on the solar disk and the flare and x-ray flux signatures will be detected as well. For events propagating towards STEREO, the only signatures that may be observed are from the EUVI instrument, which will not be as good as SDO and GOES observations. The observations in the heliosphere will be worse as well.

Observations of a CME in the heliosphere are best when the CME is propagating close to 90° from the observer (Howard & Tappin, 2009b), so when a CME is directed at an observing satellite, it will be difficult to measure accurately. Depending on the relative location of STEREO during the eruption, the CME may also be traveling 180° from the other STEREO satellite, making measurement from that satellite difficult as well. For these reasons, I focus just on the events that propagate towards the Earth.

Again, the CME will be more well observed the closer it is to 90° from the observer. This means Earth directed CMEs will be most well observed by the two STEREO spacecraft when they are in perfect quadrature with the Earth. For this reason, the events used in this study all occur between April 2010 and March 2013, when the separation between the Earth and each spacecraft ranged from about 70° to 140° . This time period also corresponds to solar maximum, so there is more solar activity.

Based on this criteria, 9 events were originally chosen. One of these events, from March 2012, is a much studied event from an active region that produced many flares and CMEs (Gopalswamy et al., 2015; Chintzoglou et al., 2015) This event was removed from the sample because the source region was too active, and it was therefore difficult to isolate the measured CME from other eruptions that occurred around the same time. Another event, from October 2010, was removed from the sample because measurements indicated it was still accelerating well into the corona. This was a so-called "stealth" CME (D'Huys et al., 2014; Howard & Harrison, 2013), a CME with a very weak and almost imperceivable coronal signature. Unlike most events, which erupt suddenly with clear emission, stealth CMEs and their lack of obvious explosiveness are generally considered to initiate more gradually (Nieves-Chinchilla et al., 2013), indicating the flux rope may be accelerating over a longer period of time than typical CMEs with clear flare or prominence association. This means that the drag assumption that the CME is just decelerating in the solar wind is no longer

valid, and the model breaks down. It was possible to, focusing just on data further from the Sun, fit the measurements and in-situ data with the drag model to determine approximate kinematic profiles, but the removal of these points did not leave enough data to form a meaningful prediction.

After removing these two events from my sample, there were seven remaining events, summarized in Table 4.1. These events have a wide variety of initial speeds, observed upstream solar wind speeds, associated flare energetics, and propagation directions relative to the Earth, allowing for a test of the deviation correction calculated from the GCS model. The diverse characteristics of these events can indicate that the method is not being biased towards a particular subset of CMEs, but can work for nearly any event that has an initial speed faster than the solar wind (apart from the admitted bias of events that propagate without interaction with another CME).

Chapter 4: Prediction Results

With our method, both fronts were fit for each of the seven events shown in Table 4.1. An example of the derived Γ profile for the July 2012 CME is shown in Figure 4.1. As is typical for the events, the Γ fitting deviates noticeably from the measurements. For many events these individual Γ values scatter quite a bit, so the purpose of this fitting is not an attempt to capture the physical evolution for the model, but rather trying to constrain the value of Γ for each event.

Figure 4.2 shows the predicted arrival time for each event plotted with the observed in situ arrival time. As a further test of the the ability of the model to capture the actual kinematic profiles, Figure 4.2 also shows the velocities of the model when the respective front is at L1 and the observed in situ velocities. The in situ velocity used for the sheath is the average velocity over the entire sheath region. The sheath velocity is usually fairly constant so this is a pretty straight forward comparison. The ejecta velocity is also the average over the duration of the flux rope passing through ACE. The ejecta velocity is more difficult to determine, because the observed velocity is a combination of the bulk motion of the ejecta and the expansion velocity. In a textbook magnetic cloud signature, this will cause a linearly decreasing velocity, where the average speed corresponds to the bulk CME motion. At the front of the magnetic cloud the additional velocity will be a result of the CME expansion, which will be in the same direction as the CME motion. At the back of the magnetic cloud the CME will be expanding opposite the bulk motion, so the net velocity will be lower.

The predictions are also shown in Table 4.2. The ejecta has an average error of 1.46 hours, with an RMS error of 0.76 hours. As can be seen in Figure 4.2, there is more error in the sheath front predictions. For the sheath front, the average error is 3.47 hours with an RMS of 1.52 hours. The most significant deviation in the sheath front numbers come from



Figure 4.1: The derived Γ profile for the July 2012 CME is shown with the solid line, as well as the ejecta Γ values determined at each point by fitting the measurements up to each individual point.

First	SH Arrival ^b	EJ Arrival ^b	Direction ^c	V_0^c	V_{sw}^d	R_0^e	R_f^e	AR^{f}	$Flare^{g}$	Flare $Peak^g$
Measurement ^a				Ť			,			
04/03/2010 10:24	$04/05 \ 08:00$	$04/05 \ 11:30$	E06S26	854.7	512.4	5.5	62.8	11059	B7	04/03 09:54
05/24/2010 14:54	05/28 $02:00$	$05/28 \ 07{:}00$	E28N03	605.7	362.3	4.6	45.0	-	-	-
09/14/2011 00:24	09/17 02:00	$09/17 \ 19:00$	W20S16	519.5	396.9	5.3	28.1	11289	-	-
07/12/2012 16:54	07/14 17:00	$07/15 \ 07:15$	W00S09	1492.0	353.7	4.3	76.6	11520	X1	07/12 15:36
09/28/2012 00:24	$09/30 \ 23:00$	10/01 06:00	E28N17	1230.5	310.4	6.3	74.1	11577	C3	09/28 00:00
10/27/2012 17:24	10/31 15:00	11/01 00:00	E12N12	400.1	289.8	6.2	49.0	-	-	-
03/15/2013 07:24	$03/17 \ 15:30$	$03/18 \ 00:00$	W24S07	1220.2	429.3	7.4	37.0	11692	M1	03/15 $05:46$

Table 4.1: a- The time step of the first SECCHI and LASCO images used for GCS fitting. Given the time offsets between the different satellites, the time given refers to the SECCHI observations

b- Sheath and Ejecta arrivals at ACE as manually determined

c- Initial Velocity (km/s) is obtained by performing a fit of the data using the drag based model over all observations

d- Solar wind speed (km/s) is determined by taking an average value of the ACE data preceding the arrival of the sheath signature

e- The measured ejecta height (R_{\odot}) of the first and last point used for fitting

f- Associated Active Region given by tracking CME back to the surface using EUV data. Not all CMEs can be linked with an active region

g- Flare Strength and Peak determined by comparing the EUV observation to X-Ray flux from GOES



Figure 4.2: Top: The predicted vs. observed arrival for the ejecta (left) and sheath front (right) for each event. The solid line represents perfect accuracy in prediction. Bottom: The predicted vs. observed velocities at L1 for the ejecta (left) and sheath front (right) for each event. The solid line again represents perfect accuracy in prediction.

ICME Date ^{a}	ΔT_{SF}^{b}	ΔT_{EJ}^{b}	$\Delta V_{SF}{}^c$	ΔV_{EJ}^{c}	$\rho_{ratio}(R(0))^d$	$\rho_{ratio}(L1)^d$	$\rho_{ratio}(ACE)^e$
04/05/2010	1.89	0.38	23.3	26.4	32.17	0.91	0.41
05/24/2010	5.69	2.52	96.3	38.1	6.70	0.15	1.21
09/14/2011	6.68	4.39	15.8	13.0	3.24	0.09	0.71
07/12/2012	0.84	1.51	24.8	22.4	18.61	0.41	0.61
09/28/2012	0.34	0.9	61.6	45.6	10.31	0.31	0.97
10/27/2012	4.99	0.28	24.5	19.0	14.78	0.47	0.67
03/15/2013	3.91	0.26	22.9	7.2	5.98	0.21	0.38
Average	3.47	1.46	38.5	24.5	13.11	0.36	0.80
RMS	1.58	0.76	17.9	12.9	-	-	-

Table 4.2: a- The date of the ICME arrival at ACE

b- The absolute value of the difference in hours between the predicted and observed arrival time of the sheath (SF) and Ejecta(EJ)

c- The difference in velocity in km/s between the speed of each feature as predicted by the model and as compared to the average speed observed for each feature in-situ

d- The derived density ratio from the model at the initial height of observation and at the point where the ejecta reaches L1

e- The ratio of the densities of the ejecta and solar wind, as determined from the average values of each from ACE.

the slower events being predicted to arrive too early. This is likely due to the linear standoffdistance fitting not accounting for the amount of resistance the sheath wave encounters in the 100 hrs it can take a slow event to reach the Earth. For a faster event that spends half that time in the heliosphere this effect will be less noticeable. These results confirm that the model for the sheath front would most likely be improved with the inclusion of a damping term, perhaps also based on aerodynamic drag, for diminishing the rate of sheath growth.

The sheath model can be compared to in situ observations by extrapolating the fit out to 1 AU to see the size of the standoff distance at that point. An approximate sheath size can be obtained from the in situ observations by integrating the sheath velocity over the time of the sheath passing through the observer. The model can then be tested by comparing the observed and modeled velocities.

Figure 4.3 shows the comparison between the ACE sheath size and the sheath from the model. Table 4.3 has the values of each event. The distances and times used for this comparison in the model and times are based on the approximate middle of the sheath,



Figure 4.3: The derived Γ profile for the July 2012 CME is shown with the solid line, as well as the ejecta Γ values determined at each point by fitting the measurements up to each individual point.

halfway between the shock/sheath front passing and the ejecta. Unsurprisingly the, modeled sheath is larger than the observed sheath for 5 of the 7 events, due to the linear standoff-distance fit.

The model still does a pretty good job of determining the standoff-distance at ACE, given its simplicity, but could definitely be improved. The two worst events (05/2010) and (09/2011) were both slow. Both had a $V_0 < 600 km/s$ and therefore had a sheath passing of more than 70 hours. This could be the cause for the error, or it could have been a result of the front curvature as both events propagate more than 20° from the Sun-Earth line. More study must be done to create a more accurate and physically descriptive sheath model.

My modeled standoff distance results are in agreement with Maloney & Gallagher (2011), who found a standoff distance of about 20 R_{\odot} at 0.5 AU, while Russell & Mulligan (2002) show a typical sheath size of about .1 AU (~21.5 R_{\odot} at 1 AU. Both of these findings would be consistent with both the models and observations in this study, which range from $20 - 60R_{\odot}$ at 1 AU, and because of the linear nature of the model will be $10 - 30R_{\odot}$ at .5 AU. The Temmer et al. (2013) results with a linear fitting show a standoff distance at 1 AU of about $20R_{\odot}$ based on measurements out to $10R_{\odot}$ (though it would be $40R_{\odot}$ using

ICME Date	Model SD	Observed SD	Δ SD $R\odot$
	$ (R\odot) $	$ (R\odot) $	
04/05/2010	21.1	12.9	8.2
05/24/2010	30.2	15.1	15.1
09/14/2011	48.7	30.1	18.6
07/12/2012	30.7	40.9	10.2
09/28/2012	20.1	25.8	5.7
10/27/2012	25.9	17.2	8.7
03/15/2013	68.3	62.4	5.9
Average	35.0	29.19	10.3

Table 4.3: Comparison between the modeled sheath size and the size of the sheath as determined from ACE. The model values are determined for finding the sheath size at the middle of the sheath passing from the linear fit. The observed values are determined from the sheath velocity and time at ACE.

only data within $2.5R_{\odot}$). All of these studies show that the values in this dissertation are at least plausible.

4.1 Sensitivity of the Predictions

Using the improved height-dependent Γ in a drag-based model, the arrival of both fronts has been successfully modeled for a number of events. Besides just testing the model by comparing the arrivals, testing the sensitivity of the model parameters to the measurements can help determine how robust the model and how effective it could be in a predictive sense.

The first step, to determine the necessity of the measurements, requires looking at the degree to which the fitted model parameters vary. In general, if a pattern in the model inputs could be seen, it could be possible to predict the Γ value and reduce the importance of the measurement. As shown in Equation 3.8, the only input for the ejecta is the density ratio of the ejecta to the ambient at the initial height of the model. The initial height of each event is different, but they should be close enough that a comparison can be made.

The range of $\rho_{ratio}(R_0)$ values vary from 3.24 to 32.17 with 6 of the 7 events between 3.24 and 18.61, as seen in Table 4.2. The values are scattered seemingly at random with no noticeable pattern that could be used for predictive purposes.



Figure 4.4: The difference in the arrival time of the ejecta at L1 by varying the initial density ratio ranges among the set of modeled values obtained from fits to measurement.

To test the importance of the initial density ratio, a series of hypothetical CMEs with initial speed of 1000 km/s and encountering an ambient solar wind with a speed of 350 km/s were created. The difference between all the different runs is a varied initial density ratio, over the range of observed initial density values. Thus the effect of the initial density ratio on arrival time is plotted in Figure 4.4. The effect of the initial $\rho_{ratio}(R_0)$ on the arrival time begins to diminish as $\rho_{ratio}(R_0)$ approaches the highest value calculated in the event sample. For values more representative of the rest of the events, between 3 and 18, the total range of arrival times is about 16 hours. Obviously this has a crucial effect on the arrival time, and the initial density ratio and by extension Γ must be constrained to improve prediction.

For forecasting purposes, in addition to accurate predictions it is also important to provide the maximum amount of lead, or warning time possible. The ability to make an accurate prediction when the CME is closer to the Sun is of the highest value to the users of space weather forecasting systems. All of the predictions in this section are based on data where the CME is within $80R_{\odot}$, and for many events the fronts become so faint beyond



Figure 4.5: The profiles for the ratio of ρ_{CME} to ρ_{sw} for each of the seven events, as given by the Γ fittings and Equation 3.8.

 $50R_{\odot}$ that measurements beyond these heights are not taken into account. Slower events tend to stabilize closer to the Sun, as there are more observations to fit. For all events presented here the model would have a lead time of at least 36 hours based upon the last SECCHI images used for each event.

4.2 CME Density Evolution from the Predictive Model

Apart from the predictive capabilities of this model, there are more basic scientific implications to CME research that can be derived, specifically about the evolution of the CME density and expansion in the heliosphere since the relation of the CME density to the ambient density is the key parameter on which the model is built. To verify that the assumptions of the model are reasonable and providing meaningful results, the density ratio of the CME as it propagates can be calculated from the model. For each event in the sample, the density evolution is plotted in Figure 4.5.

The assumption of a r^{-3} density dependence leads to the density ratio between the

CME and solar wind having the form of r^{-1} and is probably an overestimation, especially farther out in the heliosphere as the expansion of the CME diminishes.

The in situ density ratios from the model are seen in Table 4.2. Except for the extremely low value from the 2011 event, these rations are all between .15 and .9, reasonable values given the average solar wind in-situ density of approximately 6 cm^{-3} (Lepping et al., 2015) and the measured ejecta densities in-situ, which were all less than 4 cm^{-3} . Still, the majority of the events show density ratios under .5 at L1, which is lower than was expected. The initial density ranges from the fitting, reaching values as high as 32 are also likely too high to be truly realistic.

To get a better idea of the accuracy of these ratios, the average ejecta and ambient density as measured in situ can be compared to the model, the values of which are also in Table 4.2. These values are all generally in similar ranges, though there does not seem to be much correlation between the modeled values and the observations. This adds further evidence to the idea that this is too extreme of a density evolution that the r^{-3} CME density evolution is incorrect.

It is of interest that the biggest outlier of the densities is that of the April 2010 CME, as this is the only event in the sample in which a high speed solar wind stream was observed in-situ ahead of the ICME. Faster solar wind speeds have long been known to correspond to a lower solar wind density (Hundhausen, 1972). This would likely give rise to this large ratio between the CME density and the ambient and show why this CME propagates more linearly than the other events. However, in the in situ data, the solar wind density is indeed below average, but the ratio is not noticeably high, and is even well below average. With the lower solar wind density, it is possible the CME underwent more significant expansion by the time the CME reached L1 causing a lower CME internal density. While the values may be wrong, the fact that this event was identified as having the lowest solar wind density is a sign that the heliospheric conditions in Γ are being at least qualitatively captured.

It may be possible to use the white light coronagraph data, CME mass measurements and the geometry of the GCS model to calculate the density of the CME. This could be combined with a solar wind model to determine the density ratio observationally, as well as gaining a better understanding of how this quantity evolves. Colaninno & Vourlidas (2009) show a method for determining mass measurements utilizing stereoscopic observations. Using the GCS geometry it may be possible to determine the CME density throughout the heliosphere and more accurately determine the density ratio. These mass measurements typically have significant errors, but it may still work to constrain the density ratio term in the model.

4.3 Comparison with Other Models

An ability to predict each front within 3 hours with an RMS deviation of less than 2 hours is a significant improvement over other models. Colaninno et al. (2013), also using GCS fittings and a number of model fits including a similar drag model, showed an average time error of 8.1 hours with a 6.3 hour deviation. Gopalswamy et al. (2013) used the Empirical Shock Arrival (ESA) Model to predict CME arrival within 7.3 hours with a 3.2 hour deviation. Möstl et al. (2014) used a variety of j-map reconstructions to predict arrivals with an average absolute error 6.1 hours and a deviation of 5.1 hours. Using the drag based model, (Vršnak et al., 2014) predicted arrival times with an average absolute error of 14.8 hours, with deviations on a similar order. Given the limited sample of events and various data that would be unavailable in realtime, these comparisons are not a proof that this improved DBM combined with the GCS measurement will always greatly out perform other prediction methods currently in use. It is a proof of concept for the power of this method with hypothetically ideal data (Hess & Zhang, 2015).

The results can be directly compared to the published formulas of the ESA and drag model, acknowledging that every forecasting technique will be most effective in the hands of those who developed the method. Therefore, using initial velocities in these formulas will probably not be the most fair comparison, but it should still be useful. The values for each event are presented in Table 4.4 and are shown in Figure 4.6.

The most significant improvement, based on these seven events, comes from the lack

ICME Date	Improved Drag	ESA	Static DBM
	Model		
04/05/2010	-1.89	-11.6	-14.0
05/24/2010	-5.69	7.91	10.6
09/14/2011	-6.68	-11.5	-6.00
07/12/2012	0.84	17.4	2.88
09/28/2012	-0.34	32.9	22.5
10/27/2012	-4.99	-3.70	2.11
03/15/2013	3.91	8.00	-1.45
Average	3.47	13.27	8.5
RMS	1.58	6.04	4.20

Table 4.4: A comparison of the error in hours between the improved DBM method from this dissertation and the ESA and DBM models for each event. The average values for each model is the average of the absolute value of the error for each event.



Figure 4.6: A comparison of the arrival time for the sheath front with our method (blue), the ESA method (green) and DBM model (red). A negative error time corresponds to the predicted arrival being after the observed arrival.

of an extreme outlier. Both the ESA and static drag model have at least one event that is completely missed because the empirical approach of determining average characteristics fails to capture the specific characteristics of one of the CMEs. Using the measurement to feed in unique information for each CME, these big misses can be avoided. Should these results prove repeatable, the result would be a significant step forward for space weather forecasting.

4.4 Creating an Operational Model

Transferring this model from a hypothetical method to an operational forecasting tool operating in real-time will require many significant improvements. One such limitation is the difficulty in getting accurate heights of the fronts in real-time. All observations to this point have been performed with science-quality data. It will be more difficult to accurately get these measurements in real time from the lower quality data available. STEREO provides realtime coronagraph data, though these are of significantly reduced quality. A comparison between the real-time and science quality data is shown in Figure 4.7 and the difference in quality is plain to see. Making accurate measurements with this data will be more challenging, increasingly so because the Heliospheric Imagers do not currently provide realtime data.

The observational part of this technique is also made more difficult by the lack of a permanent observer somewhere other than L1. From 2006-2014 when STEREO was consistently providing multiple viewpoints, especially during the 2010- 2013 period of these events when the STEREO spacecraft were optimally positioned, it was much easier to create an accurate reconstruction. Currently the STEREO spacecraft are on the far side of the Sun, so they are not providing data and even if they were the spacecraft would be poorly positioned to observe Earth-directed CMEs. Until STEREO once again reaches a position capable of provided the best observations, forecasters are restricted to using a cone model with only LASCO data (Na et al., 2013). It is possible to estimate CME heights and velocities with this method, but using just a two dimensional projection within $30R_{\odot}$ the



Figure 4.7: An example of STEREO data with an image from the B satellite at 17:54 on July 12, 2012. The image on the left is the real-time beacon data and the image on the right is the science quality data, on which the measurements for this work have been performed. The lower quality of the real time data may affect the accuracy of the measurements.

accuracy of the measurement will be significantly degraded.

Another issue will be the treatment of the solar wind. For this method, ACE measurements ahead of the CME have been used to get an average value for the solar wind speed. In real-time, this would obviously be impossible without the deployment of more in situ spacecraft between the Sun and the Earth, so the solar wind speed would have to be input in a different way. The widely-used Wang Sheeley Arge (WSA) model (Arge & Pizzo, 2000) in the low corona can be combined with the heliospheric model ENLIL (Odstrčil & Pizzo, 1999) to predict solar wind speed from the low corona to the Earth. Using a model, provided it is accurate, would also provide the added benefit of, rather than assuming a constant solar wind speed in front of the CME, having a height-dependent solar wind speed that could account for the CME interacting with varied solar wind regimes. This may also be an improvement in the low corona, as the solar wind will still be accelerating in the coronagraph field of view and this could significantly alter the drag in the low corona. However, the extent of this improvement will entirely depend on the accuracy of the solar wind model.

The last issue is an acknowledgement that by focusing only on simple events propagating freely in the heliosphere, it may be impossible to understand events featuring multiple CMEs interacting, such as those that happened in August 2010 (Webb et al., 2013) or the March 2012 event that was removed from this study. It is also possible that the stealth CME that was removed from the sample will be evidence of another subset of CMEs for which the method will not work. The last type of CME that remains untested will be the most extreme of events, which propagate so quickly they do not allow any significant lead time or measurement to be performed. An example of this would be the July 23, 2012 CME (originating from the same active region as the July 12, 2012 event that has been discussed in great detail throughout this dissertation) (Temmer & Nitta, 2015). This CME was the fastest observed in the STEREO era and was fortunately a backsided event that propagated away from the Earth. With an initial speed over 3000 km/s, this event would have been very difficult to study with the methods in this dissertation due to the speed with which it moved through the heliosphere.

Many of these drawbacks are observational in nature and are not unique to the methods presented here. Understanding and explaining the complex and extreme events cannot even be attempted until the state of CME research is advanced to the point where the most basic events are completely understood.

Chapter 5: Comparison of Observations and Models with Simulation

One of the difficulties in studying a CME in the heliosphere is the limited number of data points. Observational and in situ data are available from primarily three viewpoints. Apart from STEREO and Earth/L1, there is no other observational viewpoint from which a CME can be imaged. The observational limits cause data sets to be sparse and CME studies to be under-constrained.

A more complete temporal and spatial resolution can be achieved through computational simulation of a CME structure. If an event can be accurately recreated on a discrete computational grid, plasma parameters such as the full magnetic field, density and temperature can be calculated at each grid point over the full time period of the propagation of the CME from the Sun to farther out in the heliosphere. This would make it possible to study the complete evolution of the CME structure as well the kinematic profiles.

Of course, the simulation data is not without limitations. The results will always be dependent upon the physical assumptions in the model to make the calculation possible, and the subjective nature of the inputs and boundary conditions in the model. To compare the simulated events to real events, the observational measurements can be used as the inputs for the event in the model. From there, artificial recreations of an in situ spacecraft pass through and remote sensing images can be used to compare the model results to observations. If there is a good agreement between the observed and simulated data, it is reasonable to assume the model is accurately recreating the event and can provide useful physical information about CME propagation (Wood et al., 2011; Tappin & Howard, 2009; Krall et al., 2006; Riley et al., 2003; Roussev et al., 2003; Wu et al., 2002; Vandas et al., 1993).

Most CME simulations are Magnetohydrodynamic (MHD) models, where the plasma of both the CME and the solar wind are treated as magnetic fluids. While this assumption is not perfect, simulating each individual particle is not computationally practical for the spatial scales and magnetic complexity of a CME propagating in the solar wind. By treating the structures in the model as a fluid, it is possible to resolve enough of the physics to show plasma interactions in the heliosphere.

One of the most widely used MHD models is ENLIL (Odstrčil et al., 1996; Odstrčil & Pizzo, 1999). This model, currently used for realtime prediction by The National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) and is publicly available at the NASA Community Coordinated Modeling Center (CCMC). ENLIL is capable of taking the low corona magnetic field extrapolations of the Wang Sheeley Arge (WSA) Model (Arge & Pizzo, 2000) as an input condition to find a solve for the ambient solar wind conditions, giving an ambient solar wind model throughout the solar system. This ambient model may be useful for putting the solar wind speed into the analytical model. ENLIL is also capable of modeling a CME by inputting a pressure pulse at 21.5 R_{\odot} from the Sun. ENLIL does not currently model the detailed magnetic structure of the flux rope ejecta. Instead the most significant portion of the model that is modeled is the sheath region and shock of the event. This is used to predict the arrival of the sheath front at any point in the heliosphere and has shown to be useful for predicting CME arrivals in an operational mode. NOAA uses ENLIL coupled with a stereoscopic measurement technique based on a similar, but more simplified, geometry to the GCS model (Steenburgh et al., 2014). ENLIL runs have also be compared to the drag-based model (Vršnak et al., 2014), showing solid agreement.

A CME in ENLIL is initiated with an initial time, speed, and orientation direction at the inner boundary of 21.5 R_{\odot} . By using the GCS measurements and model fittings, this information can be fed into the simulation and then the evolution in the model can be compared to the real observations.

Also, using the information of the location, pointing and instrument scope of each

remote-sensing observer, artificial renderings that are directly comparable to observations can be created to test the model. The heights can also be extracted and compared to measurement. A simulated time-series at the Earth can also be created that will be directly comparable to in situ measurements. An example comparing observations to simulation data from ENLIL is shown in Figures 5.1 and 5.2.

A comparison between drag-based fittings for the GCS and spheroid raytrace measurements and the ENLIL data is shown in Figure 5.3 for the July 2012 event. The height of the shock/sheath region is defined as the outermost point on the GCS nose direction of the computational grid where the density is higher than the ambient solar wind simulation density. The ejecta height is defined as the point where the density becomes lower than the ambient solar wind. The sheath region is then all the points where the density is higher than the average.

The profiles show similar behavior, but the ENLIL fronts for this particular simulation run arrive earlier and exhibit a less significant deceleration through the heliosphere. There are a number of different possibilities that could lead to this result. The model could be underestimating the physics of drag in the heliosphere, thus causing the the CME to be slowed down less by the solar wind. It could also be that the solar wind speed in front of the CME in the model is faster than the true solar wind speed, causing less drag to occur. This is not supported by the data at 1 AU, but since there is no constraint on the solar wind speed between the inner boundary and the Earth this is not enough to prove the validity of the solar wind model. Lastly, the internal plasma parameters may just be incorrect, as changing the internal density of the CME will have an impact on the effect of drag. A further improvement of the initial parameterization in the model is an interesting subject that could be explored in the future.

Another model used for comparison is the COIN-TVD MHD model (Shen et al., 2011). This model is capable of resolving the magnetic flux rope structure beginning in the low corona and beyond 1 AU by creating a non force free magnetized blob for the CME ejecta. This magnetic complexity will increase the computational cost of the model and make it less



Figure 5.1: Comparison between actual STEREO HI-1 data (middle panels) and a volumetric rendering of the model output from an ENLIL run of the same event, the July 12 CME. The top panels show the CME density with a simulation of the ambient solar wind subtracted out, The bottom panel is the actual density normalized by r^2 , to remove the effect of the inverse square nature of the solar wind profile. The background structure visible behind the CME is a Co-Rotating Interaction Region (CIR), an interaction between high speed and slow speed solar wind.



Figure 5.2: Similar to Figure 5.1, but for the HI-2 field of view.



Figure 5.3: The measurements for each front, as well as the in situ arrival times for the event between July 12 and 15, 2012. The drag model fittings to the measurements are the dashed lines, and the drag model fitting to the ENLIL data is represented with the solid lines. The middle panel is the velocity profile for each model fit for both fronts, and the bottom panel shows the acceleration



Figure 5.4: The July 12, 2012 CME in the heliosphere. The sheath is shown through the density enhancement, normalized by r^2 and the magnetic field, identified by the black and white field lines. The Sun is pictured as the yellow sphere and the Earth by the smaller blue sphere, though neither is actually to scale.

useful operationally, but does make it a valuable tool for cross-validation after the fact. An example showing the modeled CME in the heliosphere with magnetic streamlines in Figure 5.4 shows the density enhancement of the sheath region, as well as the magnetic field lines of the flux rope. The stream line tracer used struggles to completely capture the magnetic field lines, causing the nature of the field lines in the visualization.

An artificial rendering, showing the ratio between the density of the CME and that of the quiet solar wind value that was created for Shen et al. (2014b) from the point of view of both STEREO spacecraft and SOHO is shown in Figure 5.5. A comparison between the drag model fittings that were performed in Hess & Zhang (2014) for the July 12, 2012 event, j-map reconstructions and the simulation data was published in Shen et al. (2014b) and are shown here in Figure 5.6 for the sake of comparison between the drag model fittings and the model. The modeled CME has a much higher speed in the inner heliosphere before settling into a similar profile as the drag fitting. This is likely due to the initial plasma



Figure 5.5: The artificial renderings from the three observational viewpoints of the COIN-TVD modeled CME in the heliosphere. The location and pointing of each spacecraft represents the true values of the satellites at 17:54 UT on July 12, 2012. The field of view, rather than matching that of a specific instrument on board any of the spacecraft is covering the full heliospheric distance out to 40 R_{\odot} .

blob needing a higher initial velocity to erupt. For the bulk of the model propagation, the measurement/drag fittings show good agreement with the model.

These comparisons are an example of how collaboration between observers and modelers can be highly beneficial to both communities. Using the observational measurement as inputs to the models will make them more accurate, and a comparison between the observations the model can help guide the understanding of the larger physical processes that cause the observations. The agreement between the MHD models, observations and DBM is promising and can be explored further.



Figure 5.6: The comparison between the heights and velocities for the drag based model fitting (Hess & Zhang, 2014) and the MHD model for the July 12, 2012 event. Figure from Shen et al. (2014b).

Chapter 6: Conclusion

The work to complete this dissertation has been a comprehensive study of Coronal Mass Ejections in the heliosphere. This included a detailed observational study to identify the best events for linking remote sensing to in situ data and tracking the data to 1 AU with stereoscopic reconstruction methods. These methods, made possible by the multiple observational viewpoints in the heliosphere, allow for the determination of the true, threedimensional propagation characteristics of the CME.

The key contribution of this work has been the differentiation of the CME and sheath structures observationally, which has allowed for the different structures to be tracked, modeled and predicted separately. To accomplish this, in addition to using the Graduated Cylindrical Shell to measure the CME ejecta structure, a separate geometry based on a spherical bubble was applied to fit the sheath separately. Hess & Zhang (2014) was the first work to extend this type of distinct tracking technique beyond the low solar corona and deeper into the heliosphere. Tracking the two fronts independently is crucial, as the ejecta and its strong magnetic field is more capable of generating severe geomagnetic storms while the shock/sheath region is thought to be responsible for the acceleration of Solar Energetic Particles that are another important space weather concern. The separation of each front is also important if it is to be understood how the ejecta truly drives the sheath and the physical processes that govern the sheath evolution from the low corona to the Earth.

Combining the measurements with the analytical drag-based model allows for the conversion of these measurements into dynamic, kinematic profiles. In addition to reconstructing the profiles for CME events, by constraining the parameters of the DBM the model has been established in Hess & Zhang (2015) as being a potential means for creating accurate, and easy to calculate predictions for the CME ejecta arrival. Combining the ejecta arrival with measurements of the standoff can also effectively predict the sheath arrival as well. The drag-based model assumes that the bulk motion of the CME will be determined by the interaction of the CME as it collides with the solar wind, causing the CME to act as a body traveling through a fluid and ignores the effect of the Lorentz force on propagation.

The prediction method was created by using a unique form of the drag parameter, Γ , that decreased farther away from the Sun and was heavily influenced by the CME density and, by extension, the rate of CME expansion. This, coupled with a unique propagation direction dependence based on the GCS geometry is the basis for what may become a new and powerful space weather forecasting tool. To apply this tool to the sheath front, the standoff-distance is modeled as a linearly propagating wave in front of the CME. This linear assumption is an assumption and the standoff-distance will likely experience its own drag force in the heliosphere. For fast events this effect is less noticeable before the arrival of the sheath at the Earth as there is less time for the front to decelerate.

In order to turn this method into a useful prediction technique, a number of limitations will have to be addressed. The limited data available in realtime will significantly limit the quality of the observations used to make measurements and the inputs into the model. The solar wind will also have to be successfully modeled so as to accurately know the speed of the solar wind at any point in front of the solar wind.

In addition to the space weather forecasting implications, the method also has potential for studying the physical evolution of the post-eruption CME. As the model is refined and improved, the density profile in the Γ term will impact the rate at which the CME accelerates. Near the Sun when the expansion is roughly self similar, the radial expansion along the CME minor axis will be more significant. As the internal Lorentz force along the minor axis lessens relative to the lateral expansion of the CME in the solar wind, the minor axis will no longer expand at the same rate as the legs, causing a deformation and flattening of the CME front. While this has been qualitatively known, a more careful understanding of the expansion differences could lead to the quantification of the flattening of the CME front.

In order to augment the observational and theoretical methods used in this dissertation,

a comparison with MHD simulations of CMEs has also been performed. This work has to this point been a preliminary cross-validation of the techniques and has shown good agreement between the MHD models and the DBM. Artificial renderings have also been made to study the nature of CME observations in the heliosphere. As a more thorough analysis is done, these simulations could be key for overcoming the observational limits of the data used to for the prediction model.

Going forward, there are a number of different studies that can be used to further the work presented in this dissertation. Of course, any study will be improved by increasing the test sample, so the first step to be done is to increase the number of events. In addition to the events presented in this sample, I have successfully applied the DBM to more events for means of determining their propagation characteristics after reaching the Earth, but the predictive sample has not yet been expanded. This is partially due to the lack of useful, recent STEREO observation. In the fall of 2014, STEREO passed behind the Sun relative to the Earth and stopped sending data. Even in the time shortly before the data was officially lost, the degraded signal and approach towards a viewpoint directly opposite the Earth significantly reduced the ability to fully track a CME in STEREO data. While the satellites are expected to emerge from behind the Sun and begin to provide observations again, the increased effectiveness of the reconstruction methods when the STEREO spacecraft approach 90° from the Earth demonstrates the great impact a permanent observer at the Lagrangian L5 point, which is about 90° from the Earth, could have for both forecasters and scientific researchers.

Improving the physical assumptions in the model, namely the linearly propagating sheath front and the constant p_0/r^{-3} density evolution could greatly improve the model, both by making predictions more accurate and by greatly advancing the physical information that can be gotten from the model. Specifically, using a more observationally consistent expansion profile for the ejecta could help constrain the density evolution throughout the heliosphere. Since the ratio of the CME density to the ambient solar wind density is a key determinant for the drag parameter, Γ , this could be a very important next step for the model.

Another study I would like to perform involves the Eruptive Flux Rope model (Chen, 1996), first mentioned in Section 3.1. This model, which includes both the drag force as well the Lorentz forces on both the major and minor CME axes, can be used on the same height measurements as the DBM and a comparison between the two should indicate how much of the CME evolution is being missed in the DBM by ignoring magnetic effects. While the EFR model is likely too complex to be used in a realtime mode, knowing the effect of the Lorentz force could allow for the improvement of the predictive DBM. As the EFR model also includes the full magnetic field in the flux rope, it may be possible to use it as a means to try and see if the strength and orientation of the magnetic field in the Z direction could be predicted. This would be of significant importance to space weather researchers, as it is the magnetic field as well as the arrival of the front at the Earth that will determine if there will be a geomagnetic storm, and how severe a storm will be.

In addition to just the EFR model, a more thorough comparison with the simulation data could also improve the results of this dissertation. For now the heights and artificial renderings have been used for just a small number of cases. Performing the analysis on a number of different events could further demonstrate the agreement between the different data sets. Also, over a number of different events, performing this comparison with different boundary conditions input into the simulation data could also provide a useful parameterization that could help the simulation in a realtime mode. For now many numerical simulations are created by creating a number of runs with different boundary conditions and selecting which one best matches the observations. This is effective after the event when the CME is already well understood, but is less useful for predictive purposes. By determining the factors that influence the input conditions in the simulation, the entire forecasting community could benefit.

This dissertation is a first step towards a comprehensive understanding of CMEs in the heliosphere, combining the major tools available. These include the most extensive observations of the solar corona and interplanetary space that have ever been possible, analytical tools that are being constantly refined and simulations that are always pushing the limits of available computational power. Using these various data sets, it is possible to gain a detailed knowledge of the physics that govern Coronal Mass Ejection propagation. Not only does this lead to a better scientific understanding of one of the most powerful phenomena observed in the solar system, but also better predictive capabilities that allow society to prepare for CMEs at the Earth and avoid the severe space weather consequences that are possible. There is much more work to be done, but as CME knowledge grows with advances in technology, these eruptive transients can one day be fully understood.

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Biography

Phillip Hess grew up in Cornwall, PA, graduating from Cedar Crest High School in 2006. He attended Seton Hall University, receiving a Bachelor's of Science in Physics with minors in Computer Science and Mathematics in 2010. He then went to George Mason University, receiving a PhD in Computational Sciences and Informatics in 2015. In January 2016 he will begin a postdoctoral fellowship at the Naval Research Laboratory in Washington, DC.