



Eötvös Loránd University

Temporal Development of Interplanetary Shocks in the Heliosphere

Országos Tudományos Diákköri Konferencia

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Abstract

Interplanetary shocks are one of the crucial dynamic processes in the Heliosphere. They accelerate particles into high energy, generate plasma waves and could potentially trigger geomagnetic storms in the terrestrial magnetosphere disturbing significantly our technological infrastructures. In this study, two IP shock events are selected to investigate the temporal variations of the shock parameters using magnetometer and ion plasma measurements of the STEREO A and B, the Wind, and the ACE spacecraft. The shock normal vectors are determined using the minimum variance analysis (MVA) and the magnetic coplanarity methods. During the May 07 event, the shock parameters and the shock normal direction are consistent. During the April 23 event, the shock parameters do not change significantly, however, the shape of the IP shock appears to be twisted along the transverse direction to the Sun-Earth line. STEREO B does not observe the IP shock signatures during this event.

keywords: Interplanetary shock, Solar wind: space plasma, Heliosphere.

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Chapter 1

Introduction

The solar corona is hotter than the layers beneath it. As a result, electrons are constantly knocked off their nuclei to form a constantly moving gas, known as the solar wind. Historically, the existence of the solar wind was predicted by astrophysicist Eugene N. Parker and the term was coined by him based on the observation of how the comet tail always points away from the Sun by German astronomer Ludwig Biermann (E. N. Parker, 1958), (Biermann, 2013). The existence of the solar wind was confirmed by the Mariner 2 spacecraft (Snyder & Neugebauer, 1965). The solar wind is a fully ionized collisionless plasma and is both supersonic and super-Alfvenic. Shock is a transition region between supersonic to subsonic. So, fast moving solar wind has a tendency to create a shock on its journey. Hence, interplanetary shocks are common through the Heliosphere. There are a few varieties of shocks such as planetary bow shocks, shocks that are risen due to the stream interaction regions (SIR), which is called co-rotation region (CR) when extend beyond 1 AU and coronal mass ejection (CME) driven shocks. IP shocks are one of the main and efficient accelerators of energetic particles (Tsurutani & Lin, 1985), (Keith & Heikkila, 2021). These accelerated particles can cause disturbances to the geomagnetic field and are hazardous to astronauts and satellites. (IP) shocks driven by (CMEs) precede large geomagnetic storms (Gonzalez et al., 1994). Large geomagnetic storms can damage oil and gas pipelines and interfere with electrical power infrastructures. GPS navigation and high-frequency radio communications are also affected by ionosphere changes brought on by geomagnetic storms (Cid, Palacios, Saiz, Guerrero, & Cerrato, 2014) and can cause internet disruptions around the world for many months (Jyothi, 2021).

Therefore, IP shocks are important in determining and understanding space weather. The IP shock normal vector can demonstrate how shock propagates through the heliosphere. Thus, the shock normal vector determination is vital.

The main goal of this thesis is to study and determine IP shock normal vectors and how they vary in their temporal evolution. There are several methods for determining the shock normal vector. In this thesis, the minimum variance analysis (MVA) and the magnetic coplanarity method are used. These two methods are primarily utilized because they require solely magnetic field data. The data are from the STEREO A and B, the Wind, and the ACE spacecraft. In the spacecraft, the resolutions of the magnetometers are much higher and more precise than that of the plasma instruments. So, any agreement between the two methods indicates relatively accurate shock normal vectors. Here, two events are studied, one is May 07, 2007, and the other is April 2. The data selection year, 2007, is special because of location wise it was the year when twin STEREO A and B spacecraft were closer to the Sun-Earth line until their gradual separation from each other in the following years. Hence, shocks during this period are proper to study shock propagation and their temporal developments. Chapter 2 discusses the basics of plasma physics and magnetohydrodynamics, which are the governing equations of these heliosphere phenomena. Chapter 3 presents a brief description of the Sun, the solar wind, and the interplanetary magnetic field. Chapter 4 is about instrumentation, database, and methods. Chapter 5 discusses the results.

Chapter 2

Basics of Magnetohydrodynamics

2.1 Plasma

The term plasma for this state of matter was coined by Irvin Langmuir after its similarity with the blood plasma carrying white and red cells (Tonks, 1967). A plasma is a gas of charged particles made up of an equal number of free carriers for positive and negative charges. Having nearly the same number of opposite charges ensures that the plasma appears quasineutral from the outside. Free particle carriers mean the particles inside a plasma must have enough kinetic (thermal) energy to overcome their nearest neighbors' potential energies, which means a plasma is a hot and ionized gas. There are three basic criterion for a plasma (Baumjohann & Treumann, 2012)[1-4].

The first criterion is a test-charged particle is clouded by its opposite-charged particles, canceling the electric field of the test particle. This is known as the Debye shielding and its length is defined as follows:

$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T_e}{n_e e^2}}, \quad (2.1)$$

where ϵ_0 is the free space permittivity, k_B the Boltzmann constant, $T_e = T_i$ the electron and ion temperature and n_e the plasma density. To ensure the quasineutrality of a plasma, the system length must be greater than the Debye length

$$L \gg \lambda_D \quad (2.2)$$

The second criterion is since the Debye shielding results from the collective behavior of particles inside the Debye sphere with the radius λ_D , the Debye sphere must contain enough particles

$$\Lambda = n_e \lambda_D^3 \gg 1 \quad (2.3)$$

which indicates the mean potential energy of particles between their nearest neighbors must be less than their mean individual energies.

The third criterion is the collision time scale of the system is greater than the inverse of the plasma, electron, and ion cyclotron gyrofrequencies.

$$\tau \gg \omega_p^{-1}, \Omega_i^{-1}, \Omega_e^{-1} \quad (2.4)$$

By solving each particle, plasma dynamics can be described, but this approach is too difficult and inefficient. Therefore, there are certain approximations, depending on the corresponding problems. Magnetohydrodynamics is one of such approximations that instead of taking account of individual particles, the plasma is assumed as a magnetized fluid.

2.2 The Single Fluid MHD

In this section, the magnetohydrodynamics (MHD) equations are briefly introduced without too much detail and derivations. The following formulizations are based on (Baumjohann & Treumann, 2012)[138-158], (Murphy, 2014), (Freidberg, 2014) and (Jr., 2019). Magnetohydrodynamics (MHD) was developed by Hannes Alfvén (Davidson, 2002). MHD equations are the result of coupling the Navier-Stokes equations (the fluid equations) to the Maxwell equations. In the MHD, the plasma is treated as a single fluid with macroscopic parameters such as average density, temperature, and velocity. Since plasma consists of generally two species of particles, namely electrons and ions, the different species should be handled together. Hence, the single fluid approximation is utilized. The single fluid variables are defined as follows: Mass density, considering $m_e \ll m_i$:

$$\rho_m = n_e m_e + n_i m_i \approx m_i n \quad (2.5)$$

Momentum density:

$$\rho_m \mathbf{v} = n_e m_e \mathbf{u}_e + n_i m_i \mathbf{u}_i \approx \rho_m \mathbf{u}_i \quad (2.6)$$

Current density:

$$\mathbf{J} = n_e q_e \mathbf{u}_e + n_i q_i \mathbf{u}_i = en(\mathbf{u}_i - \mathbf{u}_e) \quad (2.7)$$

Total pressure:

$$\mathbf{P} = \mathbf{P}_e + \mathbf{P}_i \quad (2.8)$$

By using the single fluid variables, the single fluid MHD equations can be defined as follows: The continuity equation for the mass density:

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \vec{v}) = 0 \quad (2.9)$$

The momentum equation:

$$\frac{\partial(\rho_m \mathbf{v})}{\partial t} + \nabla \cdot (\rho_m \mathbf{v} \mathbf{v}) = -\nabla \cdot \mathbf{P} + \rho_e \mathbf{E} + \mathbf{J} \times \mathbf{B} \quad (2.10)$$

,where ρ_e denotes the charge density.

The generalized Ohm's law:

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{J} + \frac{1}{ne} \mathbf{J} \times \mathbf{B} - \frac{1}{ne} \nabla \cdot \mathbf{P}_e + \frac{m_e}{ne^2} \frac{\partial \mathbf{j}}{\partial t}, \quad (2.11)$$

where $\eta \mathbf{J}$ is resistive term

Ampère's law:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \quad (2.12)$$

Faraday's law:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (2.13)$$

And finally, the magnetic field divergence constraint:

$$\nabla \cdot \mathbf{B} = 0 \quad (2.14)$$

The MHD approximations are valid when the characteristic speeds of the system is much slower than the speed of light,

$$\mathbf{v} \ll c \quad (2.15)$$

the characteristic frequency, ω , must be smaller than the ion cyclotron frequency

$$\omega \ll \omega_i \quad (2.16)$$

the characteristic scale length of the system must be longer than the mean free path of ion gyroradius

$$L > r_{gi} \quad (2.17)$$

the characteristic scale times must be larger than the collision times as stated in equation 2.4.

2.3 MHD wave modes

Plasma is considered as a highly conductive fluid, which consists of charged particles. Therefore, MHD waves in plasma fundamentally arise from two distinct wave speeds: the sound speed of a fluid and the Alfvén speed, which is due to the magnetic field pressure and tension. Their combination gives rise to the magnetosonic waves. Thus, in MHD there are three wave modes—namely slow magnetosonic, the shear-Alfvénic and the fast magnetosonic waves (Fitzpatrick, 2014) in addition to the sound wave, as seen in Figure 2.1.

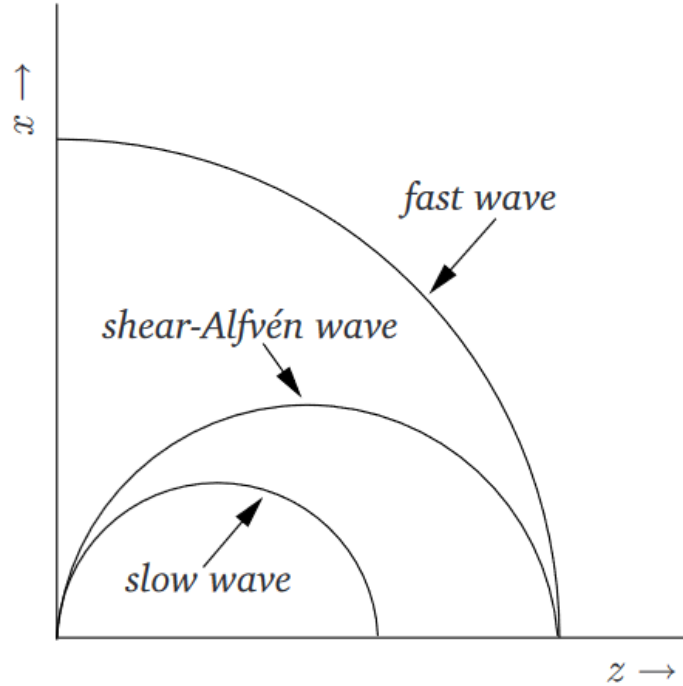


Figure 2.1: Phase velocities of the three MHD waves. The Figure is taken from (Fitzpatrick, 2014)

The derivation of the waves can be obtained from the linearized MHD dispersion relation. The sound wave is due to a compressible fluid and the wave is longitudinal. The sound speed is defined as:

$$C_s = \sqrt{\frac{\gamma k_B T}{m_i}} \quad (2.18)$$

where, γ is the polytropic index and in space plasma, it is in the range $1 < \gamma < 5/3$ (Pasachoff et al., 2014), k_B is the Boltzmann constant, T is temperature, m_i is mass of a particle species. And the Mach number, a ratio of flow to the (thermal) sound speed

$$M_s = \sqrt{\frac{m_i v^2}{\gamma k_B T}} \quad (2.19)$$

The shear Alfvénic wave is incompressible and transverse. The Alfvén speed is defined as follows:

$$V_A = \sqrt{\frac{B^2}{\mu_0 \rho}} \quad (2.20)$$

here $\frac{B^2}{\mu_0}$ is the magnetic pressure and ρ is density.

Similarly, the magnetic Mach number, which is defined as a ratio between the flow speed and the Alfvénic speed, is defined as follows:

$$M_A = \frac{V_{flow}}{V_A} \quad (2.21)$$

The magnetosonic waves are as follows:

$$C_{ms}^2 = \frac{1}{2}(C_s^2 + V_A^2) \left[1 \pm \left(1 - 4 \frac{\cos^2 \theta}{b^2} \right) \right] \quad (2.22)$$

, where b term is as follows:

$$b = \frac{C_s}{V_A} + \frac{V_A}{C_s} \geq 2 \quad (2.23)$$

The equation 2.22 has two roots. The root containing (+) is the fast magnetosonic wave while the one containing (-) is the slow magnetosonic wave.

When $V_A \gg V_s$ or $V_s \gg V_A$ in 2.23 as well as the wave propagation direction is nearly perpendicular to the magnetic field ($\cos^2 \theta \ll 1$), the slow magnetosonic wave speed becomes as follows:

$$C_{ms}^2 = \cos^2 \theta \frac{C_s^2 V_A^2}{(C_s^2 + V_A^2)} \quad (2.24)$$

while the fast magnetosonic wave is simplified as follows:

$$C_{ms} = \sqrt{C_s^2 + V_A^2} \quad (2.25)$$

from 2.25, the fast magnetosonic Mach number is defined as

$$M_{ms} = \frac{V}{C_{ms}} \quad (2.26)$$

2.4 MHD discontinuities

When plasmas of different properties collide, they reach equilibria, resulting in the boundaries separating adjacent plasma regions (Baumjohann & Treumann, 2012). These boundary regions are called discontinuities, and in astrophysics, heliopause and magnetopause are examples of these discontinuities. Through discontinuities, the field and plasma parameters change abruptly, but these sudden changes satisfy a few conditions, namely the jump conditions. To derive the jump conditions, it is suitable to integrate the

conservation laws across the discontinuity. So, it is better to write the single fluid MHD equations 2.2 in conservative form, assuming that at the two sides of the discontinuity an ideal single-fluid MHD holds. Following some notations and derivations of (Baumjohann & Treumann, 2012)[8], the ideal single-fluid MHD equations in conservative forms are defined as below:

$$\frac{\partial(\rho\mathbf{v})}{\partial t} + \nabla \cdot \left[(\rho\mathbf{v}\mathbf{v}) + \left(\mathbf{P} + \frac{B^2}{2\mu_0}\mathbf{I} \right) - \frac{1}{\mu_0}(\mathbf{B}\mathbf{B}) \right] = 0, \quad (2.27)$$

where $\mathbf{P}$ the plasma pressure, B the magnetic field magnitude, $\mathbf{B}$ the magnetic field vector, μ_0 the vacuum permeability and $\mathbf{I}$ the identity tensor.

The induction equation:

$$\frac{\partial\mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) \quad (2.28)$$

The divergence of the magnetic field:

$$\nabla \cdot \mathbf{B} = 0 \quad (2.29)$$

The energy conservation equation:

$$\nabla \cdot \left\{ \rho\mathbf{v} \left[\frac{1}{2}v^2 + w + \frac{1}{\rho} \left(p + \frac{B^2}{\mu_0} \right) \right] - \frac{1}{\mu_0}(\mathbf{v} \cdot \mathbf{B})\mathbf{B} \right\} = 0, \quad (2.30)$$

where for slowly variable fields $\mu_0\mathbf{j} = \nabla \times \mathbf{B}$ and the ideal Ohm's law $\mathbf{E} = -\nabla \times \mathbf{B}$ are implemented as well as neglecting charges $\rho\mathbf{E} = 0$, and $w = \frac{c_v P}{\rho k_B}$ is the internal enthalpy.

For completion, the equation of state is set:

$$\mathbf{P} = p\mathbf{I} \quad (2.31)$$

Choosing a co-moving reference frame with discontinuity, a steady-state situation is assumed that all the time-dependent terms are canceled, leaving the flux terms in the conservation laws. A discontinuity causes the plasma parallel to the discontinuity to stay the same while the plasma perpendicular to the discontinuity changes. For these reasons, a two-dimensional function $S(\mathbf{x})=0$ can be used to characterize the discontinuity surface, and the normal vector to the discontinuity, $\mathbf{n}$, is defined as follows

$$\mathbf{n} = -\frac{\nabla S}{|\nabla S|} \quad (2.32)$$

To the direction of the $\mathbf{n}$ the vector derivative has only one component $\nabla = \mathbf{n}(\frac{\partial}{\partial n})$. After these considerations, integrating over the discontinuity for the flux terms has to be done. Remembering only two perpendicular sides of the discontinuity contribute twice to the integration, a quantity X crossing S becomes

$$\oint_s \frac{\partial X}{\partial n} dn = 2 \int_1^2 \frac{\partial X}{\partial n} dn = 2(X_2 - X_1) = 2[X] \quad (2.33)$$

where $[X]$ indicates the jump of a quantity X . Now replacing the conservation laws of the ideal one-fluid MHD with the jump conditions, **the Rankine-Hugoniot** conditions are defined as follows:

$$\mathbf{n} \cdot [\rho_m \mathbf{v}] = 0 \quad (2.34)$$

$$\mathbf{n} \cdot [\rho_m \mathbf{v}\mathbf{v}] + \mathbf{n} \left[p + \frac{B^2}{2\mu_0} \right] - \frac{1}{\mu_0} \mathbf{n} \cdot [\mathbf{B}\mathbf{B}] = 0 \quad (2.35)$$

$$[\mathbf{n} \times \mathbf{v} \times \mathbf{B}] = 0 \quad (2.36)$$

$$\mathbf{n} \cdot [\mathbf{B}] = 0 \quad (2.37)$$

$$\left[\rho_m \mathbf{n} \cdot \mathbf{v} \left\{ \frac{v^2}{2} + w + \frac{1}{\rho} \left(p + \frac{B^2}{\mu_0} \right) \right\} - \frac{1}{\mu_0} (\mathbf{v} \cdot \mathbf{B}) \mathbf{n} \cdot \mathbf{B} \right] = 0 \quad (2.38)$$

From the equations above, the normal component of the magnetic field is continuous across all discontinuities, which leads to its jump condition being vanished.

$$[B_n] = 0 \quad (2.39)$$

Also normal direction mass flow is continuous:

$$[\rho_m v_n] = 0 \quad (2.40)$$

Splitting the fields between the normal and tangential components, the remaining jump conditions are derived:

$$\rho_m v_n [v_n] = - \left[p + \frac{B^2}{2\mu_0} \right] \quad (2.41)$$

$$\rho_m v_n [\mathbf{v}_t] = \frac{B_n}{\mu_0} [\mathbf{B}_t] \quad (2.42)$$

$$B_n [v_t] = [v_n \mathbf{B}_t] \quad (2.43)$$

where subscript t and n denote normal and tangential components respectively. The equations 2.39 and 2.40 demonstrate that the normal components of the magnetic field as well as the mass flow are constant across the discontinuity. **The Rankine-Hugoniot** conditions give rise to four types of MHD discontinuities (Baumjohann & Treumann, 2012), namely contact discontinuity, tangential discontinuity, rotational discontinuity, and shocks as the values are defined in Table 2.1.

The properties of MHD discontinuities			
Discontinuity type	Normal Mass flux	Normal Magnetic field	Density
Contact	$v_n = 0$	$B_n \neq 0$	$\rho \neq 0$
Tangential	$v_n = 0$	$B_n = 0$	$\rho \neq 0$
Rotational	$v_n \neq 0$	$B_n \neq 0$	$\rho = 0$
Shocks	$v_n \neq 0$	$B_n \neq 0$ or $B_n = 0$	$\rho \neq 0$

Table 2.1: Some properties of MHD discontinuities. The values are taken from (Oliveira, 2015)

Contact discontinuity is determined by the condition when there is no normal mass flow across discontinuities, which means from the Rankine-Hugoniot conditions $v_n = 0$. When $B_n \neq 0$ or $[B_n] = 0$, the only quantity that experiences a change across the discontinuity is the density, $[\rho] \neq 0$. Due to these constraints, the plasma on the two sides of the discontinuity are attached and connected by the normal component of the magnetic field. As a result, they flow together at the same tangential speed. This is known as the contact discontinuity.

Tangential discontinuity is when $B_n = 0$ in addition to $v_n = 0$, only non-trivially satisfied jump condition is the total pressure balance in the equation 2.41, which indicates that a discontinuity is created between two plasma with total pressure balance on both sides, and no mass and magnetic fluxes are crossing across the discontinuity while all other quantities are changing. This is known as the tangential discontinuity.

Rotational discontinuity is formed when there is a continuous normal flow velocity $[v_n] = 0$ with a non-vanishing $B_n \neq 0$ such that from the equations 2.42 and 2.43 the tangential velocity and the magnetic

field can only change together, especially the equation 2.43 indicates they rotate together when crossing the discontinuity.

Shocks Unlike the previous three discontinuities, shocks are irreversible that the entropy increases (Goedbloed, Keppens, & Poedts, 2019). And one of the main distinctive characteristics of shocks is normal fluxes of the Rankine-Hugonot conditions take non-zero values, $\rho v_n \neq 0$, and the density ρ is discontinuous.

Consequently of having the three wave modes, there are corresponding three shocks – fast shock (FS), intermediate shock (IS), and slow shock (SS) (Tsurutani et al., 2011). When the fast wave speed is greater than the upstream magnetosonic speed 2.25, the fast shocks (FSs) are formed. Similarly, when the shear-Alfvén wave speed is greater than the upstream Alfvén velocity 2.20, the intermediate shocks (ISs) are formed, and when the slow wave speed is greater than the upstream (thermal) sound speed 2.18, the slow shocks (SSs) are formed with their respective Mach numbers greater than at least 1.

The three MHD waves 2.3 are anisotropic, meaning their speeds depending on the angle between wave propagation direction and the upstream (unshocked) magnetic field. An illustration of this is the Parker spiral propagation of the solar wind such that the Interplanetary magnetic field hits, for example, the Earth from the morning side, it creates parallel and perpendicular shocks with respect to the shock normal and the upstream magnetic field B as shown in Figure 2.2

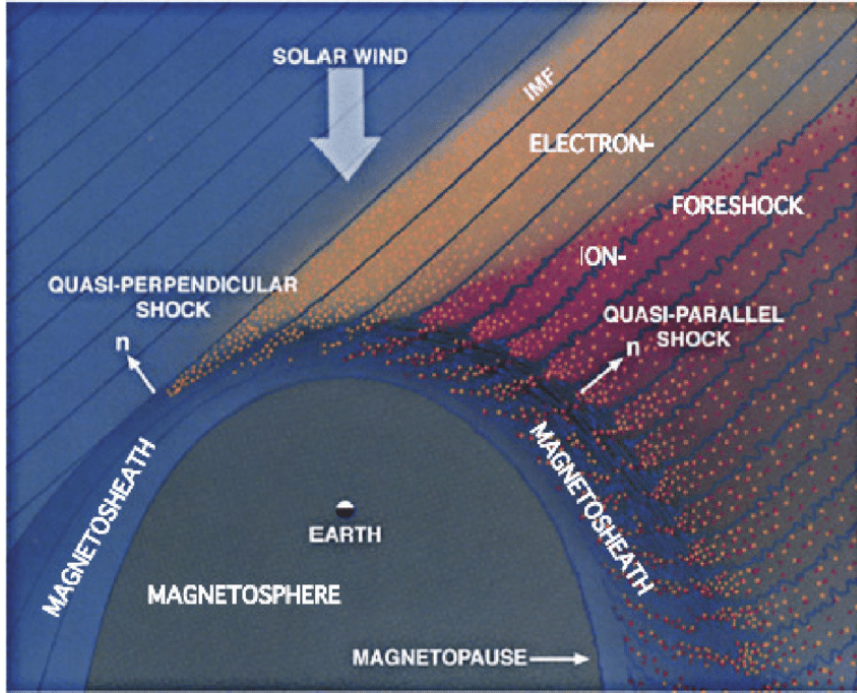


Figure 2.2: The solar wind interaction with the Earth's bow shock. The Figure is taken from (Oliveira, 2015)

Hence, depending on the shock normal angle θ_{B_n} , the shocks can be geometrically classified as **parallel**, $\theta_{B_n} = 0^\circ$, **perpendicular**, $\theta_{B_n} = 90^\circ$ and **oblique**, $0^\circ < \theta_{B_n} < 90^\circ$ (Chao & Hsieh, 1984). In parallel shock, the magnetic field remains unchanged by the shock while in the perpendicular case, both the pressure and field strength are increased at the shock.

Chapter 3

The Solar and Heliospheric Physics

The Sun is the main source of energy for all lives on the earth as well as the main defining object of the solar system dynamics. Like all other stars, the Sun has both inner complex dynamics as well as interplanetary dynamics. The later dynamics are our main interest in this thesis work. In this chapter, for the sake of completeness and to explain the origin of these tremendous dynamics, the inner structure of the Sun as well as some important heliospheric activities are briefly discussed.

3.1 The Sun

Our star, the Sun, is a G2-V type (M. J. Aschwanden, 2014) star. How the sun or in general stars work is in a way of opposing forces between outward radiation fueled by nuclear fusion and inward pressure dictated by the gravitational force. The radiative force is the product of the fusion of hydrogen atoms, which constitutes about 75 %, into helium atoms, which constitute 25 % of the Sun. This process is a thermonuclear reaction that requires the weak force, which is one of the fundamental forces in nature, via turning proton into neutron.

Structurally, the Sun has the inner zones and the outer zones. The former consists of the Core, Radiative Zone, the Interface Layer (Tachocline), and Convection Zone. The latter consists of the Photosphere, the Chromosphere, the Transition region, and the Corona as shown in Figure 3.1.

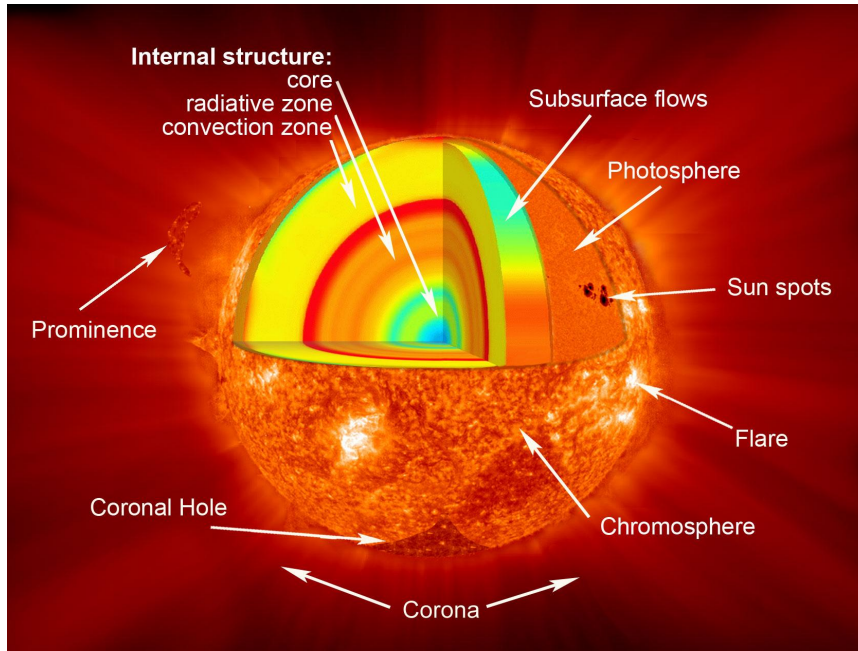


Figure 3.1: The layers of the Sun (nasa.gov)

The core of the sun is 25% of the solar radius (García et al., 2007), the density is about $150g/cm^3$ (Basu, Chaplin, Elsworth, New, & Serenelli, 2009) contains 34% of the Sun's mass even though only 0.8% of the total volume, and it is the hottest part of the Sun that a temperature of 15 million kelvins (Dr. David H. Hathaway, 2015). This is the zone where the thermonuclear reaction takes place. For the radiative zone, it starts from the edge of the core to the Interface layer (Tachocline), and much of the energy generated in the core is carried away by photons though photons take a million years to reach the next layer due to the dense material of the region (Chemin, 2022).

The very next layer, the interface layer (Tachocline) is much of our interest because it is believed that the solar magnetic dynamo originates in this very thin layer (Tobias & Weiss, 2007) that magnetic field lines can become stronger due to the changes in the fluid flow velocities crossing this layer. However, recent radio observations of brown dwarf stars show that, despite not having a tachocline layer, they can have similar magnetic strength and activities just like the sun, which indicates the convection zone may be solely responsible for the solar dynamo (Route, 2016). Next, the convection zone is the outermost layer of the inner zones and it extends about 200,000 km from the depth and the temperature is approximately 2 million kelvins (Christensen-Dalsgaard, Gough, & Thompson, 1991), which makes the zone relatively cooler for heavy ions to keep their electrons so that the zone is opaque to the radiation (Ortuño-Araujo, Barranco-Jiménez, Zsargo, & Angulo-Brown, 2012), which in turns traps the heat and eventually the fluid becomes unstable and start convecting. As a result, this layer is very turbulent (Brummell, Toomre, & Cattaneo, 1995), which in addition to the rotational motion creates electric currents and magnetic fields, and the gas pressure is much more dominant than the magnetic pressure in this region, and because of this the magnetic field is dragged and twisted by the fluid, which then propagates passing through the photosphere, chromosphere, the transition region up to the corona and creates a multitude of activities on the surface of the sun called solar activity. In the photosphere, visible dark areas called sunspots appear due to localized strong magnetic regions, which inhibit some of the heat from reaching the surface and this makes the areas cooler than the other parts of the sun (Babcock & Babcock, 1955). Because of the mentioned strong magnetic nature, the magnetic field lines around the sunspot often twist and cross, causing a tension of energy that bursts in a sudden explosion called a solar flare (Chakraborty & Basak, 2022).

The corona is the hot and ionized outermost layer of the sun that it is millions of kelvins greater than that of the surface of the sun (M. Aschwanden, 2006). The solar magnetic field confines much of the coronal plasma, but some of the plasma spread with a supersonic speed into interplanetary space, which is called

the solar wind. Sometimes the excessive release of the plasma occurs with the following magnetic field, which is called coronal mass ejection (CME), which sometimes accompanies solar flares. These phenomena and solar activities define space weather. The solar activities are cyclic, which is called the solar cycle, and it is approximately 11 years (Center/SDO, 2015), see Figure 3.2. Each cycle the magnetic field of the sun flips, and the periods, in which, the sunspots are the greater in number are called solar maximum and the lower in number are called solar minimum.

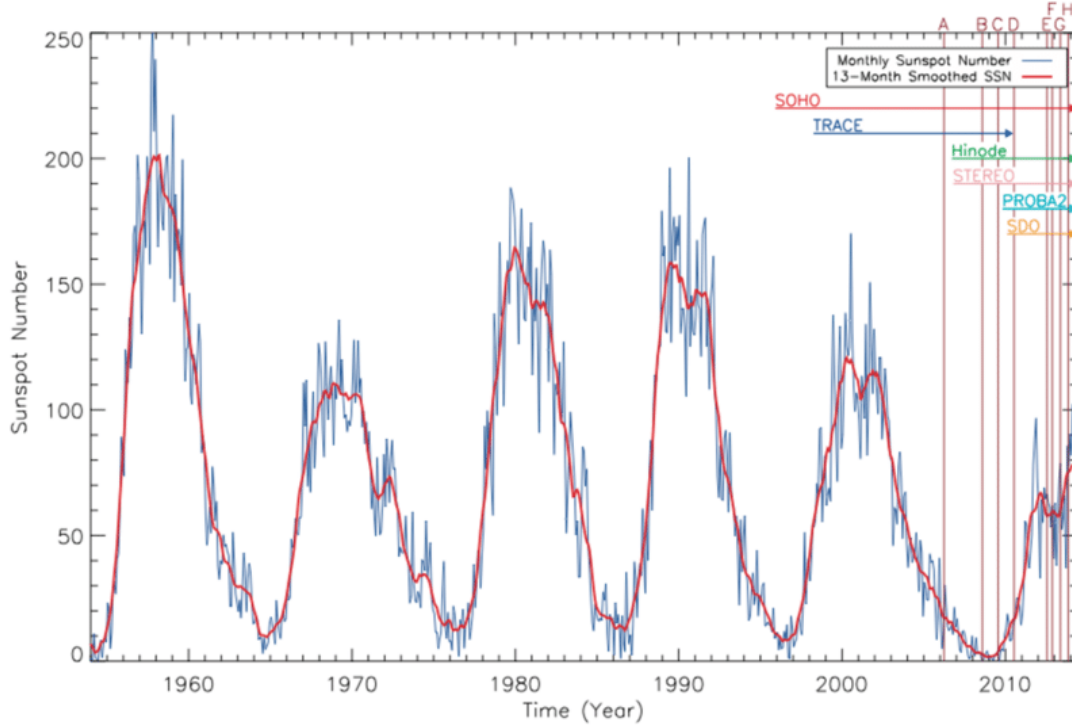


Figure 3.2: The sunspot cycle over the last several decades. The image extracted from (Pasachoff et al., 2014)

3.2 The Solar Wind and The Interplanetary Magnetic Field

The Sun ejects highly energized and ionized charged particles continuously in all directions, which is the feature of the solar wind. The solar wind is a fully ionized collisionless plasma that it consists of mostly equal amounts of protons and electrons with addition of negligible 3 to 6% helium (Neugebauer, 1981). As a result, the solar wind is a quasi-neutral plasma that whose characteristics can be defined by magnetohydrodynamics (MHD). In MHD, Alfvén theorem states that in a fluid with high electric conductivity the magnetic field line is frozen in it and moves along with it (Alfvén, 1942). Since the solar wind is one such fluid the Sun's magnetic field lines are frozen in the flow that they are forced to propagate with the solar wind (Roberts, 2007), forming the interplanetary magnetic field (IMF). Depending on the origination point whether in the coronal holes or the equatorial belt of the sun, the solar wind is classified as the fast solar wind with a velocity of 750 km/s and the slow solar wind with a velocity of 400 km/s respectively (Feldman, Landi, & Schwadron, 2005). The coronal holes are areas that appear dark in X-ray images because these areas are much cooler and less denser than other regions (Cranmer, 2009) and the magnetic field around these areas does not loop back down, but extend into the interplanetary space (E. Parker, 1959), so the plasma can easily flow out, creating the fast solar wind. The coronal holes can appear anywhere on the coronal areas during the solar maximum while they usually appear northern or southern poles of the sun during the solar minimum (McComas et al., 2003).

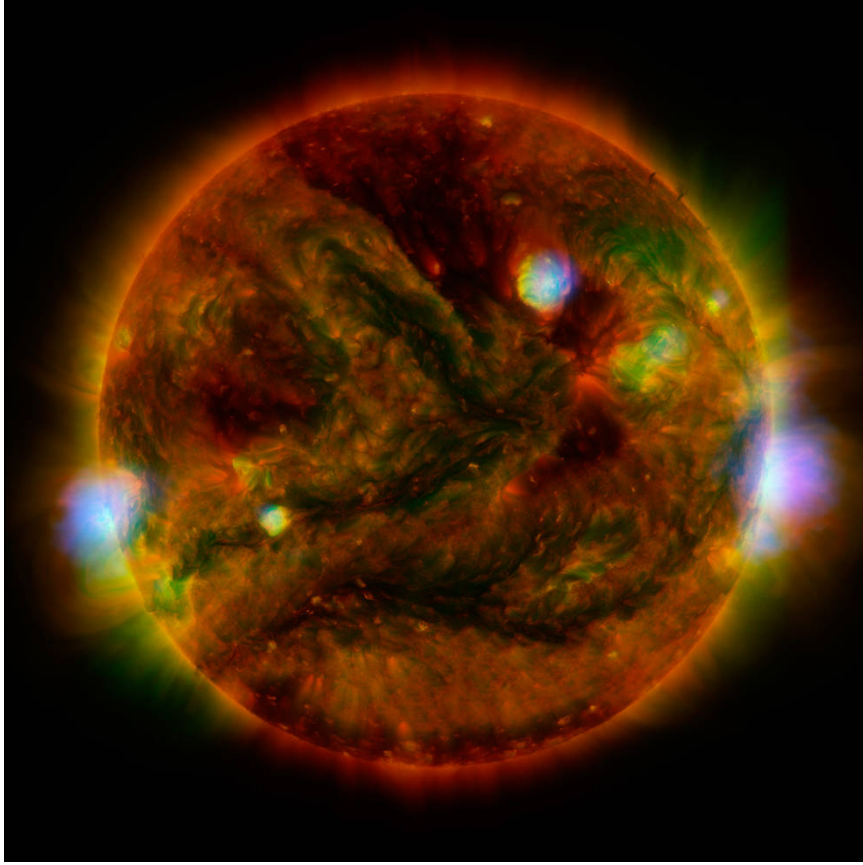


Figure 3.3: Combined X-ray image of the sun's active regions observed from several telescopes. High-energy X-rays from NASA's Nuclear Spectroscopic Telescope Array (NuSTAR) are shown in blue, low-energy X-rays from Japan's Hinode spacecraft are green, and extreme ultraviolet light from NASA's Solar Dynamics Observatory (SDO) is yellow and red, extracted from (NASA/JPL-Caltech/GSFC/JAXA, 2015)

The expansion of the solar wind is a radial propagation away from the sun that it is diluted and cools down on its journey. As seen from some observations the density of the solar wind decreases approximately as r^{-2} while the temperature decrease is less significant about a factor of 20 (Baumjohann & Treumann, 2012). During the expansion of the radial flow, the sun rotates, which is 27 days on average, and because the magnetic field lines are anchored in the sun, the radial flow looks like an Archimedean spiral called the Parker Spiral. At 1 AU the spiral makes 45° to the Earth-Sun line, see Figure 3.4.

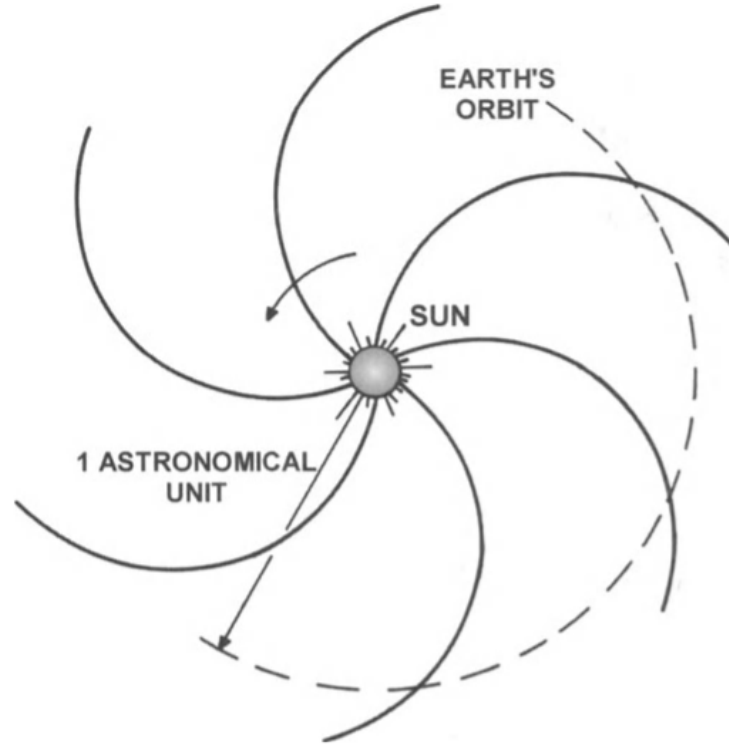


Figure 3.4: Schematic representation of the Archimedes spiral structure of the interplanetary magnetic field, figure extracted from (Bittencourt, 2004)

The solar wind travels throughout the solar system and defines the heliosphere the region in space whose frontier is impeded by the interstellar medium. Consequently, the heliosphere is a giant bubble whose center is the sun and protects the solar system from interstellar radiations and cosmic rays. The size of the heliosphere is about 121 AU (Cowen, 2013). At the boundary of the heliosphere, the supersonic solar wind becomes subsonic because of its interaction with the interstellar medium and this turning point is called the termination shock. Furthermore, due to the interaction the solar wind becomes turbulent and this region is called heliosheath which is in between the termination shock and the heliopause, where the solar wind is stopped by the interstellar medium.

3.3 Interplanetary shocks

The average interplanetary magnetic field strength is around 6 nT at 1 AU (Lowrie & Fichtner, 2020) and considering the average speed of the solar wind, the solar wind is both supersonic and super-Alfvénic, which means it is supermagnetosonic. As a result of this nature of the solar wind, when it collides with celestial objects such as planets, moons, asteroids, and comets or its own slow flowing part, shocks are formed just like how the aforementioned termination shock is created at the end of the heliosphere. The main characteristic of shocks that can be found in interplanetary space to interstellar regions is a denser state in contrast to the medium in which they propagate due to the shock formation. Furthermore, if the celestial objects are magnetized, then the shock formations are more interesting. One such fascinating magnetized object is our planet, the Earth. The Earth has its magnetic field, known as the magnetosphere, which originated from its inner core via the dynamo effect (Gilbert, 2003). The Earth's magnetosphere extends 60'000 kilometers in the Sunward direction while a million kilometers in the anti-Sunward direction (Lakhina, Alex, & Rawat, 2009). Such big extension is a common characteristic of all the magnetized planets, and as a result of this extension, the cross-section of a planet is increased by a large factor. For example for the Earth, the factor is 150 (Baumjohann & Treumann, 2012). Once the solar wind

impacts the magnetosphere, it cannot easily enter the Earth's magnetosphere because the interplanetary field lines, which are frozen in the highly conductive solar wind plasma, cannot penetrate the Earth's field lines. Instead, the solar wind is slowed down and deflected around the magnetosphere (Baumjohann & Nakamura, 2007), creating a bow shock, see Figure 3.5.

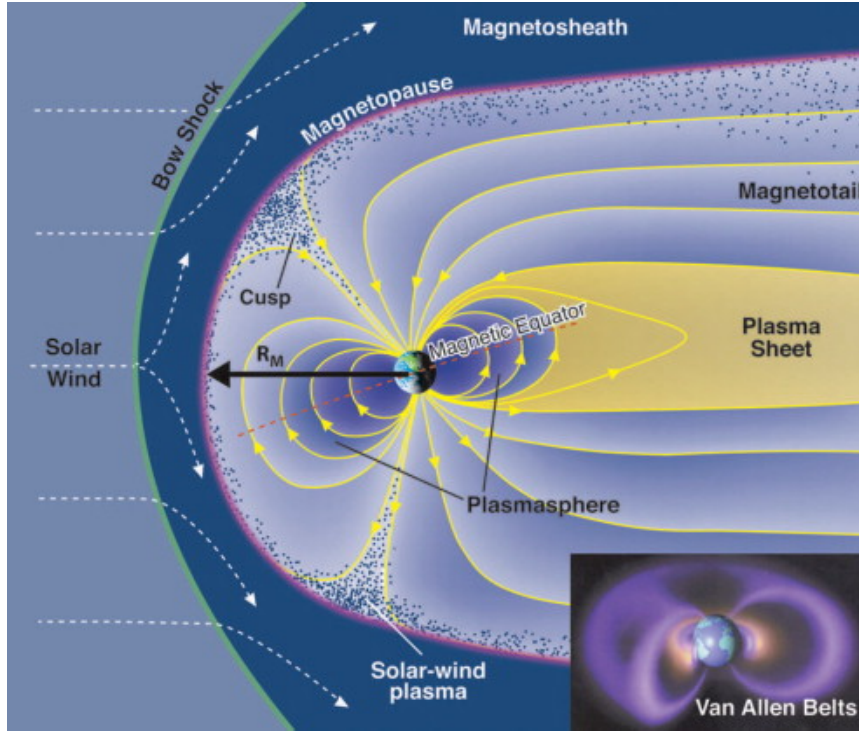


Figure 3.5: Illustration of the Earth's magnetosphere and its interaction with the solar wind. The figure is extracted from (Kivelson & Bagenal, 2007)

As a result of the slowing down of the solar wind plasma, the kinetic energy of some of the particles is converted into thermal energy, which occurs behind the bow shock, and this region is called the magnetosheath. The thin boundary region between two magnetic field lines is called the magnetopause. Bow shock formation is common to all the planets and celestial objects (Mazelle et al., 2004).

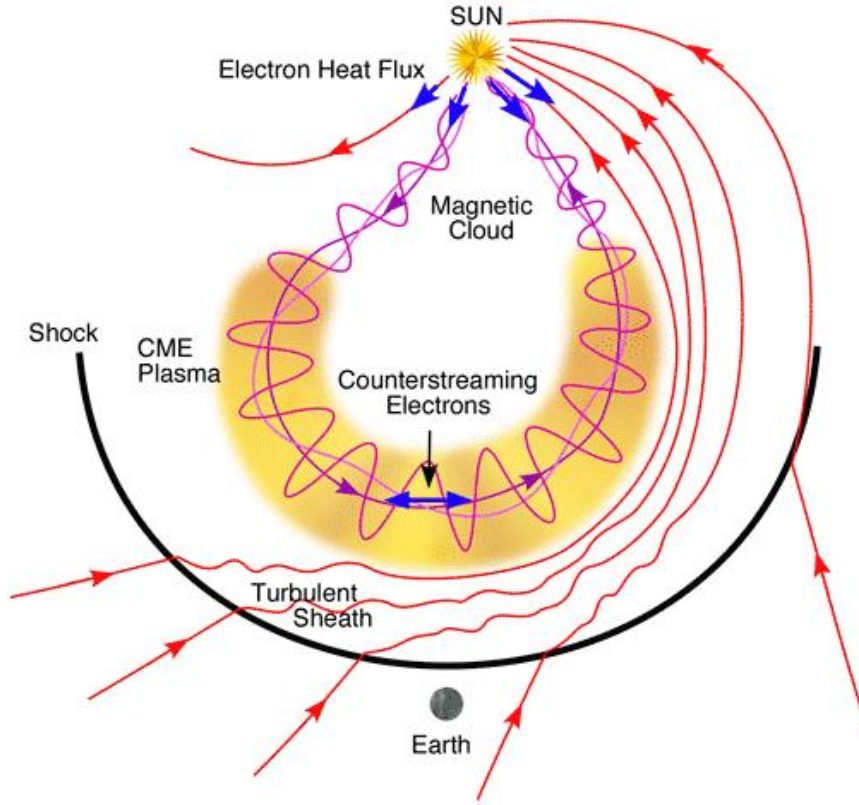


Figure 3.6: Illustration of a CME event. The figure is taken from (NASA, 2017)

In addition, there are several other shocks, the previously mentioned termination shock, CME (the Coronal Mass Ejection) shock, and CIR (corotating interaction region) shock. When a CME event occurs, it moves faster than the background solar wind flow, resulting in a shock wave. The created shock waves accelerate charged particles in front of them. So usually CMEs are the main cause of the solar energetic particles (SEPs) (Cane & Lario, 2006), see Figure 3.6.

Similarly to the CME cause shocks, when the fast solar wind flow catches the slow solar wind flow, the so called co-rotating interaction region is formed and if the pressure gradient gets sufficiently large and the speed difference surpasses the local speed shocks can arise (Heber, Sanderson, & Zhang, 1999), Figure 3.7.

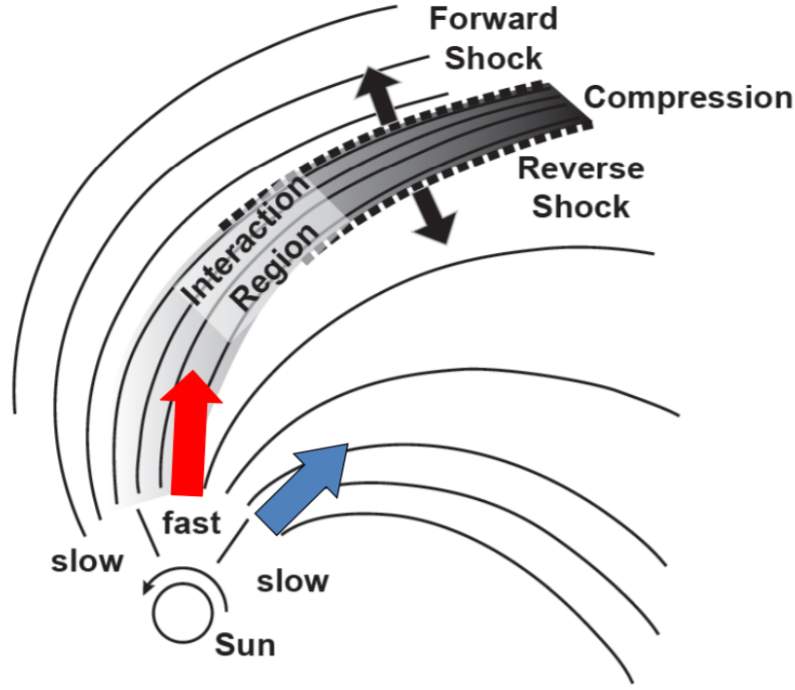


Figure 3.7: Co-rotating interaction region. The Figure is taken from (David Burgess, 2017)

3.3.1 Classifications of Interplanetary (IP) shocks

Armed with the above shock definitions and categorizations knowledge, now we can finally be able to classify IP shocks. The IP shocks can be classified based on their travel directions with respect to the solar wind frame of reference. If the shock is moving away from its driver, here the Sun is referred but drivers can be detailed such as ICMEs, CIRs, etc, the shock is called forward shock (FS), and if it is moving toward its driver, it is called reverse shock (RS). Adding the previous definitions of fast and slow shocks, IP shocks are usually categorized as fast forward (FF), fast reverse (FS), slow forward (SF) and slow reverse (SR) shocks (Berdichevsky, Szabo, Lepping, Viñas, & Mariani, 2000), see Figure 3.8.

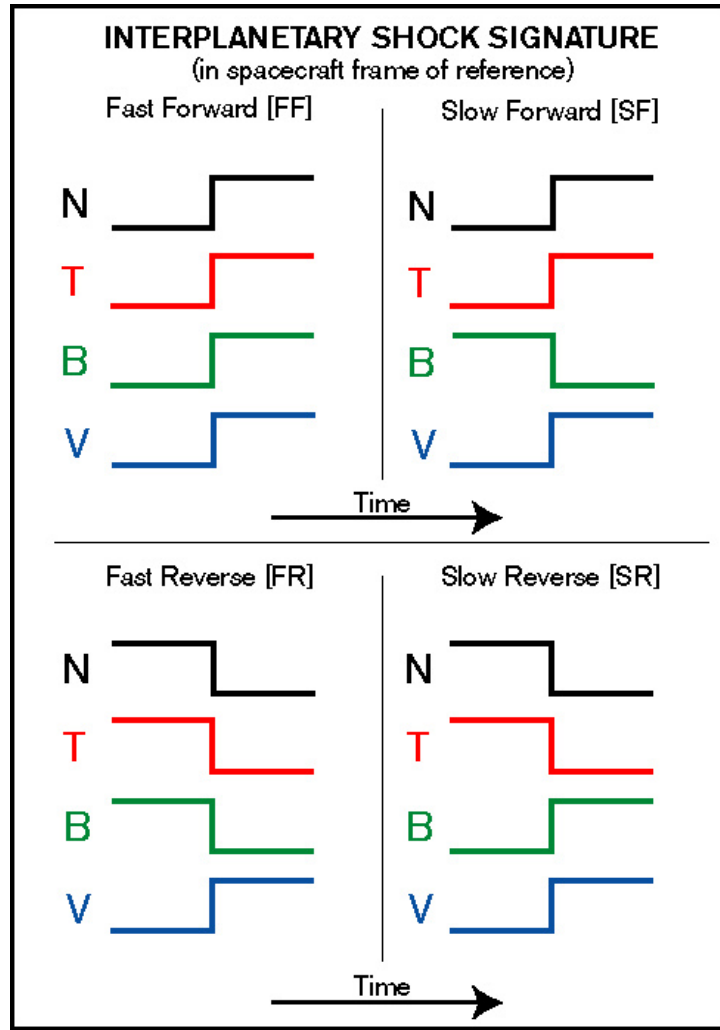


Figure 3.8: Categorizations of IP shocks. N, T, B, and V denote number density, the proton temperature, the magnitude of the magnetic field, and speed respectively. The Figure is from (WIND MFI Team Science, 2001)

As you can see from Figure 3.8, the solar wind plasma parameters – number density N, the proton temperature T, the magnitude of the magnetic field B, and the bulk speed V parameters increase dramatically from upstream (unshocked) to downstream (shocked) regions in fast forward (FF) shocks while the parameters except for the bulk speed decrease in fast reverse (FR) shocks¹. In the case of slow forward (SF) shocks, the parameters except for the magnitude of the magnetic field increase from upstream to downstream whereas in the case of slow reverse (SR) shocks, the number density N and the proton temperature T decrease while the magnitude of magnetic field B and the bulk speed V increase².

Within 1 AU, the most frequent IP shocks are fast forward (FF) shocks (Richter, Hsieh, Luttrell, Marsch, & Schwenn, 1985)

¹In a sense of the reverse upstream to downstream in fast reverse (FR) shocks, the parameters except for the bulk speed increase from reversed upstream to downstream

²Again in the sense of the reversed upstream to downstream in slow reverse (SR) shocks, the number density N and the proton temperature T increase while the magnitude of magnetic field B and the bulk speed V decrease

Chapter 4

Analysis methods

4.1 Instruments

In this thesis work, STEREO (Solar Terrestrial Relations Observatory) A and B, Wind and ACE (Advanced Composition Explorer) spacecraft magnetic field and plasma data are used. In the following subsections, the basic descriptions of each spacecraft, their orbits, and their instruments are mentioned.

4.1.1 STEREO A and B

The twin STEREO (Solar Terrestrial Relations Observatory) A and B spacecraft were launched on October 26, 2006, from Kennedy Space Center (M. L. Kaiser et al., 2008). In heliospheric orbit at 1 AU, STEREO A (Ahead) leads while STEREO B (Behind) trails Earth. The two spacecraft separate at 44 degrees from each other annually, see figure 4.1. This formation allows the stereoscopic image of the Sun from the sun-earth axis angle in 3D. The purposes of the mission are to study the cause and initiation mechanisms of coronal mass ejection (CME) and their propagation through the heliosphere, discover the sites and procedures of solar energetic particles in the corona as well as the interplanetary medium, and construct a three dimensional and time-dependent model of the parameters of the solar wind (M. Kaiser, 2005).

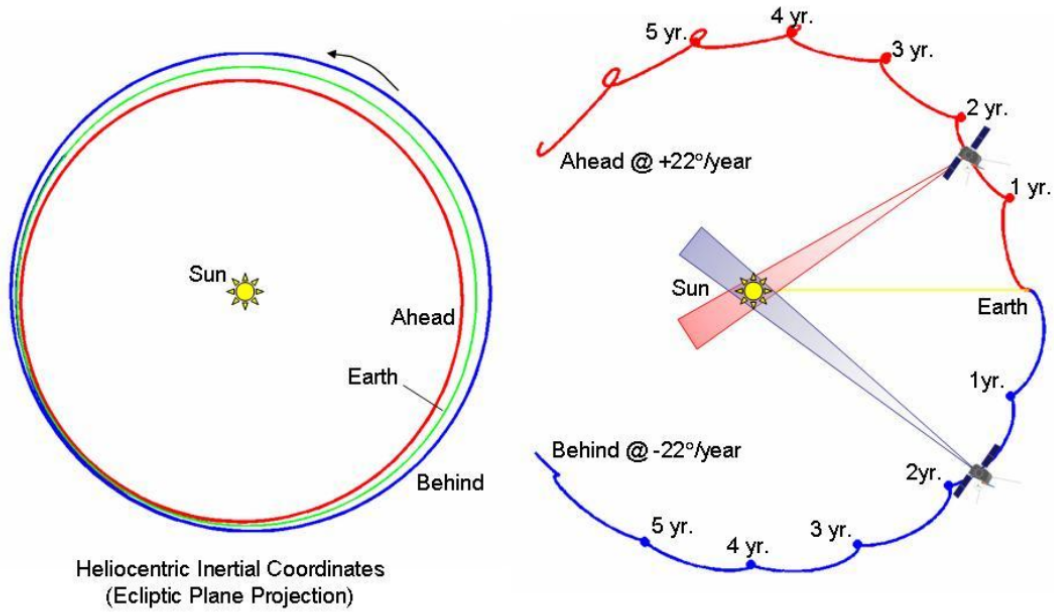


Figure 4.1: Left panel shows the orbits of STEREO A and B relative to that of Earth. The right panel shows the degree of separation of two spacecraft in years from their first launch period. The Figure is from (M. Kaiser, 2005)

The two spacecraft are each equipped with the complement of four scientific instruments, particularly two instruments and two instrument suites, with a total of 13 instruments on each spacecraft. The complements of the four instruments are as follows:

1. Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI)
2. STEREO/WAVES (S/WAVES)
3. In situ Measurements of Particles and CME Transients (IMPACT)
4. Plasma and Suprathermal Ion Composition (PLASTIC)

The SECCHI suite of instruments has two white light coronagraphs, an extreme ultraviolet imager, and two heliospheric white light imagers for tracking CMEs. S/WAVES instrument utilizes radio waves to trace locations of the CME-driven shocks and the 3-D open field lines for the particles created by solar flares. The PLASTIC instrument measures proton, the composition of heavy ions and alpha particles in the solar wind plasma. The IMPACT suite of instruments consists of seven instruments, and three of them are located on the 6-meter boom as shown in Figure 4.2 while the others are in the main hull of the spacecraft. IMPACT measurements protons, heavy ions, and electrons, and the MAG magnetometer sensor in it measures the in situ magnetic fields in a range of $\pm 512 nT$ with 0.1 nT accuracy (M. L. Kaiser & Adams, 2007).

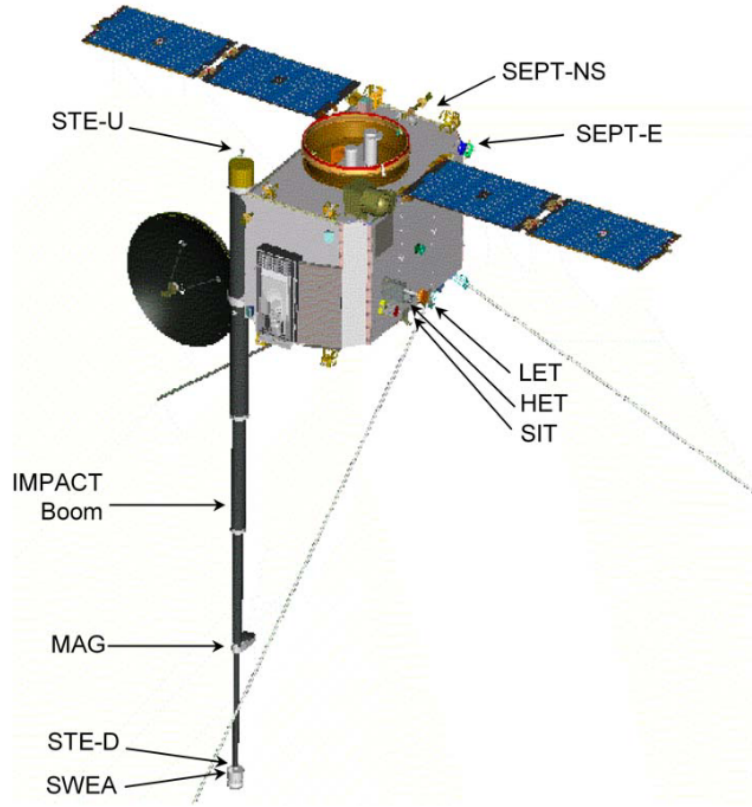


Figure 4.2: Relative placement of the IMPACT boom on the STEREO (Acuña et al., 2008)

Unfortunately, multiple hardware issues affecting control of the spacecraft resulted in the loss of contact with STEREO B on October 1, 2014 (STEREO Science Center, 2018).

4.1.2 Wind

NASA's Wind spacecraft was launched on November 1, 1994 (Wilson III et al., 2021). The Wind was initially planned sent to L_1 Lagrangian point but was delayed to study the magnetosphere and lunar environment. And after a series of orbital maneuvers, To study incoming solar wind that is about to impact the Earth's magnetosphere, Wind was deployed in a Lissajous orbit near the L_1 Lagrange point in early 2004 (NASA WIND Spacecraft, 2020), see Figure 4.3.

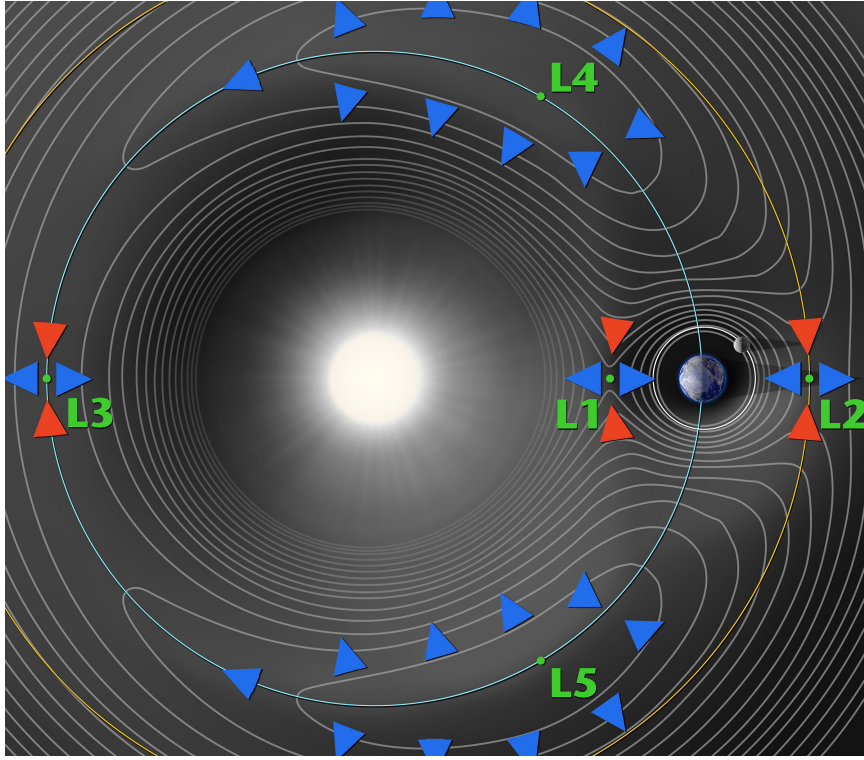


Figure 4.3: Lagrangian points in the Sun-Earth system. (NASA Solar System Exploration, 2020)

The object of the mission is to study solar wind plasma, magnetic field, and solar and cosmic energetic particles. The spacecraft is equipped with the eight instruments such as Solar wind experiment (SWE), 3-D plasma (3DP), Magnetic field investigation (MFI), Solar wind/mass suprathermal ion composition studies (SMS), Energetic particles: acceleration, composition transport (EPACT), Radio and plasma wave experiment (WAVES), KONUS and Transient gamma-ray spectrometer (TGRS), see Figure 4.4. From these instruments, Magnetic field investigation (MFI) and Solar wind experiment (SWE) are of interest of this thesis work. The MFI consists of two magnetometers at the 12 meter boom and measures vector magnetic field up in a time resolution of 22 or 11 vectors per second for the calibrated high resolution data and primary science data is in time resolutions of 3 seconds, 1 minute and 1 hour (NASA WIND Spacecraft, 2022). The SWE measures the solar wind key parameters such as velocity, density, and temperature.

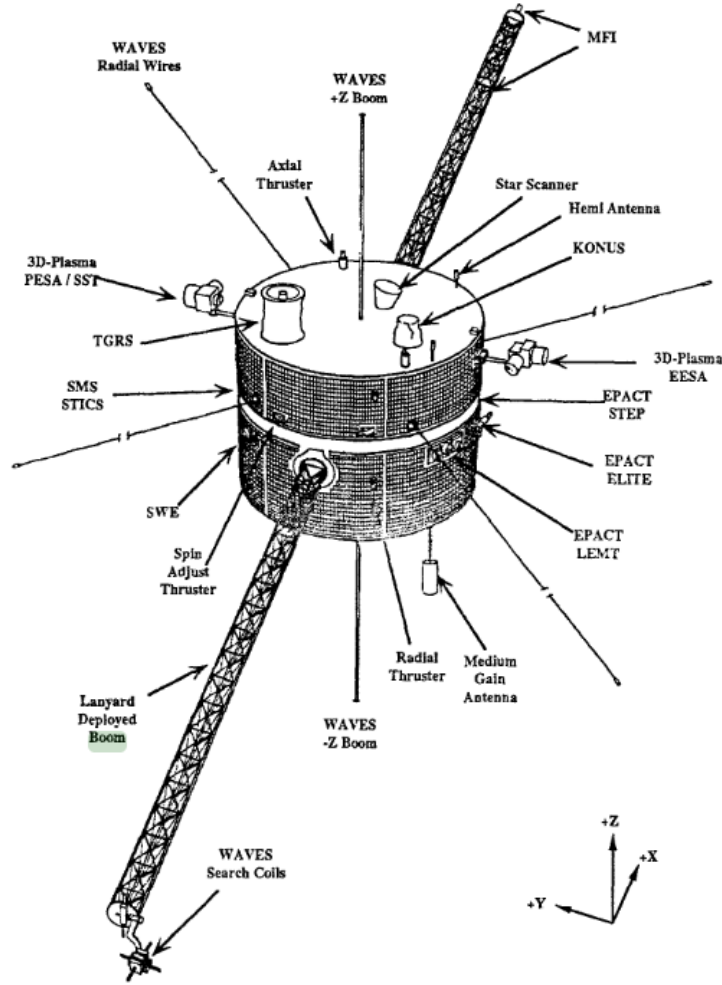


Figure 4.4: Configuration of the Wind instruments (Harten & Clark, 1995)

4.1.3 ACE

NASA's Advanced Composition Explorer (ACE) spacecraft was launched on August 25, 1997 (Stone et al., 1998). The spacecraft is located at L_1 Lagrangian point same as the Wind spacecraft, see Figure 4.3. The general purposes of ACE are to gather and study particles originating from the sun, interplanetary or interstellar mediums, and the galaxy as well as to investigate the solar wind structures such as ICMEs and magnetic clouds. The spacecraft is equipped with nine primary scientific instruments and one engineering instrument such as Cosmic-Ray Isotope Spectrometer (CRIS), Electron, Proton, and Alpha-particle Monitor (EPAM), Magnetometer (MAG), Real-Time Solar Wind (RTSW), Solar Energetic Particle Ionic Charge Analyzer (SEPICA), Solar Isotope Spectrometer (SIS), Solar Wind Electron, Proton and Alpha Monitor (SWEPAM), Solar Wind Ion Composition Spectrometer (SWICS) and Solar Wind Ion Mass Spectrometer (SWIMS) and Ultra-Low-Energy Isotope Spectrometer (ULEIS), see Figure 4.5. The MAG consists of a twin triaxial flux-gate magnetometers such that magnetometer sensors have between 3 and 6 vectors s^{-1} resolutions for continuous observation of the interplanetary magnetic field (Smith et al., 1998).

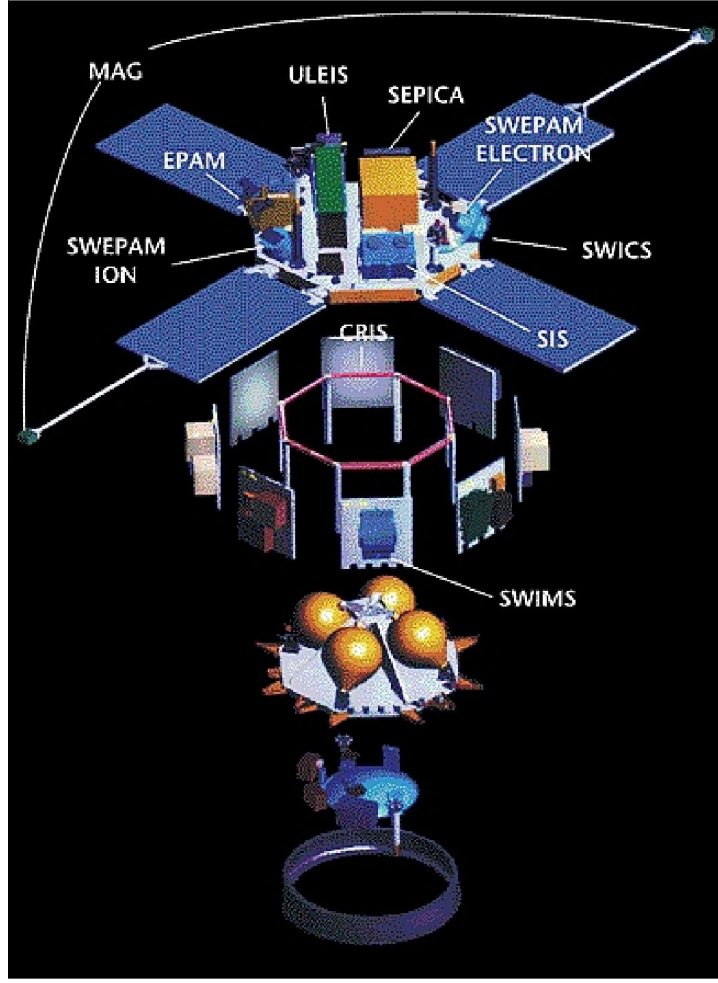


Figure 4.5: Instruments of ACE spacecraft (Stone et al., 1998)

4.2 Methods

The following two methods are suitable for single-spacecraft measurements and both of them are based on the divergence of the magnetic field, $\nabla \cdot \mathbf{B} = 0$, constraint, and both of them use solely magnetic field data. The following formalization, descriptions, and derivations are based on (B. U. Sonnerup & Scheible, 1998) and (Paschmann & Daly, n.d.).

4.2.1 Minimum Variance Analysis

The Minimum variance analysis technique was first developed by (B. Ö. Sonnerup & Cahill Jr, 1967). It is based on the assumption that variations in the magnetic field would be observed when single-spacecraft passes through a 1-D¹ current layer or wavefront. Remembering the divergence of the magnetic field constraint, $\nabla \cdot \mathbf{B} = 0$, such that the normal component of the magnetic field must remain constant. If such a normal direction can be found, then the variations in the magnetic field are zero or at the least has a minimum variance. Thus, $\hat{\mathbf{n}}$ can be determined by the minimization of the following equation:

$$\sigma^2 = \frac{1}{M} \sum_{m=1}^M \left| (\mathbf{B}^{(m)} - \langle \mathbf{B} \rangle) \cdot \hat{\mathbf{n}} \right|^2, \quad (4.1)$$

where $\mathbf{B}^{(m)}$, ($m = 1, 2, 3 \dots M$) is the magnetic field in a time series data and $\mathbf{B}$ is the average magnetic field.

¹In reality, it is a 2-D or 3-D transition layer

Taking the account of the normalization constraint $|\hat{\mathbf{n}}|^2 = 1$, on which minimization is conditioned, and introducing a Lagrange multiplier, λ , for utilizing the constraint, the solution of three homogeneous linear equations can be found. The three homogeneous equations are:

$$\begin{aligned}\frac{\partial}{\partial n_X} \left(\sigma^2 - \lambda |\hat{\mathbf{n}}|^2 - 1 \right) &= 0 \\ \frac{\partial}{\partial n_Y} \left(\sigma^2 - \lambda |\hat{\mathbf{n}}|^2 - 1 \right) &= 0 \\ \frac{\partial}{\partial n_Z} \left(\sigma^2 - \lambda |\hat{\mathbf{n}}|^2 - 1 \right) &= 0,\end{aligned}\tag{4.2}$$

where σ^2 is given by 4.1 and $\hat{\mathbf{n}}$ is expressed in its three components, which are along X, Y, and Z coordinates. After the differentiation procedures of 4.2 are done, the resulting sets of equations can be written in matrix form :

$$\sum_{\nu=1}^3 M_{\mu\nu} n_{\nu} = \lambda n_{\mu},\tag{4.3}$$

where the subscripts μ and ν indicate cartesian coordinates and $M_{\mu\nu}$ is the magnetic variance matrix:

$$M_{\mu\nu} n_{\nu} = \langle B_{\mu} B_{\nu} \rangle - \langle B_{\mu} \rangle \langle B_{\nu} \rangle\tag{4.4}$$

with λ being the eigenvalues with three possible values λ_1 , λ_2 , and λ_3 with decreasing order. The eigenvalues have their corresponding eigenvectors $\mathbf{x}_1$, $\mathbf{x}_2$, and $\mathbf{x}_3$ of the matrix where they represent the directions of maximum, intermediate, and minimum variance of the magnetic field component. The eigenvectors corresponding to the smallest value of the λ eigenvalues are the shock normal vectors.

4.2.2 The Magnetic Coplanarity method

If two vectors that lie inside a coplanar surface can be determined, the normal to the coplanar surface can be found.

The coplanarity methods are based on the magnetic coplanarity theorem, which stated that both sides of the magnetic field vectors on the shock and the shock normal lie in the same plane. Similarly, the velocity on both sides or, in another word, the velocity jump through the shock also lie in the same plane. The upstream and downstream magnetic field and velocities satisfy the Rankine-Hugoniot conditions. So, there are multiple vectors lie in the shock plane, and the resulting constraint equations are as follows:

$$(\mathbf{B}_{down} - \mathbf{B}_{up}) \cdot \hat{\mathbf{n}} = 0\tag{4.5}$$

$$(\mathbf{B}_{down} \times \mathbf{B}_{up}) \cdot \hat{\mathbf{n}} = 0\tag{4.6}$$

$$(\mathbf{B}_{up} \times (\mathbf{V}_{down} - \mathbf{V}_{up})) \cdot \hat{\mathbf{n}} = 0\tag{4.7}$$

$$(\mathbf{B}_{down} \times (\mathbf{V}_{down} - \mathbf{V}_{up})) \cdot \hat{\mathbf{n}} = 0\tag{4.8}$$

$$((\mathbf{B}_{up} - \mathbf{B}_{down}) \times (\mathbf{V}_{down} - \mathbf{V}_{up})) \cdot \hat{\mathbf{n}} = 0,\tag{4.9}$$

where the indexes up and down denote upstream and downstream, respectively. From 4.5 and 4.6 the magnetic coplanarity normal is defined:

$$\hat{\mathbf{n}}_{MC} = \pm \frac{(\mathbf{B}_{down} \times \mathbf{B}_{up}) \times (\mathbf{B}_{down} - \mathbf{B}_{up})}{|(\mathbf{B}_{down} \times \mathbf{B}_{up}) \times (\mathbf{B}_{down} - \mathbf{B}_{up})|},\tag{4.10}$$

where the signs are arbitrary.

The magnetic coplanarity schematic illustration is shown in Figure 4.6.

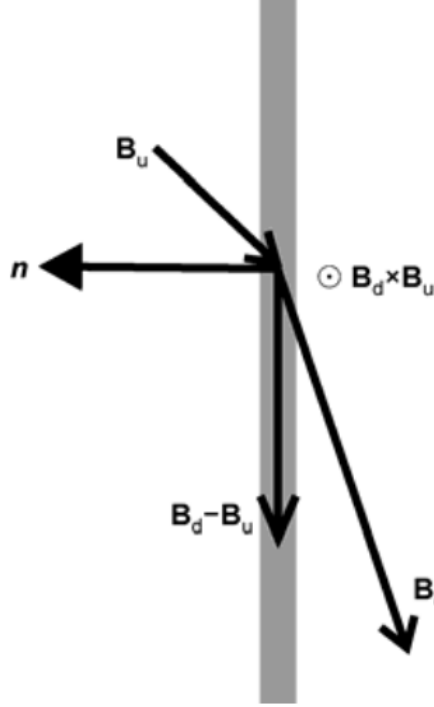


Figure 4.6: The illustration of the magnetic coplanarity. The gray vertical line represents the shock layer. The figure is taken from (Shan et al., 2013)

Similarly, from 4.7, 4.8 and 4.9 the mixed modes for normals can be defined, respectively.

$$\hat{n}_{mix1} = \pm \frac{(B_{up} \times (V_{down} - V_{up})) \times (B_{down} - B_{up})}{|(B_{up} \times (V_{down} - V_{up})) \times (B_{down} - B_{up})|} \quad (4.11)$$

$$\hat{n}_{mix2} = \pm \frac{(B_{down} \times (V_{down} - V_{up})) \times (B_{down} - B_{up})}{|(B_{down} \times (V_{down} - V_{up})) \times (B_{down} - B_{up})|} \quad (4.12)$$

$$\hat{n}_{mix3} = \pm \frac{((B_{down} - B_{up}) \times (V_{down} - V_{up})) \times (B_{down} - B_{up})}{|((B_{down} - B_{up}) \times (V_{down} - V_{up})) \times (B_{down} - B_{up})|} \quad (4.13)$$

4.2.3 The Utilization of the Methods

By comparing the two methods, the upstream and downstream time intervals of the magnetic field measurements are set. In this thesis work, as stated before the magnetic coplanarity method 4.10 is used out of the other coplanarity methods. To accept the intervals, there are some criteria to be put such as the angle between the vectors defined by the minimum variance analysis (MVA) and the magnetic coplanarity method must be less than 15° and the ratio between intermediate eigenvalue and the smallest eigenvalue should be greater than 2 (Facskó et al., 2008) or the ratio between the smallest eigenvalue to the intermediate eigenvalue should be smaller than $1/3$ (Shan et al., 2013).

4.2.4 Estimating the solar wind parameters

The following parameter estimations are based on this paper (Lumme, Kilpua, Isavnin, & Andreeva, 2017)

Shock criteria:

The solar wind bulk speed jump should fulfill the following conditions:

$$V_{down} - V_{up} \geq 20 \text{ km/s for FF} \quad \text{and} \quad V_{up} - V_{down} \geq 20 \text{ km/s for FR} \quad (4.14)$$

And downstream to upstream ratios should fulfill the following ratios of upstream and downstream the magnetic field, density, and temperature respectively:

$$\frac{B_{down}}{B_{up}} \geq 1.2 \quad \frac{N_p^{down}}{N_p^{up}} \geq 1.2 \quad \text{and} \quad \frac{T_p^{down}}{T_p^{up}} \geq \frac{1}{1.2} \quad (4.15)$$

Shock theta:

This is the angle between the normal vector $\hat{\mathbf{n}}$ and the upstream magnetic field lines:

$$\theta_{Bn} = \cos^{-1} \left(\left| \frac{\mathbf{B}_{up} \cdot \hat{\mathbf{n}}}{|\mathbf{B}_{up}| |\hat{\mathbf{n}}|} \right| \right) \quad (4.16)$$

Shock speed:

The shock speed in the spacecraft frame of reference:

$$V_{sh} = \left| \frac{N_p^{up} \mathbf{V}_{up} - N_p^{down} \mathbf{V}_{down}}{N_p^{down} - N_p^{up}} \cdot \hat{\mathbf{n}} \right| \quad (4.17)$$

Upstream sound speed:

$$C_s^{up} = \left\langle \sqrt{\gamma k_B \frac{T_p + T_e}{m_p}} \right\rangle, \quad (4.18)$$

where m_p is the proton mass, T_p and T_e are proton and electron temperature. In the solar wind, the electron temperature at 1 AU is assumed to be $\sim 140,000$ K (Newbury, 1996).

Upstream Alfvén speed:

$$V_A^{up} = \left\langle \frac{B}{\sqrt{\mu_0 N_p m_p}} \right\rangle, \quad (4.19)$$

where μ_0 is the magnetic vacuum permeability, N_p is the proton density and m_p is the proton mass.

Upstream magnetosonic speed:

The equation 2.25 is used for here

Upstream plasma beta:

$$\beta^{up} = \left\langle \frac{2\mu_0 k_B N_p (T_p + T_e)}{B^2} \right\rangle \quad (4.20)$$

Alfvén Mach number:

$$M_A = \frac{|\mathbf{V}_{up} \cdot \hat{\mathbf{n}} \pm V_{sh}|}{V_A^{up}}, \quad (4.21)$$

where V_{up} is the upstream velocity, V_{sh} is shock speed and V_A^{up} is the Alfvén speed. The reason for $\pm V_{sh}$ is a Galilean coordinate transformation to the shock rest frame. The sign $\pm$ is depend on FF shock, for which (-) or FR shock, for which (+).

Magnetosonic Mach number:

Similarly to 4.21 the Magnetosonic Mach number is defined as follows:

$$M_{ms} = \frac{|V_{up} \cdot \hat{\mathbf{n}} \pm V_{sh}|}{C_{ms}^{up}}, \quad (4.22)$$

where C_{ms}^{up} is the magnetosonic upstream speed.

4.3 Data

There are several steps for data acquiring process. First of all, for the purpose of determining the propagation of a shocks, shocks occurred in a single day are needed. For this purpose, shock candidates are chosen from the shock lists in the Database of Heliospheric Shock Waves maintained at University of Helsinki <http://www.ipshocks.fi/> as shown in Figure 4.7.

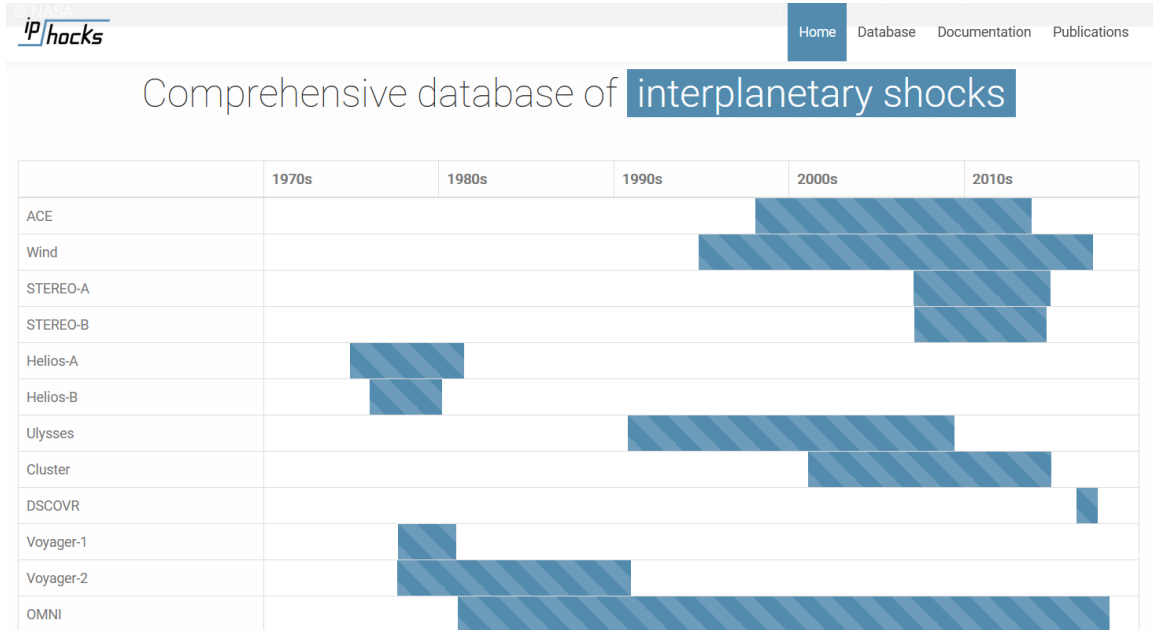


Figure 4.7: Identified shocks detected by the spacecraft in the list

For the event selection the year 2007 is chosen for the reason that STEREO A and STEREO B were closer to each other as well as to the Sun-Earth line. Hence, the two events are from this year, particularly on May 07, 2007, and April 23, 2007. In the first event, May 07 of 2007, the selected spacecraft are STEREO A, STEREO B, and Wind, while for the second event, April 23, 2007, the spacecraft are STEREO A, ACE, and Wind. After choosing the shock candidates, the shock data are downloaded from

NASA's Coordinated Data Analysis Web (CDAWeb) <https://cdaweb.gsfc.nasa.gov/>. The STEREO A and B magnetic field observation and the plasma data were obtained from the STEREO In-situ Measurements of Particles and CME Transients (IMPACT) magnetic field experiment (Luhmann et al., 2008) with the time resolution of 100 ms and the STEREO PLASMA and SupraThermal Ion Composition (PLASTIC) (Galvin et al., 2008) respectively. The magnetic field and the plasma data of the STEREO A and B are in the RTN² coordinate system. The Wind magnetic and plasma data were obtained from the Magnetic Field Investigation (MFI) instrument (Lepping et al., 1995) with a time resolution of 3 sec and The Solar Wind Experiment (SWE) (Ogilvie et al., 1995) with a time resolution of 1 min respectively. The magnetic field and the plasma data of the Wind are in the Geocentric Solar Ecliptic System (GSE)³ coordinate system. The Advanced Composition Explorer (ACE) magnetic and plasma data were obtained from the ACE Magnetic Field Experiment (MAG) (Smith et al., 1998) with a time resolution of 1 sec and the Solar Wind Electron Proton Alpha Monitor (SWEPAM) (McComas et al., 1998) with the time resolution of 64 sec, respectively. The magnetic field and the plasma data are in both the RTN and GSE coordinate systems.

After obtaining the data, the coordinate system transformation is performed in such a way that all the coordinate systems are changed to the Heliocentric Earth Ecliptic (HEE)⁴ coordinate system, To transform from the RTN and the GSE coordinate systems to the HEE coordinate system, TREPS (Transformation de REpères en Physique Spatiale) online tool is used. The TREPS tool, which is developed by the CDPDP the national data centre in France for the solar system plasmas, is based on SPICE kernels created by NASA/NAIF. Its use is simple, with a 4-step process, which includes importing data, selecting the original coordinate system of the data and a coordinate system to transform, see Figure 4.8, choosing how the transformed vector should be exported, and finally, exporting the transformed file (Génot et al., 2018).

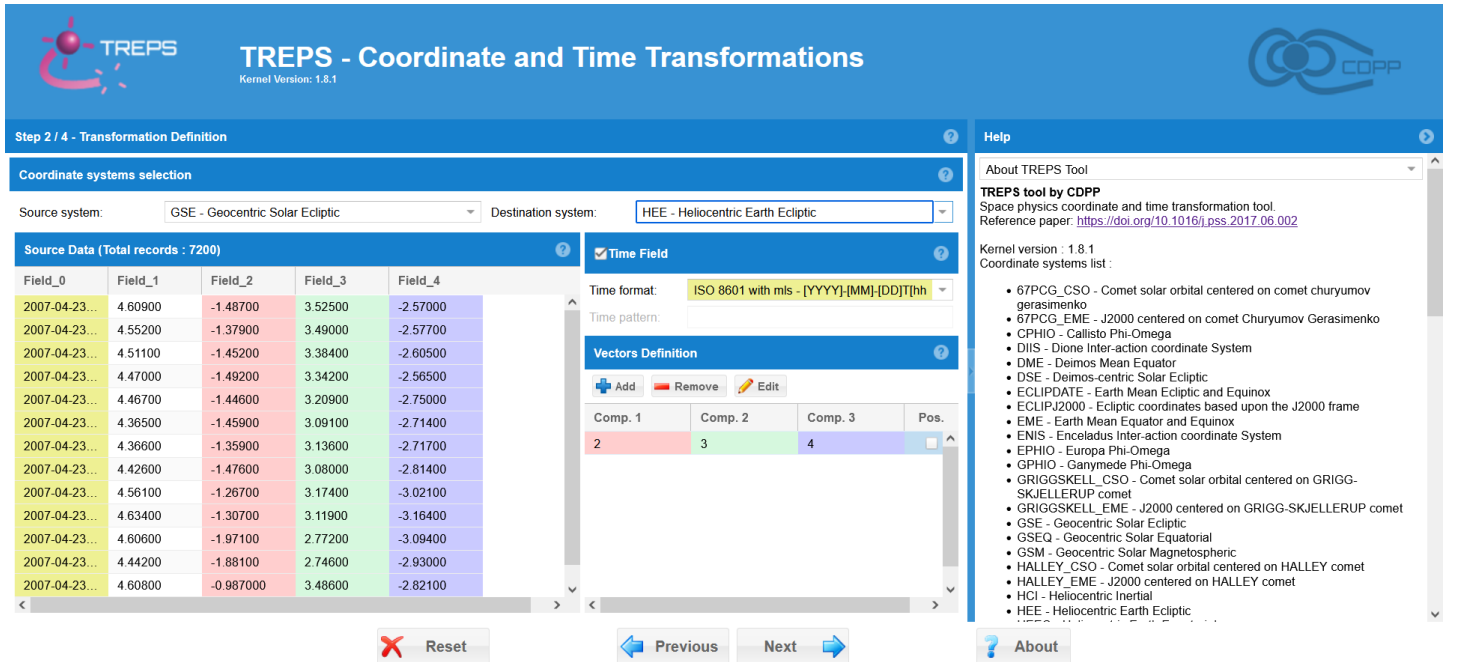


Figure 4.8: TREPS interface, showing a transformation from the GSE to the HEE coordinate system. The green colored column denotes the time field and the other three colored columns denote X,Y and Z vector components

²it is the spacecraft coordinate system and R is radially outward from the Sun, T is along the planetary orbital and N is northward direction

³X-axis is pointing to the Sun from the Earth, Y-axis is in the ecliptic plane against the planetary motion and Z-axis is northward direction

⁴In which the X-axis is toward the Earth from the Sun, Z-axis is northward direction. This system is fixed with respect to the Sun-Earth line

4.3.1 Data observations

With the visual inspection of the magnetic field and plasma data, the shock occurring times are determined for each spacecraft data of each event. And from the plots, The shocks detected by the spacecraft in each event are believed to be propagation of the same shock due to their timing and the similarities of the magnetic field and plasma data profile with one another. The following case studies of two events are not orderly defined for one another. I firstly analyzed May 07, 2007 event and then April 23, 2007 event. Hence, the order follows this fashion.

May 07, 2007 event:

On this day, the Wind spacecraft first detected the shock at 07:02:30 am. The magnetic field and the plasma plot are shown in Figure 4.9.

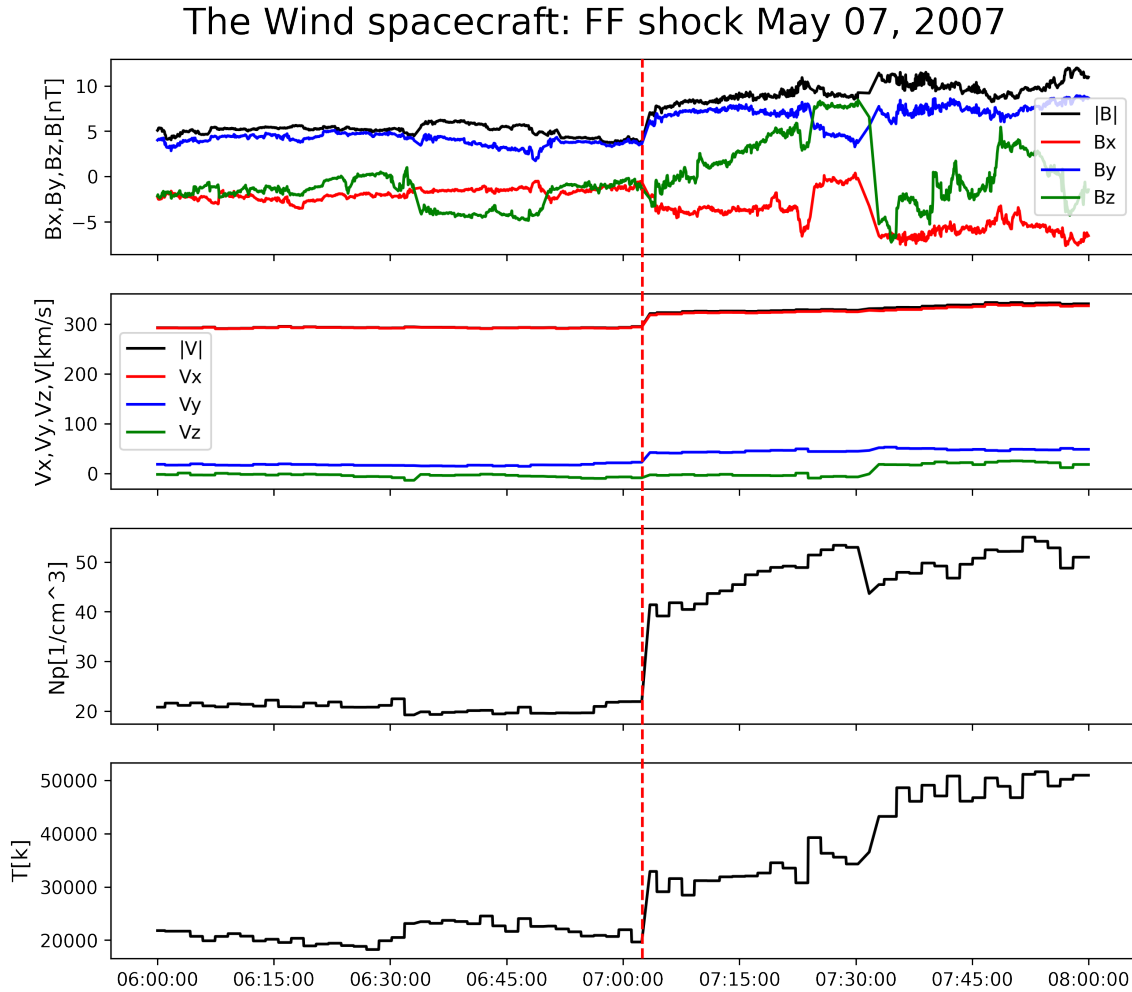


Figure 4.9: The plot of the shock detected by the Wind spacecraft on May 07, 2007, at 07:02:30 am. The panels show from top to bottom, the magnetic field magnitude as well as its components, the total velocity and its components, density, and temperature. The dashed red line represents the exact shock time. The duration of the plot is 2 hours.

The STEREO A spacecraft detected the shock at 08:11:30 am. The magnetic field and the plasma plot are shown in Figure 4.10.

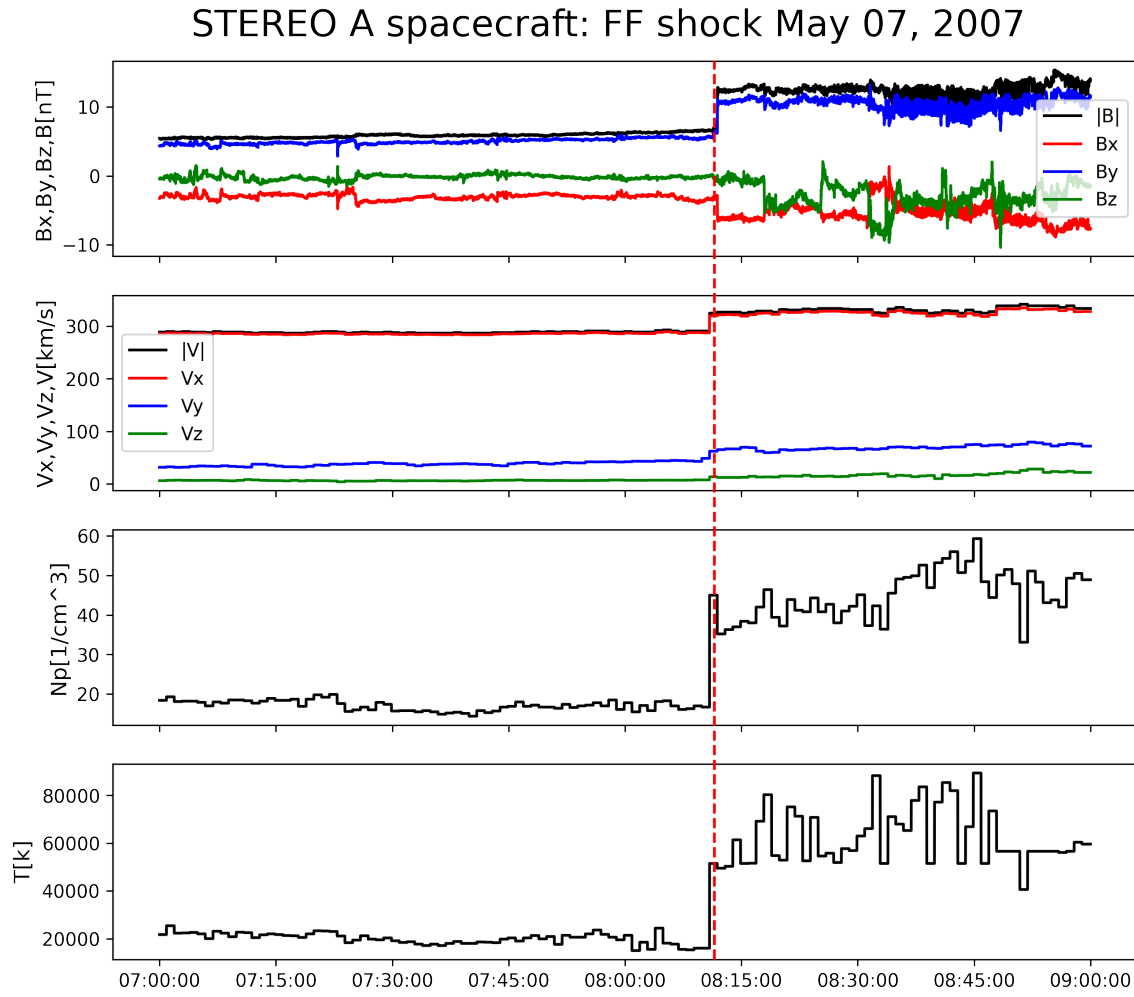


Figure 4.10: The plot of the shock detected by the STEREO A spacecraft on May 07, 2007, at 08:11:30 am. The panels show from top to bottom, the magnetic field magnitude as well as its components, the total velocity and its components, density, and temperature. The dashed red line represents the exact shock time. The duration of the plot is 2 hours.

The STEREO B spacecraft detected the shock at 09:42:00 am. The magnetic field and the plasma plot are shown in Figure 4.11

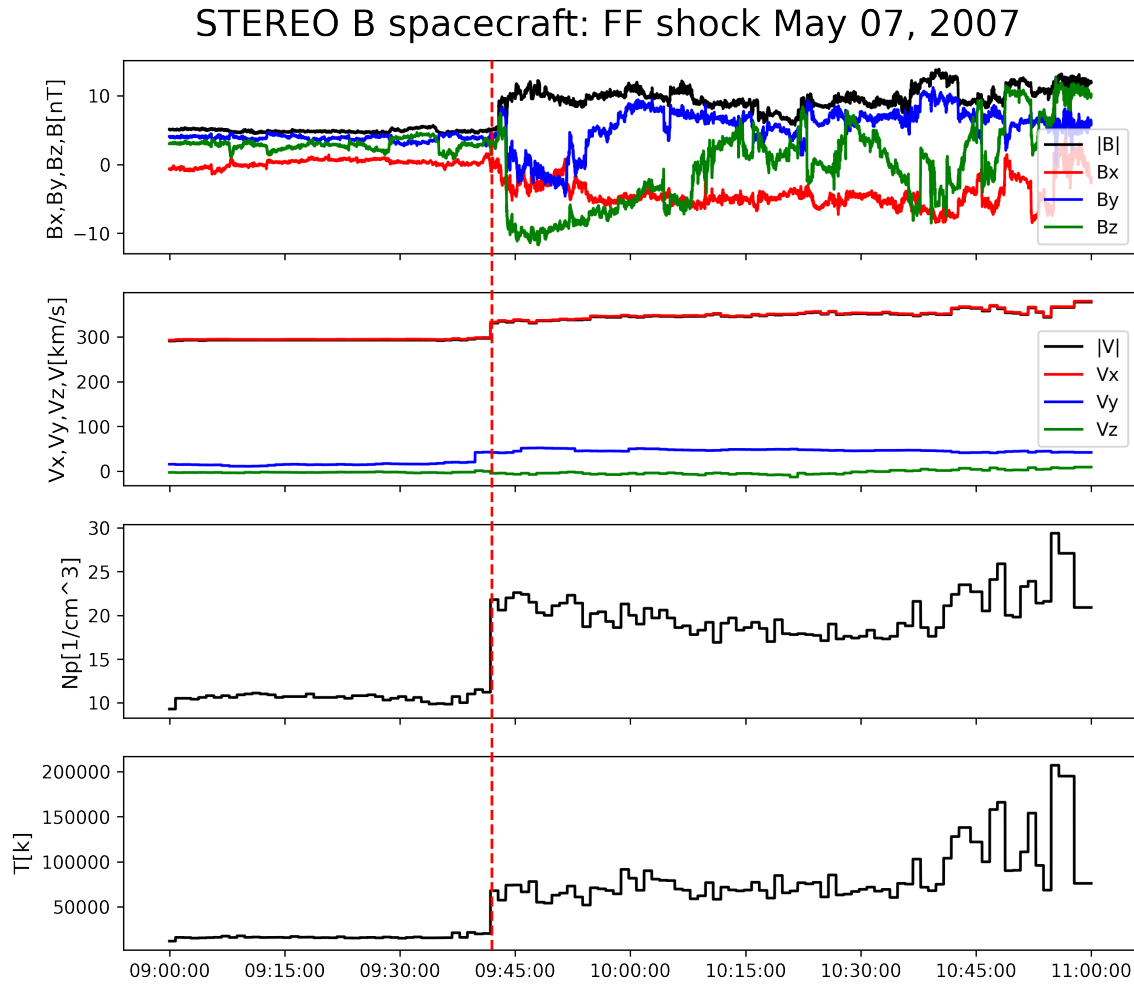


Figure 4.11: The plot of the shock detected by the STEREO B spacecraft on May 07, 2007, at 09:42:00 am. The panels show from top to bottom, the magnetic field magnitude as well as its components, the total velocity and its components, density, and temperature. The dashed red line represents the exact shock time. The duration of the plot is 2 hours.

April 23, 2007 event:

In this specific event STEREO A spacecraft detected a shock first at 06:53:35 am. The magnetic field and the plasma data are shown in Figure 4.12.

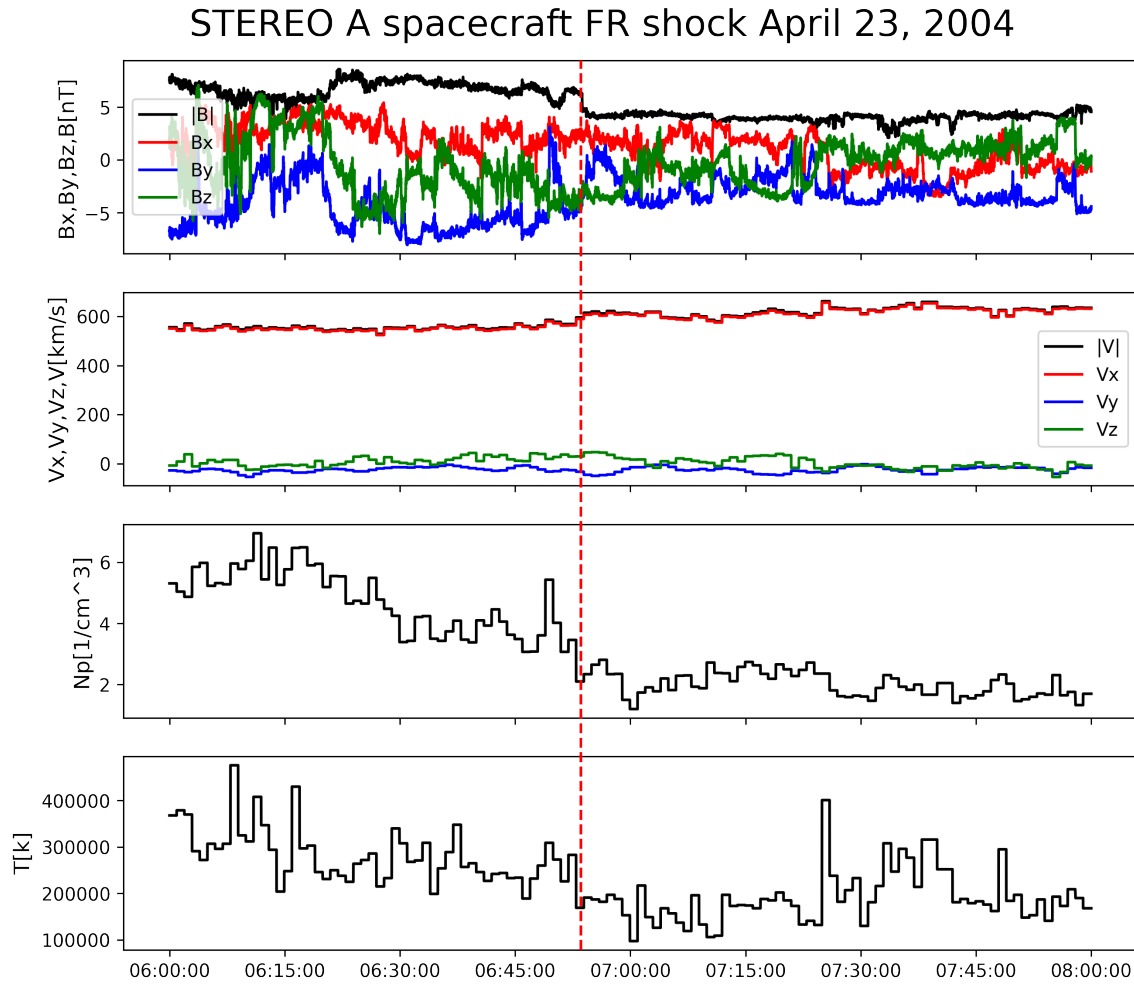


Figure 4.12: The plot of the shock detected by the STEREO A spacecraft on April 23, 2007 at 06:53:35 am. The panels show from top to bottom, the magnetic field magnitude as well as its components, the total velocity and its components, density, and temperature. The dashed red line represents the exact shock time. The duration of the plot is 2 hours

ACE spacecraft detected the shock at 08:57:00 am. The magnetic field and the plasma plot are shown in Figure 4.13

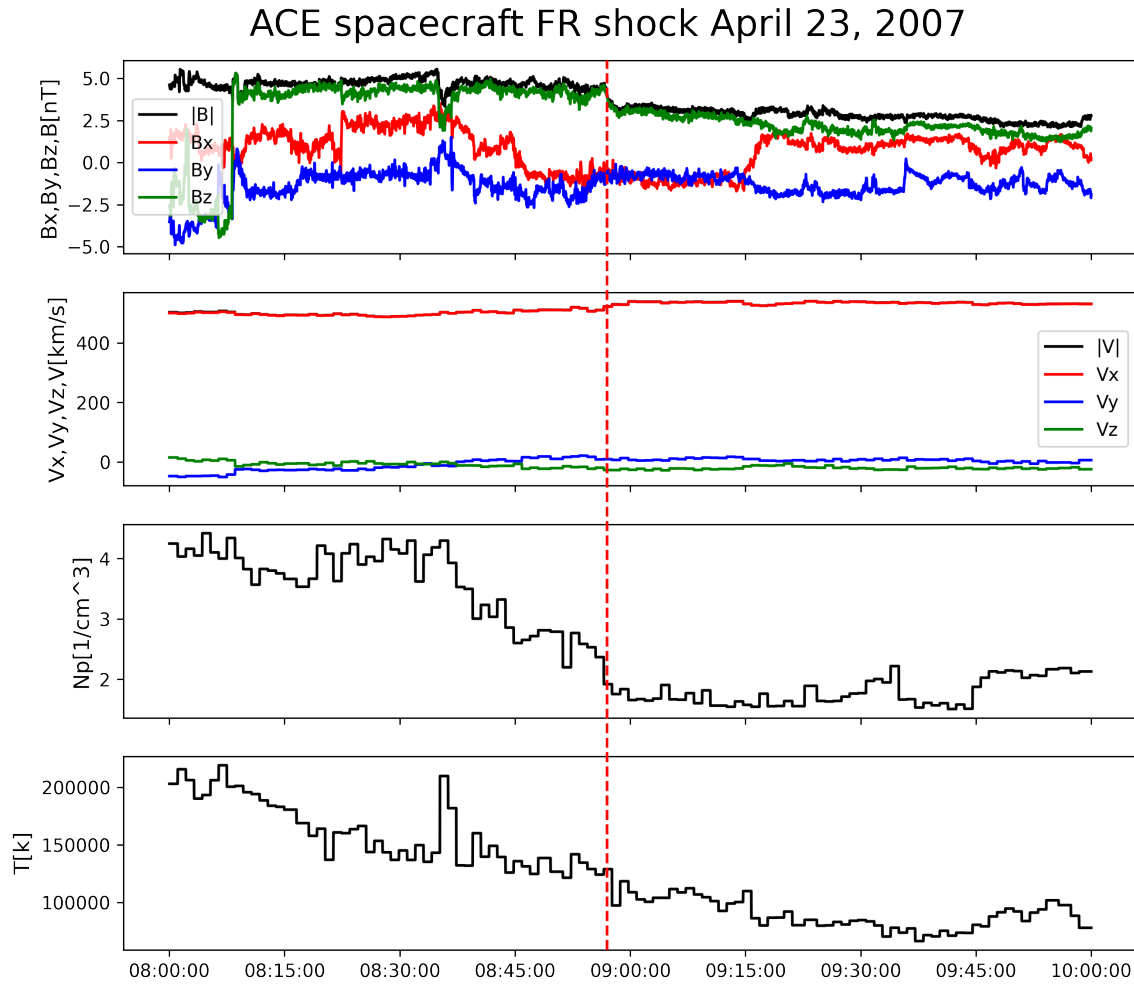


Figure 4.13: The plot of the shock detected by the ACE spacecraft on April 23, 2007 at 08:57:00 am. The panels show from top to bottom, the magnetic field magnitude as well as its components, the total velocity and its components, density, and temperature. The dashed red line represents the exact shock time. The duration of the plot is 2 hours.

The Wind spacecraft detected the shock at 09:12:00 am. The magnetic field and the plasma plot are shown in Figure 4.14

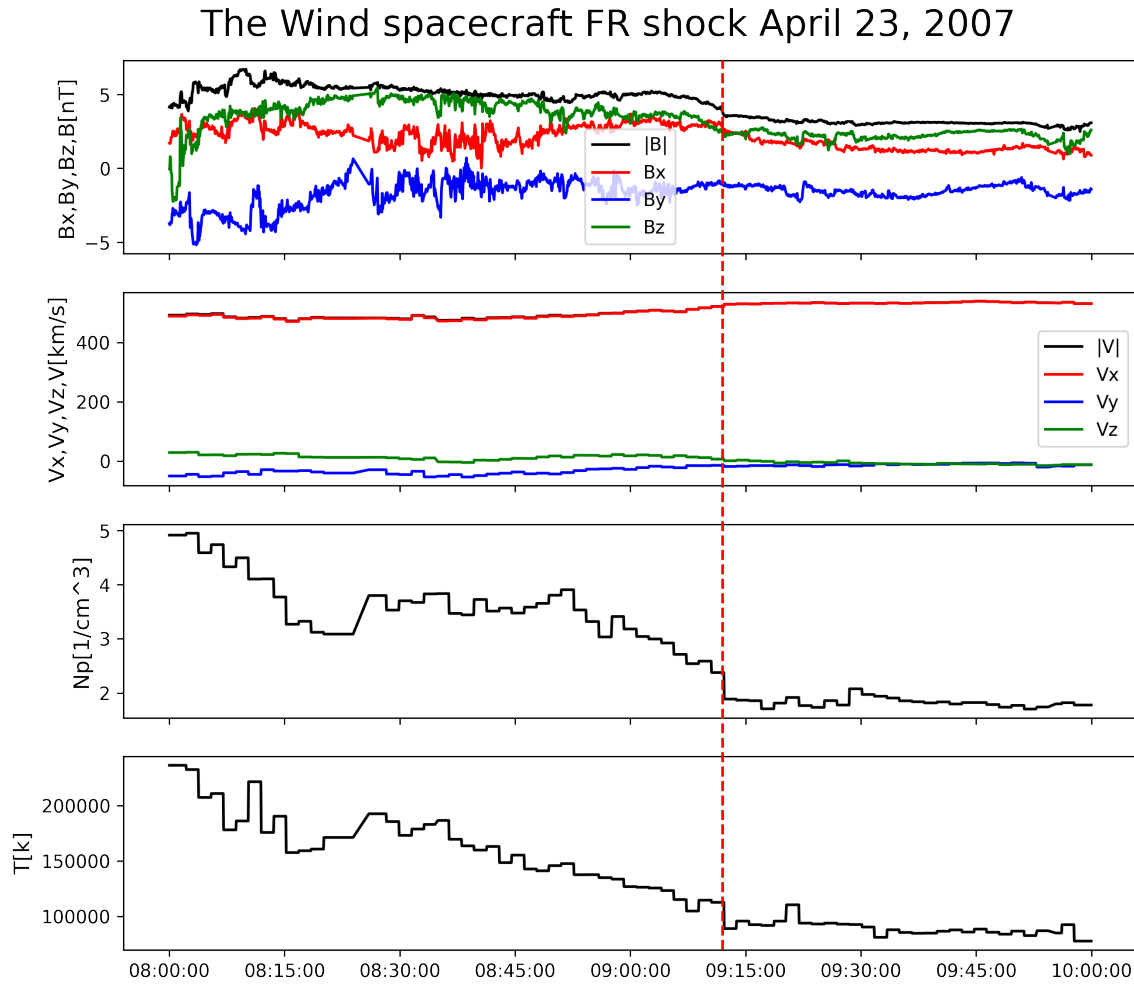


Figure 4.14: The plot of the shock detected by the Wind spacecraft on April 23, 2007 at 09:12:00 am. The panels show from top to bottom, the magnetic field magnitude as well as its components, the total velocity and its components, density, and temperature. The dashed red line represents the exact shock time. The duration of the plot is 2 hours.

Chapter 5

Results

5.1 May 07, 2007 Event

The Wind magnetic field measurement: The upstream and downstream time intervals that most agree between the minimum variance analysis and the magnetic coplanarity are:

Δt_{up} for the upstream is between (06:59:00 - 07:01:47)

Δt_{down} for the downstream is between (07:03:50 - 07:05:50), see Figure 5.1.

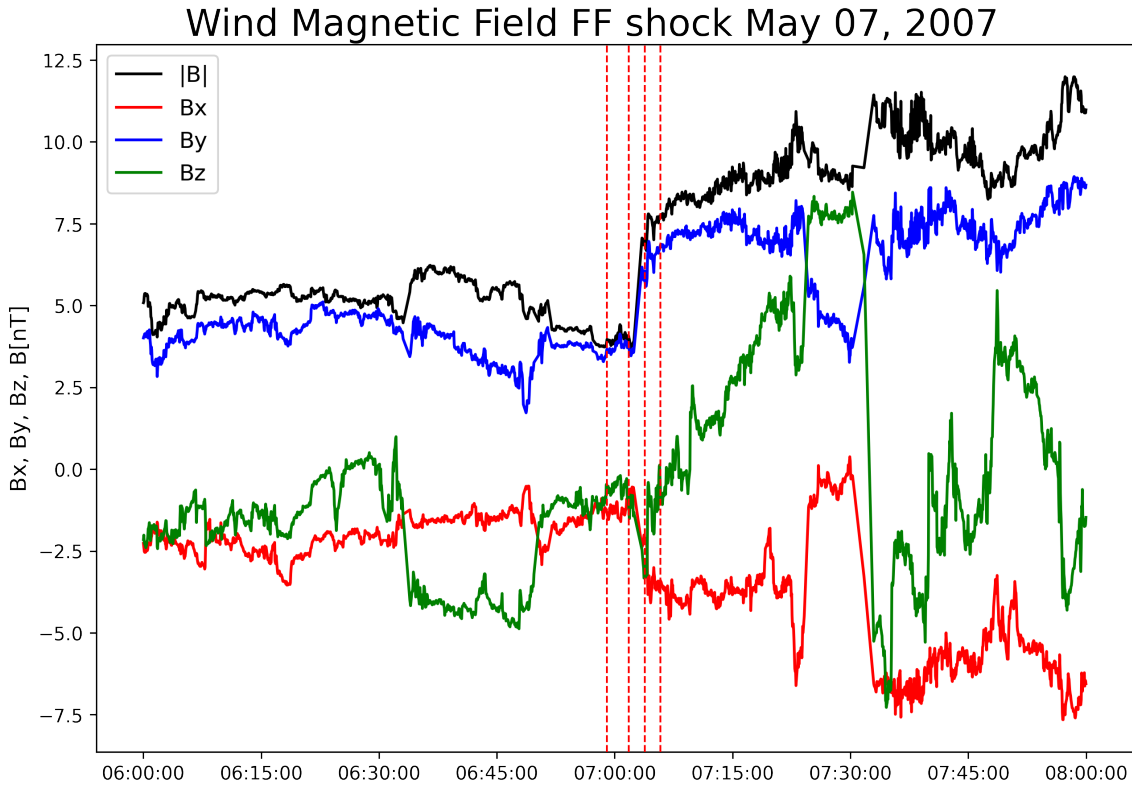


Figure 5.1: The Wind magnetic field measurement. The chosen intervals of the upstream and downstream magnetic field. The red dashed lines each represent the upstream starting time and ending time and the downstream starting time and ending time respectively

In these intervals, the angle between the MVA normal and the magnetic coplanarity normal is 0.38° and the ratio between the smallest eigenvalue λ_3 and the intermediate eigenvalue λ_2 is $\lambda_3/\lambda_2 = 0.067$

The STEREO A magnetic field measurement: The upstream and downstream time intervals that most agree between the minimum variance analysis and the magnetic coplanarity are:

Δt_{up} for the upstream is between (08:08:00 - 08:10:05)

Δt_{down} for the downstream is between (08:12:30 - 08:13:50), see Figure 5.2.

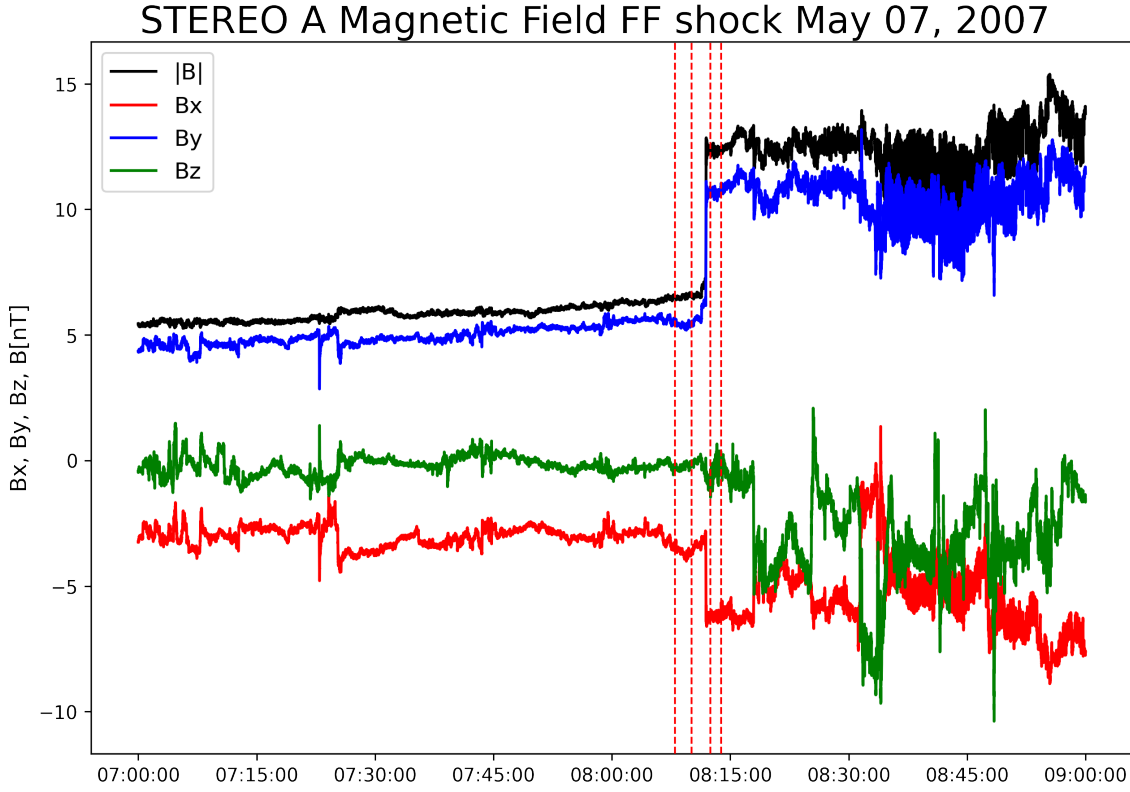


Figure 5.2: The STEREO A magnetic field measurement. The chosen intervals of the upstream and downstream magnetic field. The red dashed lines each represent the upstream starting time and ending time and the downstream starting time and ending time respectively

In these intervals, the angle between the MVA normal and the magnetic coplanarity normal is 0.375° and the ratio between the smallest eigenvalue λ_3 and the intermediate eigenvalue λ_2 is $\lambda_3/\lambda_2 = 0.316$

The STEREO B magnetic field measurement: The upstream and downstream time intervals that most agree between the minimum variance analysis and the magnetic coplanarity are:

Δt_{up} for the upstream is between (09:37:00 - 09:40:35)

Δt_{down} for the downstream is between (09:42:57 - 09:43:38), see Figure 5.3.

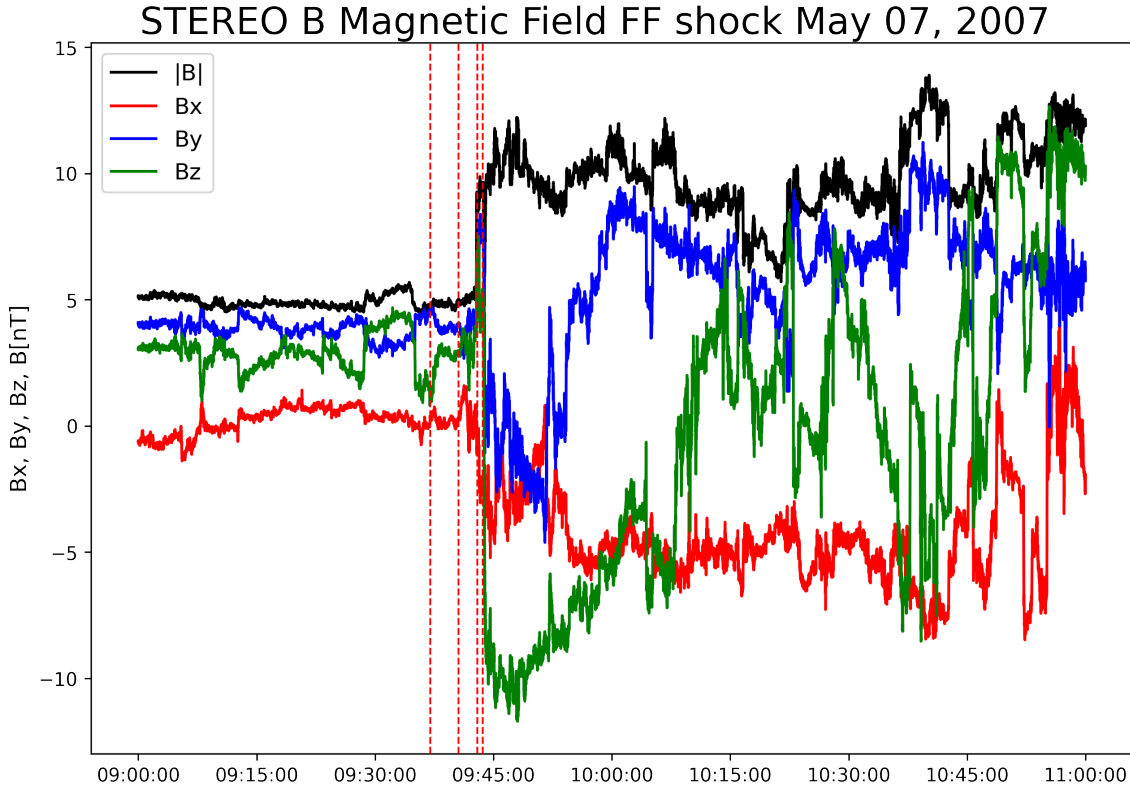


Figure 5.3: The STEREO B magnetic field measurement. The chosen intervals of the upstream and downstream magnetic field. The red dashed lines each represent the upstream starting time and ending time and the downstream starting time and ending time respectively

In these intervals, the angle between the MVA normal and the magnetic coplanarity normal is 1.1° and the ratio between the smallest eigenvalue λ_3 and the intermediate eigenvalue λ_2 is $\lambda_3/\lambda_2 = 0.1$

Result 1

The accepted upstream and downstream time intervals are highly accurate considering the angle difference between the two methods is minimal and the eigenvalue criteria are sufficient for each spacecraft data. Using the determined time intervals, the calculations of the ratio between the upstream and downstream magnetic fields, densities, and temperatures as well as the bulk speed, and shock θ angle are made. These parameters, the minimum variance analysis normal and the magnetic coplanarity normals are shown in Table 5.1, where the solar wind bulk speed and the downstream to upstream ratios for the shock criteria are fulfilled as stated in 4.14 and 4.15, and the results of the additional parameters calculations as stated in 4.2.4 are shown in Table 5.2.

Spacecraft	B_d/B_u	N_d/N_u	T_d/T_u	ΔV	θ_{Bn}
Wind	1.86 ± 0.1	1.78^*	1.33^*	29.6^*	70.8
STEREO A	1.89 ± 0.023	2.18 ± 0.9	3.21 ± 2.4	36 ± 6	81.83
STEREO B	1.9 ± 0.07	1.9 ± 0.6	2.9 ± 6	40.25 ± 11	59.45

Table 5.1: Result core parameters of studying the data of the Wind, STEREO A, and STEREO B spacecrafts. Here θ_{Bn} is the shock θ angle. The values with the asterisk (*) symbol indicate the parameters with indefinite uncertainties because the determined intervals of the upstream and downstream magnetic fields are smaller than the resolution of the plasma data

MVA	Coplanarity	$\Delta\theta_{MVA-CP}$
[-0.763 -0.63 -0.144]	[-0.763 -0.629 -0.15]	0.37
[0.889 0.436 0.137]	[0.888 0.436 0.144]	0.38
[-0.855 -0.511 -0.087]	[-0.864 -0.497 -0.077]	1.1

Table 5.1: (Continue) Result core parameters of studying the data of the Wind, STEREO A, and STEREO B spacecrafts. θ_{MVA-CP} is the angle difference between the minimum variance normal vectors and the magnetic coplanarity normal vectors.

Spacecraft	V_{sh} km/s	C_s^{up} km/s	V_A^{up} km/s	C_{ms}^{up} km/s
Wind	313.60	47.2 ± 1.6	18.7 ± 6.08	50.78 ± 2.7
Stereo A	352.41	46.27 ± 3.3	34.89 ± 15	57.95 ± 9.41
Stereo B	354.91	46.89 ± 5.85	31.95 ± 7.33	56.74 ± 6.35

Table 5.2: Result additional parameters of studying the data of the three spacecraft. V_{sh} is the shock speed, C_s^{up} is the upstream sound speed, V_A^{up} is the upstream Alfvén speed and C_{ms}^{up} is the upstream magnetosonic speed.

Plasma β_{up}	Alfvén Mach	Magnetosonic Mach
7.6 ± 4.9	4.14 ± 1.72	1.5 ± 0.4
2.11 ± 1.8	2.19 ± 1.12	1.32 ± 0.42
2.58 ± 1.34	2.76 ± 1.07	1.55 ± 0.52

Table 5.2: (Continue) Result additional parameters of studying the data of the three spacecraft. Plasma β_{up} , Alfvén Mach, and Magnetosonic Mach are shown

Using the results, the 2D sketches of the IP shocks that were detected by the spacecraft are shown in Figure 5.4, 5.5, 5.6. In these 2D sketches, the shock propagation and normal vector orientation are shown in a temporal development manner. The 3D sketch is shown in 5.7, and in the 3D sketch the STEREO A and STEREO B positions are time shifted to the Wind's position to see the overall shape of this IP shock. From the 3D sketch, the overall shape of the IP shock is a planner and can be fitted with a line. The IP shock planar line is tilted 32.94° with respect to the Sun-Earth line. The tilt appears as almost the same degree as the Parker spiral impacting the Earth from the dawn side. Hence, it is the reason why the Wind detected the shock first even though STEREO A's position is relatively closer to the Sun's direction.

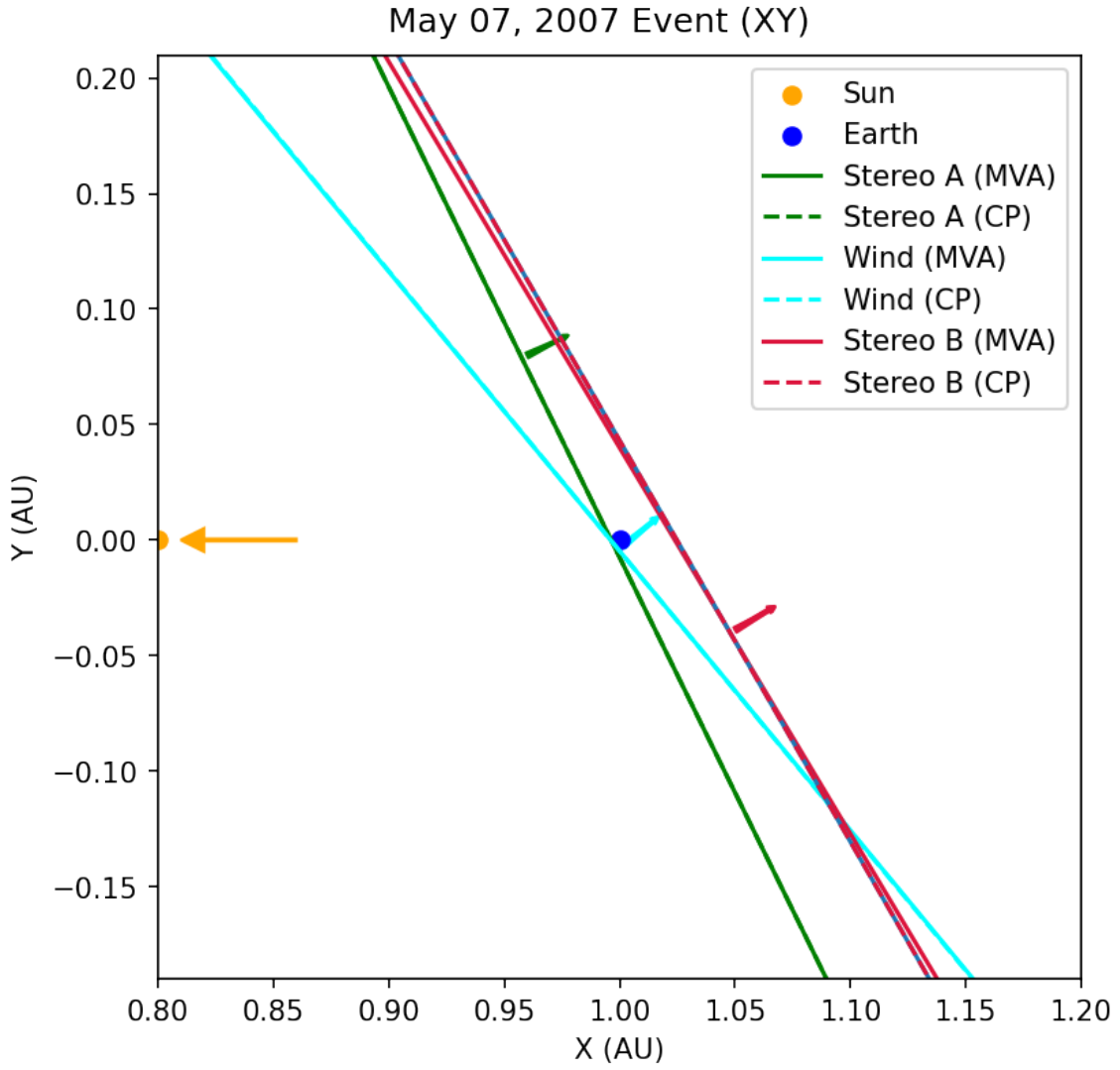


Figure 5.4: A XY coordinate 2D sketch of the propagation of the IP shock through 3 spacecraft– Wind, STEREO A, and STEREO B. The arrows indicate the normal vector direction and the lines perpendicular to the normal vectors indicate the shock surface orientations. The size of the lines are arbitrary.

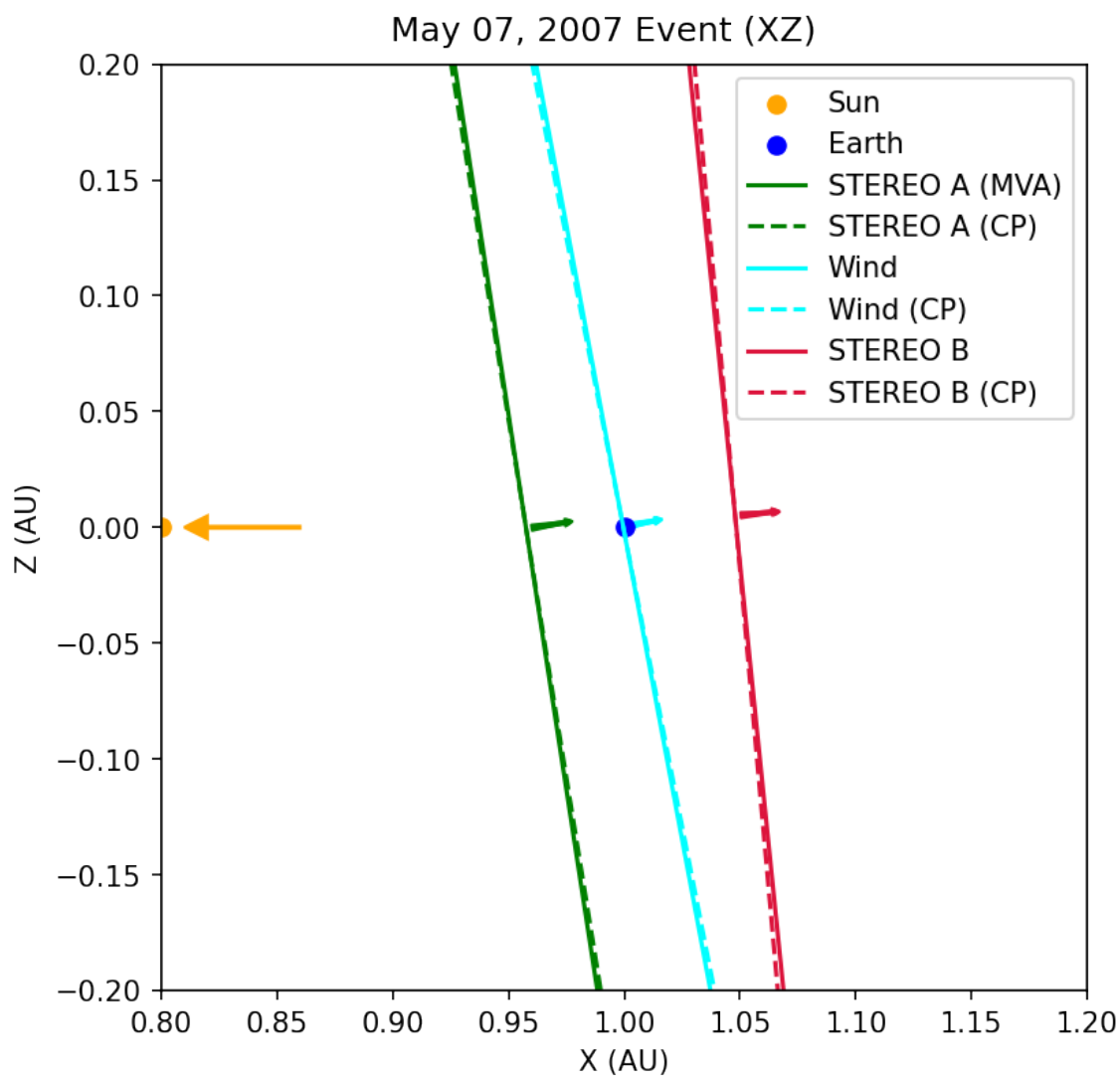


Figure 5.5: A XZ coordinate 2D sketch of the propagation of the IP shock through 3 spacecraft– Wind, STEREO A, and STEREO B. The arrows indicate the normal vector direction and the lines perpendicular to the normal vectors indicate the shock surface orientations. The size of the lines are arbitrary.

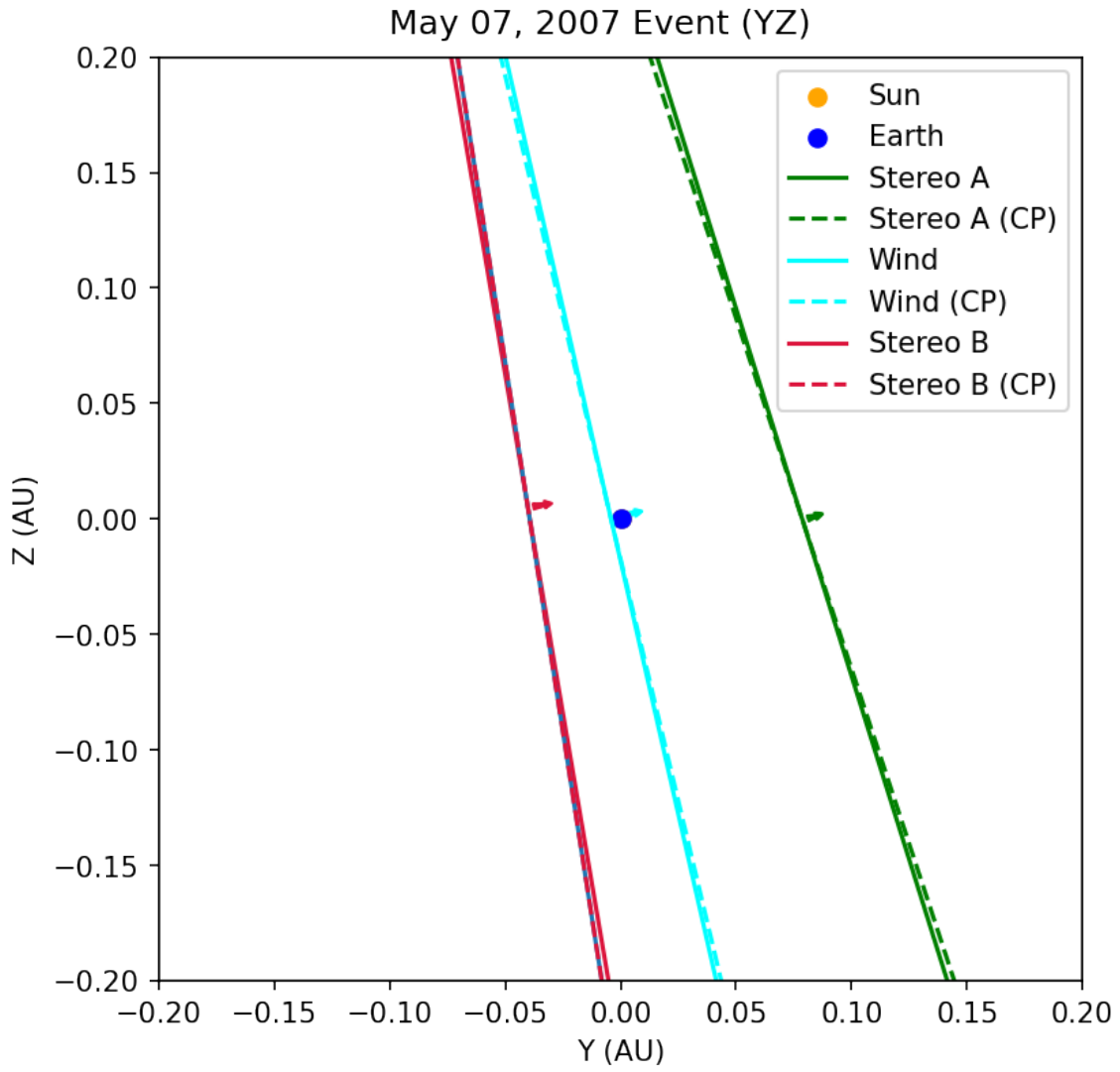


Figure 5.6: A YZ coordinate 2D sketch of the propagation of the IP shock through 3 spacecraft– Wind, STEREO A, and STEREO B. The arrows indicate the normal vector direction and the lines perpendicular to the normal vectors indicate the shock surface orientations. The size of the lines are arbitrary.

May 07, 2007 Event (3D)

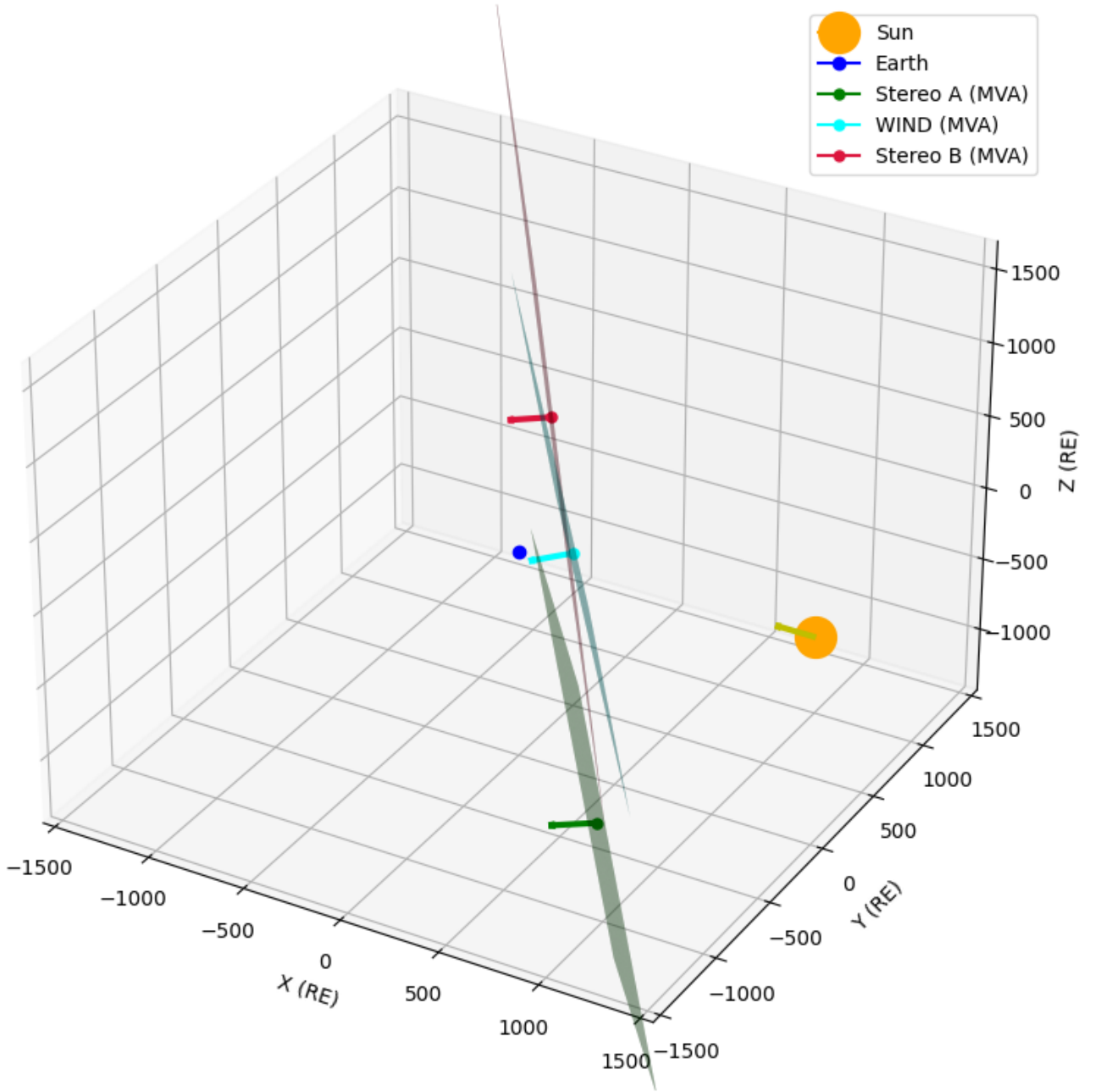


Figure 5.7: A 3D sketch of the propagation of the IP shock through 3 spacecraft– Wind, STEREO A, and STEREO B. The positions of STEREO A and STEREO B are shifted back to Wind. The arrows indicate the normal vector direction and the planes perpendicular to the normal vectors indicate the shock surface orientations. The size of the planes are arbitrary.

5.2 April 23, 2007 Event

The STEREO A magnetic field measurement:

Δt_{up} for the upstream is between (06:46:00 - 06:52:23)

Δt_{down} for the downstream is between (06:57:03 - 07:02:34), see Figure 5.8.

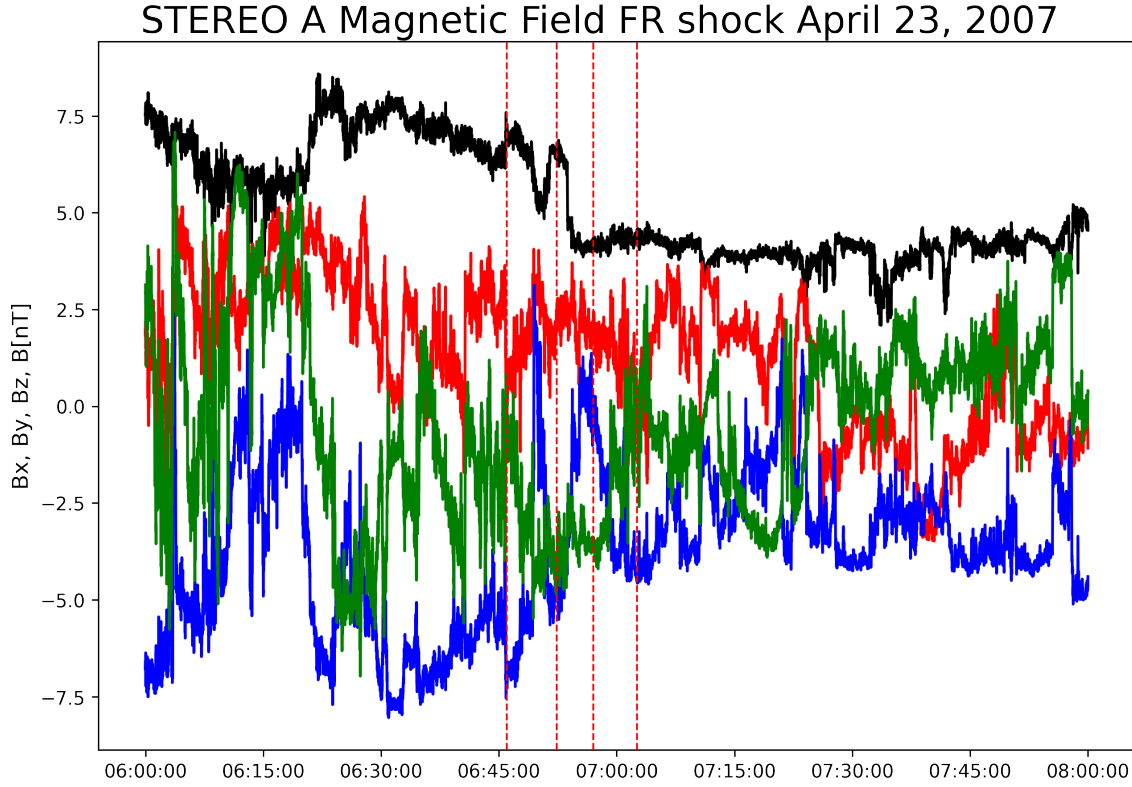


Figure 5.8: The STEREO A magnetic field measurement. The chosen intervals of the upstream and downstream magnetic field. The red dashed lines each represent the upstream starting time and ending time and the downstream starting time and ending time respectively

In these intervals, the angle between the MVA normal and the magnetic coplanarity normal is 1.07° and the ratio between the smallest eigenvalue λ_3 and the intermediate eigenvalue λ_2 is $\lambda_3/\lambda_2 = 0.3036$

ACE magnetic field measurement: The upstream and downstream time intervals that most agree between the minimum variance analysis and the magnetic coplanarity are:

Δt_{up} for the upstream is between (08:50:04 - 08:56:52)

Δt_{down} for the downstream is between (09:01:50 - 09:08:00), see Figure 5.9.

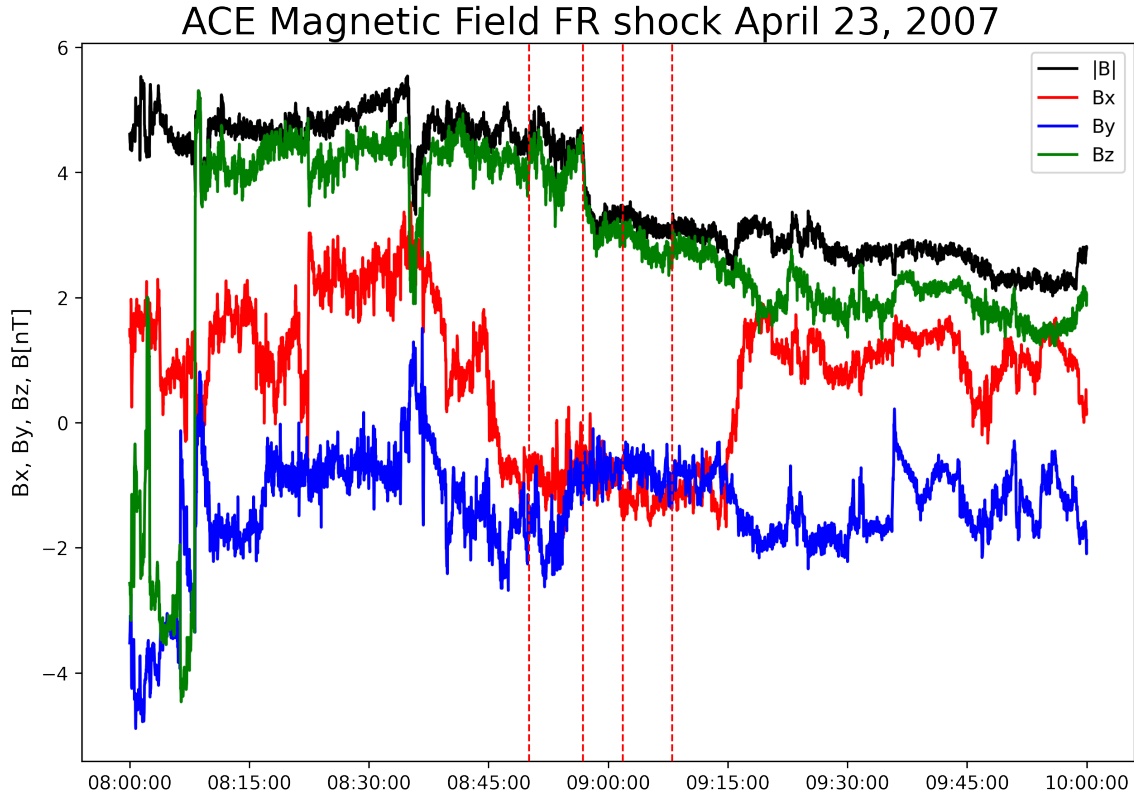


Figure 5.9: ACE magnetic field measurement. The chosen intervals of the upstream and downstream magnetic field. The red dashed lines each represent the upstream starting time and ending time and the downstream starting time and ending time respectively

In these intervals, the angle between the MVA normal and the magnetic coplanarity normal is 3.43° and the ratio between the smallest eigenvalue λ_3 and the intermediate eigenvalue λ_2 is $\lambda_3/\lambda_2 = 0.25$

Wind magnetic field measurement: The upstream and downstream time intervals that most agree between the minimum variance analysis and the magnetic coplanarity are:

Δt_{up} for the upstream is between (09:04:00 - 09:10:00)

Δt_{down} for the downstream is between (09:12:20 - 09:13:15), see Figure 5.10.

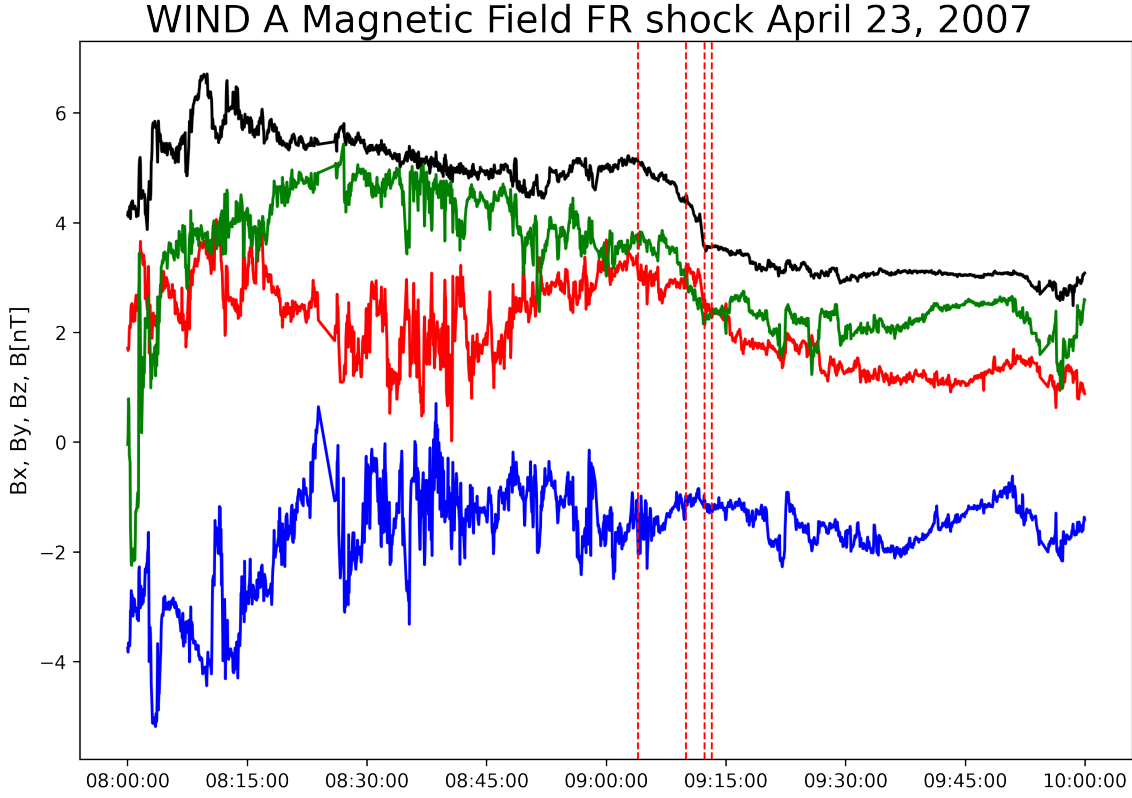


Figure 5.10: The Wind magnetic field measurement. The chosen intervals of the upstream and downstream magnetic field. The red dashed lines each represent the upstream starting time and ending time and the downstream starting time and ending time respectively

In these intervals, the angle between the MVA normal and the magnetic coplanarity normal is 1.46° and the ratio between the smallest eigenvalue λ_3 and the intermediate eigenvalue λ_2 is $\lambda_3/\lambda_2 = 0.295$

Result 2

Similarly to the event about, the upstream and downstream time intervals are highly accurate as well considering the angle difference between the two methods is minimal and the eigenvalue criteria are fulfilled for each spacecraft data.

Also, using the determined time intervals, the estimations of the ratio between the upstream and downstream magnetic field, densities, and temperatures as well as the bulk speed, and shock θ angle are made. These parameters, the minimum variance analysis normal and the magnetic coplanarity normal are shown in Table 5.3, where also the solar wind bulk speed and the downstream to upstream ratios for the shock criteria are fulfilled accordingly with 4.14 and 4.15, and the calculated results of additional parameters are shown in Table 5.4

Spacecraft	B_d/B_u	N_d/N_u	T_d/T_u	ΔV	θ_{Bn}
STEREO A	1.47 ± 0.16	2 ± 0.7	1.48 ± 0.5	46 ± 13	88.4
ACE	1.414 ± 0.09	1.475 ± 0.16	1.212 ± 0.09	24.563 ± 5	47.39
Wind	1.349 ± 0.06	1.424 ± 0.4	1.285 ± 0.7	19.26 ± 0.13	61.85

Table 5.3: Result core parameters of studying the data of the STEREO A, ACE, and Wind spacecrafts. Here θ_{Bn} is the shock θ angle.

MVA	Coplanarity	$\Delta\theta_{MVA-CP}$
[-0.86 0.02 -0.502]	[-0.858 0.007 -0.51]	1.07
[0.899 -0.146 -0.412]	[0.888 -0.205 -0.411]	3.429
[-0.823 0.43 0.369]	[-0.809 0.438 0.39]	1.349

Table 5.3: (Continue) Result core parameters of studying the data of the STEREO A, ACE, and Wind spacecrafts. θ_{MVA-CP} is the angle difference between the minimum variance normal vectors and the magnetic coplanarity normal vectors.

Spacecraft	V_{sh} km/s	C_s^{up} km/s	V_A^{up} km/s	C_{ms}^{up} km/s
STEREO A	467.95	64.97 ± 7.74	68.715 ± 29.2	94.57 ± 21.85
ACE	412.36	58.28 ± 4.94	52.82 ± 15.9	78.66 ± 11.26
Wind	372.59	56.14 ± 5.36	56.22 ± 14.71	79.45 ± 11.08

Table 5.4: Result additional parameters of studying the data of the three spacecraft. V_{sh} is the shock speed, C_s^{up} is the upstream sound speed, V_A^{up} is the upstream Alfvén speed and C_{ms}^{up} is the upstream magnetosonic speed.

Plasma β_{up}	Alfvén Mach	Magnetosonic Mach
1.07 ± 0.94	0.998 ± 0.67	0.725 ± 0.41
1.46 ± 0.91	1.49 ± 0.56	1.0 ± 0.27
1.19 ± 0.66	1.24 ± 0.52	0.88 ± 0.31

Table 5.4: (Continue) Result additional parameters of studying the data of the three spacecraft. Plasma β_{up} , Alfvén Mach, and Magnetosonic Mach are shown

Similarly, the sketches of the IP shocks that were detected by the spacecraft are shown in 5.11, 5.12, 5.13. In these 2D sketches, the shock propagation and normal vector orientation are shown in a temporal development manner. The 3D sketch is shown in 5.14 and in the 3D sketch, the Wind and ACE positions are time-shifted to the STEREO A's position to see the overall shape of this IP shock. It appears the shape of the shock is not uniform and twisted along the transverse direction to the Sun-Earth line. STEREO B does not observe the IP shock signatures during this event, which adds strangeness to this shock event considering the relatively closer position of STEREO B to these three spacecraft at that time. This IP shock is a fast reverse shock, meaning it travels toward the Sun even though the shock propagates away from the sun with the solar wind. So, due to this nature, the IP shock could be a local ripple.

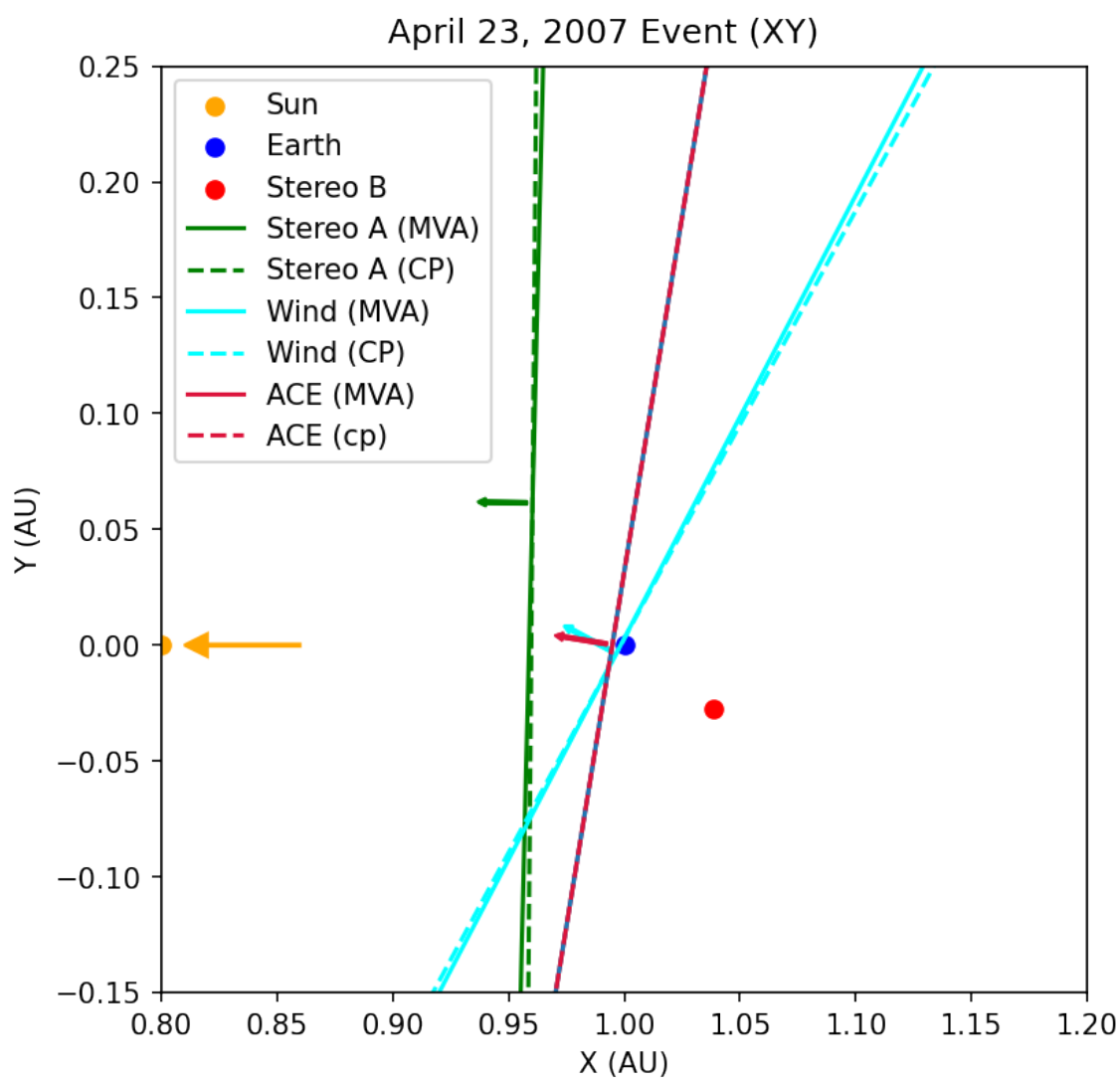


Figure 5.11: A XY coordinate 2D sketch of the propagation of the IP shock through 3 spacecraft– STEREO A, Wind, and ACE. The arrows indicate the normal vector direction and the lines perpendicular to the normal vectors indicate the shock surface orientations. The size of the lines are arbitrary.

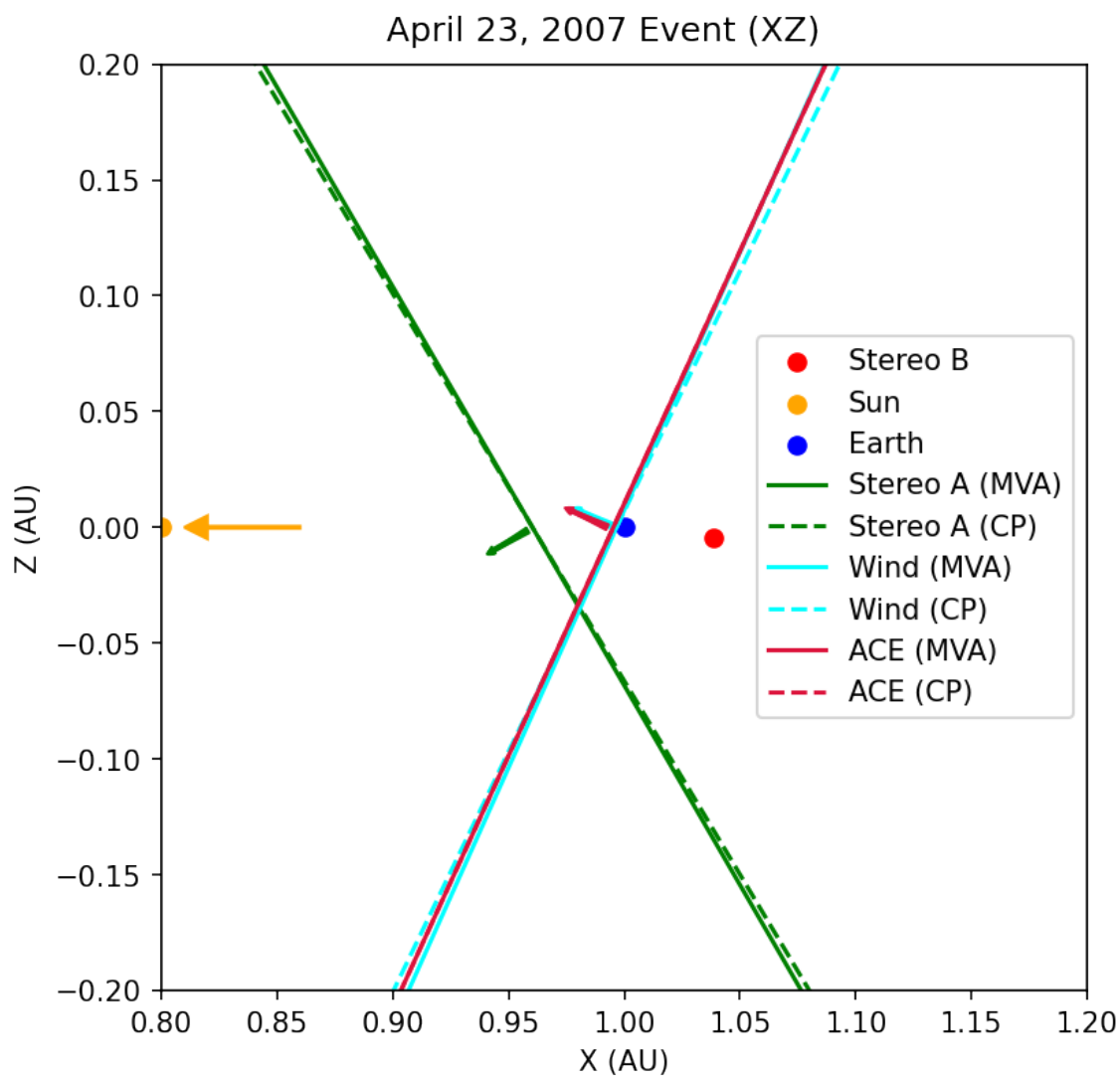


Figure 5.12: A XZ coordinate 2D sketch of the propagation of the IP shock through 3 spacecraft– STEREO A, Wind, and ACE. The arrows indicate the normal vector direction and the lines perpendicular to the normal vectors indicate the shock surface orientations. The size of the lines are arbitrary.

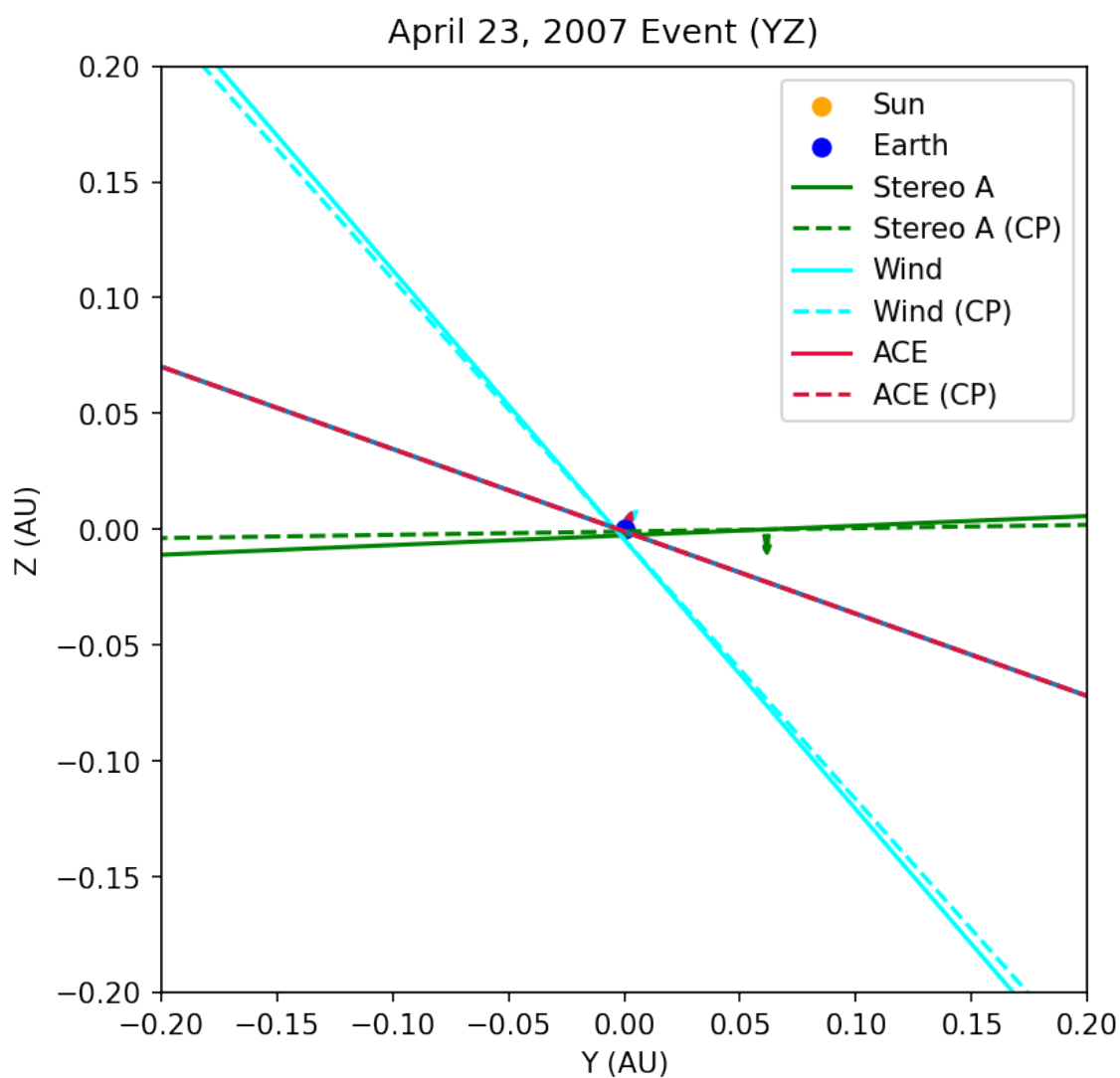


Figure 5.13: A YZ coordinate 2D sketch of the propagation of the IP shock through 3 spacecraft– STEREO A, Wind, and ACE. The arrows indicate the normal vector direction and the lines perpendicular to the normal vectors indicate the shock surface orientations. The size of the lines are arbitrary.

April 23, 2007 Event (3D)

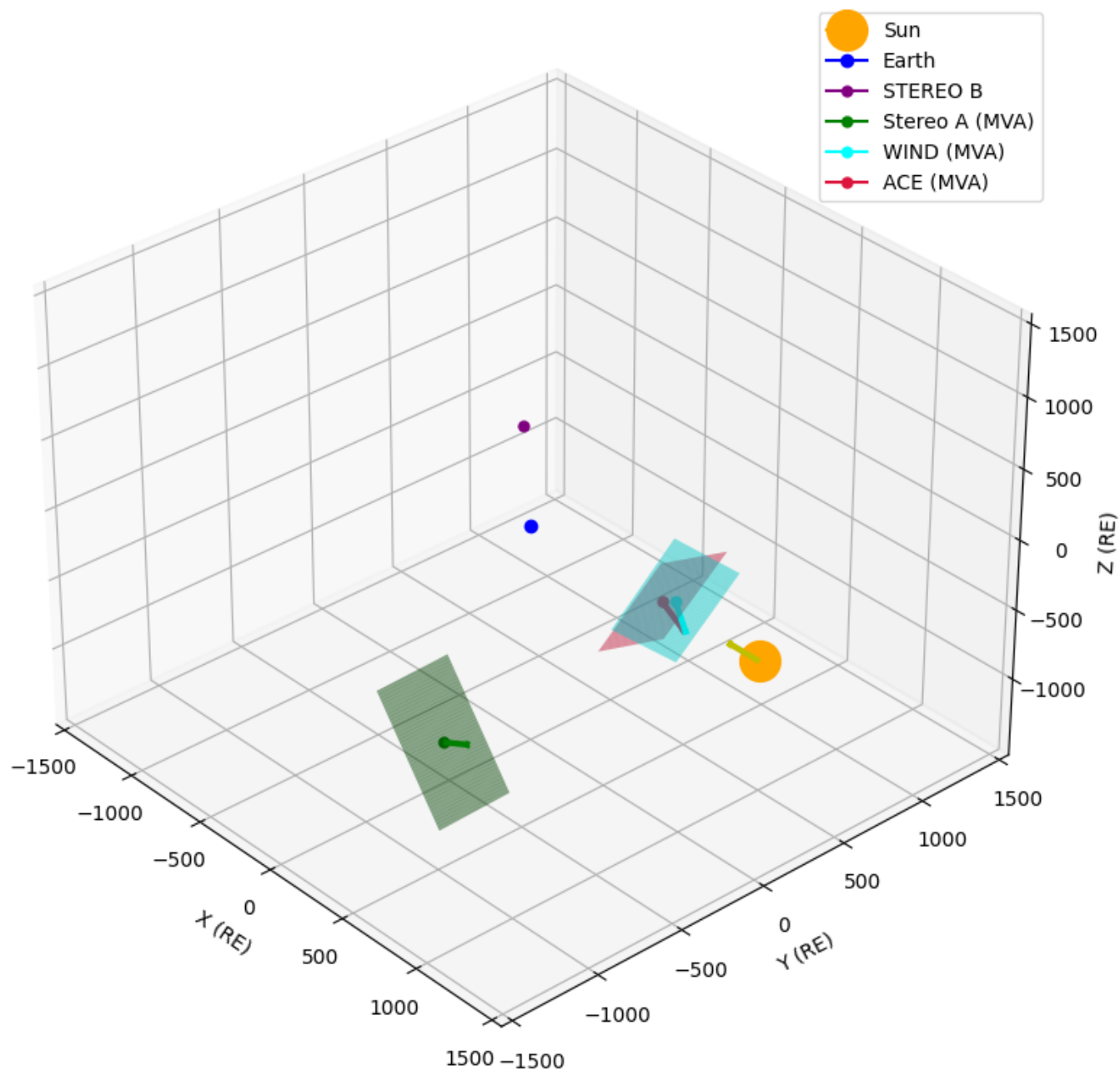


Figure 5.14: A 3D sketch of the propagation of the IP shock through 3 spacecraft– STEREO A, Wind, and ACE. The positions of Wind and ACE are shifted back to Wind. The arrows indicate the normal vector direction and the planes perpendicular to the normal vectors indicate the shock surface orientations. The size of the planes are arbitrary.

Chapter 6

Summary and conclusions

In this thesis, a single spacecraft study of the interplanetary (IP) shock is presented. This thesis aims to study and determine how IP shocks are changing from one spacecraft to another spacecraft location.

For this purpose, two methods are implemented, namely the minimum variance analysis of the magnetic field (MVA) and the magnetic coplanarity methods for the determination of upstream and downstream time intervals. The two methods use magnetic field measurement data, which is known for its high resolution compared to plasma data. To acquire data, the Coordinated Data Analysis Web (CDAWeb) of NASA is used for each spacecraft. DATA are in the first event case – from early morning to noon in 2007-05-07 for three different spacecraft, namely Wind, Stereo A, and B, and the second event case, similarly, - from early morning to noon in 2007-04-23 for three different spacecraft, namely Wind, Stereo A, and ACE. After acquiring data, every coordinate, and system of the data is changed to HEE by this site <http://treps.irap.omp.eu/> so that it will be easy to compare the data and how the shock parameters change when propagating through space. For accepting the upstream and downstream time intervals, two criteria are made such as the θ angle differences between MVA and the magnetic coplanarity must be considerably small (Facskó et al., 2008) and the ratio between the smallest eigenvalue to the intermediate eigenvalue must be less than 1/3 (Shan et al., 2013). For both case studies, such upstream and downstream intervals are found, indicating our result is highly accurate. So, pinpointing the shock formations has been very successful due to using the two methods to determine the shock normal vectors.

The two event studies are not timely ordered, I first studied the May 07, 2007 event and then April 23, 2007 event. Hence May 07 event is referred to as the first event and April 23 event as the second event. The first event is a fast-forward (FF) shock event, meaning the shock propagating away from the Sun in the solar wind frame of reference in addition to the solar wind on which it propagates is also traveling away from the Sun. From the 2D sketches as well as the 3D sketch, on which the STEREO A and B spacecraft positions are time-shifted to the Wind spacecraft to see the geometry of the shock, the shock appears planar and tilted 32.94° to the Sun-Earth line, explaining why the Wind first detected the IP shock even though its location is behind the STEREO A in respect to the Sun-Earth line. There is no sign of temporal change in this scale. The second event is fast reverse (FR) shock event, meaning the shock propagates toward the Sun in the solar wind frame of reference although the shock propagates away from the sun with its carrier solar wind. There are several peculiarities with this shock event, it appears the shape of the shock is not uniform and twisted along the transverse direction to the Sun-Earth line and STEREO B did not detect any shock around in a range of considerable time that to conclude as the same shock. So, it can be assumed that this IP shock shape is non-uniform and locally rippled. Further studies are needed for determining this shock's surface.

Bibliography

- Acuña, M., Curtis, D., Scheifele, J., Russell, C., Schroeder, P., Szabo, A., & Luhmann, J. (2008). The stereo/impact magnetic field experiment. *Space Science Reviews*, 136.
- Alfvén, H. (1942). Existence of electromagnetic-hydrodynamic waves. *Nature*, 150(3805), 405–406.
- Aschwanden, M. (2006). *Physics of the solar corona: an introduction with problems and solutions*. Springer Science & Business Media.
- Aschwanden, M. J. (2014). Chapter 11 - the sun. In T. Spohn, D. Breuer, & T. V. Johnson (Eds.), *Encyclopedia of the solar system (third edition)* (Third Edition ed., p. 235-259). Boston: Elsevier. Retrieved from <https://www.sciencedirect.com/science/article/pii/B9780124158450000116> doi: <https://doi.org/10.1016/B978-0-12-415845-0.00011-6>
- Babcock, H. W., & Babcock, H. D. (1955). The sun's magnetic field, 1952-1954. *The Astrophysical Journal*, 121, 349.
- Basu, S., Chaplin, W. J., Elsworth, Y., New, R., & Serenelli, A. M. (2009). Fresh insights on the structure of the solar core. *The Astrophysical Journal*, 699(2), 1403.
- Baumjohann, W., & Nakamura, R. (2007). 5.03 - magnetospheric contributions to the terrestrial magnetic field. In G. Schubert (Ed.), *Treatise on geophysics* (p. 77-92). Amsterdam: Elsevier. Retrieved from <https://www.sciencedirect.com/science/article/pii/B9780444527486000882> doi: <https://doi.org/10.1016/B978-044452748-6.00088-2>
- Baumjohann, W., & Treumann, R. A. (2012). *Basic space plasma physics (revised edition)*. World Scientific Publishing Company.
- Berdichevsky, D. B., Szabo, A., Lepping, R. P., Viñas, A. F., & Mariani, F. (2000). Interplanetary fast shocks and associated drivers observed through the 23rd solar minimum by wind over its first 2.5 years. *Journal of Geophysical Research: Space Physics*, 105(A12), 27289–27314.
- Biermann, L. F. (2013). 25. solar corpuscular radiation and the interplanetary gas. In *A source book in astronomy and astrophysics, 1900–1975* (pp. 147–148). Harvard University Press.
- Bittencourt, J. A. (2004). *Fundamentals of plasma physics*. Springer Science & Business Media.
- Brummell, N., Toomre, J., & Cattaneo, F. (1995). Turbulent dynamics in the solar convection zone. *Science*, 269(5229), 1370–1379.
- Cane, H., & Lario, D. (2006). An introduction to cmes and energetic particles. *Space science reviews*, 123(1), 45–56.
- Center/SDO, N. G. S. F. (2015). *Sdo solar comparison october 2010 to october 2012*.
- Chakraborty, S., & Basak, T. (2022). Brief review on lower ionosphere and the effects of solar flare thereon. *Advances in Modern and Applied Sciences*, 137.
- Chao, J., & Hsieh, K. (1984). On determining magnetohydrodynamic shock parameters bn and ma. *Planetary and Space Science*, 32(5), 641-646. Retrieved from <https://www.sciencedirect.com/science/article/pii/0032063384901156> doi: [https://doi.org/10.1016/0032-0633\(84\)90115-6](https://doi.org/10.1016/0032-0633(84)90115-6)
- Chemin, Y.-H. (2022). Introductory chapter: The sun and its phenomenal material flux. In *Magnetosphere and solar winds, humans and communication*. IntechOpen.
- Christensen-Dalsgaard, J., Gough, D., & Thompson, M. (1991). The depth of the solar convection zone. *The Astrophysical Journal*, 378, 413–437.
- Cid, C., Palacios, J., Saiz, E., Guerrero, A., & Cerrato, Y. (2014). On extreme geomagnetic storms. *Journal of Space Weather and Space Climate*, 4, A28.

- Cowen, R. (2013). *Voyager 1 has reached interstellar space*.
- Cranmer, S. R. (2009). Coronal holes. *Living Reviews in Solar Physics*, 6(1), 1–66.
- David Burgess. (2017). *Theory of particle acceleration at collisionless shocks les houches 2017*. Queen Mary University of London. (<https://ipag.osug.fr/~lesurg/plasmas2017/talks/Burgess-Houches-2017.pdf/>, Last accessed on 2022-04-04)
- Davidson, P. A. (2002). *An introduction to magnetohydrodynamics*. American Association of Physics Teachers.
- Dr. David H. Hathaway, d. (2015). *The solar interior*.
- Fackó, G., Kecskeméty, K., Erdős, G., Tátrallyay, M., Daly, P. W., & Dandouras, I. (2008). A statistical study of hot flow anomalies using cluster data. *Advances in space research*, 41(8), 1286–1291.
- Feldman, U., Landi, E., & Schwadron, N. (2005). On the sources of fast and slow solar wind. *Journal of Geophysical Research: Space Physics*, 110(A7).
- Fitzpatrick, R. (2014). *Plasma physics: an introduction*. Crc Press.
- Freidberg, J. P. (2014). *ideal mhd*. Cambridge University Press.
- Galvin, A. B., Kistler, L. M., Popecki, M. A., Farrugia, C. J., Simunac, K. D., Ellis, L., ... others (2008). The plasma and suprathermal ion composition (plastic) investigation on the stereo observatories. *Space Science Reviews*, 136(1), 437–486.
- García, R. A., Turck-Chièze, S., Jiménez-Reyes, S. J., Ballot, J., Pallé, P. L., Eff-Darwich, A., ... Provost, J. (2007). Tracking solar gravity modes: the dynamics of the solar core. *Science*, 316(5831), 1591–1593.
- Gilbert, A. D. (2003). Chapter 9 - dynamo theory. In S. Friedlander & D. Serre (Eds.), (Vol. 2, p. 355–441). North-Holland. Retrieved from <https://www.sciencedirect.com/science/article/pii/S1874579203800113> doi: [https://doi.org/10.1016/S1874-5792\(03\)80011-3](https://doi.org/10.1016/S1874-5792(03)80011-3)
- Goedbloed, H., Keppens, R., & Poedts, S. (2019). *Magnetohydrodynamics: Of laboratory and astrophysical plasmas*. Cambridge University Press.
- Gonzalez, W., Joselyn, J.-A., Kamide, Y., Kroehl, H. W., Rostoker, G., Tsurutani, B., & Vasyliunas, V. (1994). What is a geomagnetic storm? *Journal of Geophysical Research: Space Physics*, 99(A4), 5771–5792.
- Génot, V., Renard, B., Dufourg, N., Bouchemit, M., Lormant, N., Beigbeder, L., ... Gangloff, M. (2018). Treps, a tool for coordinate and time transformations in space physics. *Planetary and Space Science*, 150, 86–90. Retrieved from <https://www.sciencedirect.com/science/article/pii/S0032063316304445> (Enabling Open and Interoperable Access to Planetary Science and Helio physics Databases and Tools) doi: <https://doi.org/10.1016/j.pss.2017.06.002>
- Harten, R., & Clark, K. (1995). The design features of the ggs wind and polar spacecraft. *Space Science Reviews*, 71(1), 23–40.
- Heber, B., Sanderson, T., & Zhang, M. (1999). Corotating interaction regions. *Advances in Space Research*, 23(3), 567–579. Retrieved from <https://www.sciencedirect.com/science/article/pii/S0273117799800131> (The Transport of Galactic and Anomalous Cosmic Rays in the Heliosphere: Observations, Simulations and Theory) doi: [https://doi.org/10.1016/S0273-1177\(99\)80013-1](https://doi.org/10.1016/S0273-1177(99)80013-1)
- Jr., T. M. A. (2019, October). *Single fluid ideal mhd phys 761 physics 761*. Physics Department, University of Maryland. (https://terpconnect.umd.edu/~antonsen/PHYS761_F19/LECTURES/Single_Fluid_MHD.pdf)
- Jyothi, S. A. (2021). Solar superstorms: planning for an internet apocalypse. In *Proceedings of the 2021 acm sigcomm 2021 conference* (pp. 692–704).
- Kaiser, M. (2005). The stereo mission: an overview. *Advances in Space Research*, 36(8), 1483–1488. Retrieved from <https://www.sciencedirect.com/science/article/pii/S0273117705000505> (Solar Encounter, Solar-B and STEREO) doi: <https://doi.org/10.1016/j.asr.2004.12.066>
- Kaiser, M. L., & Adams, W. J. (2007). Stereo mission overview. In *2007 ieee aerospace conference* (pp. 1–8).

- Kaiser, M. L., Kucera, T., Davila, J., St Cyr, O., Guhathakurta, M., & Christian, E. (2008). The stereo mission: An introduction. *Space Science Reviews*, 136(1), 5–16.
- Keith, W., & Heikkila, W. (2021). 1 - historical introduction. In W. Keith & W. Heikkila (Eds.), *Earth's magnetosphere (second edition)* (Second Edition ed., p. 1-88). Academic Press. Retrieved from <https://www.sciencedirect.com/science/article/pii/B9780128181607000016> doi: <https://doi.org/10.1016/B978-0-12-818160-7.00001-6>
- Kivelson, M. G., & Bagenal, F. (2007). Chapter 28 - planetary magnetospheres. In L.-A. McFadden, P. R. Weissman, & T. V. Johnson (Eds.), *Encyclopedia of the solar system (second edition)* (Second Edition ed., p. 519-540). San Diego: Academic Press. Retrieved from <https://www.sciencedirect.com/science/article/pii/B9780120885893500323> doi: <https://doi.org/10.1016/B978-012088589-3/50032-3>
- Lakhina, G., Alex, S., & Rawat, R. (2009). An overview of the magnetosphere, substorms and geomagnetic storms. *Turbulence, Dynamos, Accretion Disks, Pulsars and Collective Plasma Processes*, 293–309.
- Lepping, R., Acuña, M., Burlaga, L., Farrell, W., Slavin, J., Schatten, K., ... others (1995). The wind magnetic field investigation. *Space Science Reviews*, 71(1), 207–229.
- Lowrie, W., & Fichtner, A. (2020). *Fundamentals of geophysics* (3rd ed.). Cambridge University Press. doi: 10.1017/9781108685917
- Luhmann, J., Curtis, D., Schroeder, P., McCauley, J., Lin, R., Larson, D., ... others (2008). Stereo impact investigation goals, measurements, and data products overview. In *The stereo mission* (pp. 117–184). Springer.
- Lumme, E., Kilpua, E., Isavnin, A., & Andreeva, K. (2017). Database of heliospheric shock waves.
- Mazelle, C., Winterhalter, D., Sauer, K., Trotignon, J., Acuña, M., Baumgärtel, K., ... Slavin, J. (2004, 01). Bow shock and upstream phenomena at mars. *Space Science Reviews*, 111, 115-181. doi: 10.1023/B:SPAC.0000032717.98679.d0
- McComas, D., Bame, S., Barker, P., Feldman, W., Phillips, J., Riley, P., & Griffee, J. (1998). Solar wind electron proton alpha monitor (swepam) for the advanced composition explorer. *The Advanced Composition Explorer Mission*, 563–612.
- McComas, D., Elliott, H., Schwadron, N., Gosling, J., Skoug, R., & Goldstein, B. (2003). The three-dimensional solar wind around solar maximum. *Geophysical research letters*, 30(10).
- Murphy, N. (2014, February). *Ideal magnetohydrodynamics*. Harvard-Smithsonian Center for Astrophysics. (https://lweb.cfa.harvard.edu/~namurphy/Lectures/Ay253_01_IdealMHD.pdf)
- NASA. (2017). *Total solar eclipse - august 21, 2017*. (<https://eclipse2017.nasa.gov/>, Last accessed on 2022-04-04)
- NASA Solar System Exploration. (2020). *What is a lagranian point?* (<https://solarsystem.nasa.gov/resources/754/what-is-a-lagrange-point/>)
- NASA WIND Spacecraft. (2020). *Stereo-b status update*. (<https://wind.nasa.gov/>)
- NASA WIND Spacecraft. (2022). *Wind data sources*. (https://wind.nasa.gov/data_sources.php)
- NASA/JPL-Caltech/GSFC/JAXA. (2015). *Nustar stares at the sun*. (Nasa, <https://www.nasa.gov/jpl/pia19821/nustar-stares-at-the-sun/>, Last accessed on 2022-03-08)
- Neugebauer, M. (1981). Observations of solar-wind helium. *Fundamentals of Cosmic Physics*, 7, 131–199.
- Newbury, J. (1996). Electron temperature in the solar wind at 1 au. *Eos, Transactions American Geophysical Union*, 77(47), 471–471.
- Ogilvie, K., Chornay, D., Fritzenreiter, R., Hunsaker, F., Keller, J., Lobell, J., ... others (1995). Swe, a comprehensive plasma instrument for the wind spacecraft. *Space Science Reviews*, 71(1), 55–77.
- Oliveira, D. M. (2015). *A study of interplanetary shock geoeffectiveness controlled by impact angles using simulations and observations* (Unpublished doctoral dissertation). University of New Hampshire.
- Ortuño-Araujo, J., Barranco-Jiménez, M., Zsargo, J., & Angulo-Brown, F. (2012). An endoreversible thermodynamic model applied to the convective zone of the sun. *International Scholarly Research Notices*, 2012.

- Parker, E. (1959). Extension of the solar corona into interplanetary space. *Journal of Geophysical Research*, 64(11), 1675–1681.
- Parker, E. N. (1958). Dynamics of the interplanetary gas and magnetic fields. *The Astrophysical Journal*, 128, 664.
- Pasachoff, J., Rusin, V., Saniga, M., Babcock, B., Lu, M., Davis, A., ... Shiota, K. (2014, 12). Structure and dynamics of the 13/14 november 2012 eclipse white-light corona !!! *The Astrophysical Journal*, 800. doi: 10.1088/0004-637X/800/2/90
- Paschmann, G., & Daly, P. W. (n.d.). Shock and discontinuity normals, mach numbers, and related parameters.
- Richter, A., Hsieh, K., Luttrell, A., Marsch, E., & Schwenn, R. (1985). Review of interplanetary shock phenomena near and within 1 au. *Collisionless shocks in the heliosphere: reviews of current research*, 35, 3350.
- Roberts, P. (2007). Alfvén’s theorem and the frozen flux approximation. *Encyclopedia of geomagnetism and paleomagnetism*, 7–11.
- Route, M. (2016). The discovery of solar-like activity cycles beyond the end of the main sequence? *The Astrophysical Journal Letters*, 830(2), L27.
- Shan, L., Lu, Q., Zhang, T., Gao, X., Huang, C., Su, Y., & Wang, S. (2013). Comparison between magnetic coplanarity and mva methods in determining the normal of venusian bow shock. *Chinese Science Bulletin*, 58(20), 2469–2472.
- Smith, C. W., L’Heureux, J., Ness, N. F., Acuna, M. H., Burlaga, L. F., & Scheifele, J. (1998). The ace magnetic fields experiment. *The advanced composition explorer mission*, 613–632.
- Snyder, C. W., & Neugebauer, M. (1965). Interplanetary solar-wind measurements by mariner ii. In *Proceedings of the plasma space science symposium* (pp. 67–90).
- Sonnerup, B. Ö., & Cahill Jr, L. (1967). Magnetopause structure and attitude from explorer 12 observations. *Journal of Geophysical Research*, 72(1), 171–183.
- Sonnerup, B. U., & Scheible, M. (1998). Minimum and maximum variance analysis. *Analysis methods for multi-spacecraft data*, 1, 185–220.
- STEREO Science Center. (2018). *Stereo-b status update*. (https://stereo-ssc.nascom.nasa.gov/behind_status.shtml, Last accessed on 2018-10-23)
- Stone, E. C., Frandsen, A., Mewaldt, R., Christian, E., Margolies, D., Ormes, J., & Snow, F. (1998). The advanced composition explorer. *Space Science Reviews*, 86(1), 1–22.
- Tobias, S., & Weiss, N. (2007). The solar dynamo and the tachocline. *The solar tachocline*, 319–350.
- Tonks, L. (1967). The birth of “plasma”. *American Journal of Physics*, 35(9), 857–858.
- Tsurutani, B., Lakhina, G., Verkhoglyadova, O., Gonzalez, W., Echer, E., & Guarnieri, F. (2011). A review of interplanetary discontinuities and their geomagnetic effects. *Journal of Atmospheric and Solar-Terrestrial Physics*, 73(1), 5-19. Retrieved from <https://www.sciencedirect.com/science/article/pii/S1364682610001173> doi: <https://doi.org/10.1016/j.jastp.2010.04.001>
- Tsurutani, B., & Lin, R. (1985). Acceleration of ~ 47 keV ions and ~ 2 keV electrons by interplanetary shocks at 1 au. *Journal of Geophysical Research: Space Physics*, 90(A1), 1–11.
- Wilson III, L. B., Brosius, A. L., Gopalswamy, N., Nieves-Chinchilla, T., Szabo, A., Hurley, K., ... others (2021). *A quarter century of wind spacecraft discoveries*. Wiley Online Library.
- WIND MFI Team Science. (2001). *On interplanetary shocks*. (https://wind.nasa.gov/mfi/ip_descr.html, Last accessed on 2022-05-31)