



Anisotropic Jovian electron transport

AM Dumont

 **orcid.org/0000-0002-5687-9494**

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Abstract

Jovian electrons are released into the heliosphere as a result of events caused by the dynamics within the Jovian magnetosphere, including magnetic flux tubes formed in the magnetosphere because of centrifugal forces as a result of the fast rotation rate of Jupiter. A two-dimensional focused transport model is used to simulate the propagation of Jovian electrons in the heliosphere. The optimization of the model for parallel computing was investigated as it increases the performance as well as determines the optimal runtime of the model. Observed intensities of Jovian electrons from the PSP spacecraft is used to yield the best-fitting mean free paths when compared to simulation results from the two-dimensionally focused transport model. The obtained mean free path values are compared to various mean free paths from different sources as well as to the theoretical estimates. These mean free paths are used in the model to simulate two types of Jovian events: The Jovian clock that releases Jovian electrons, in 10-hour and 5-hour periodicities and Jovian jets where Jovian electrons are released sporadically.

Keywords: Jovian electrons; heliosphere; focused transport equation; Jupiter; pitch-angle scattering.

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Table of abbreviations

AU	Astronomical Units ¹
CIR	Co-rotating Interacting Region
DOY	Day Of the Year
EPI-HI	Energetic Particles from the Instrument for High Energy
eV	Electron Volt ²
HET	High Energy Telescope
HMF	Heliospheric Magnetic Field
MeV	Mega Electron Volt ³
PSP	Parker Solar Probe
R_J	Radius of Jupiter ⁴
SIMD	Single Instruction/Multiple Data
SIR	Stream Interaction Region
SW	Solar Wind

¹1 AU = 1.496×10^{11} m

²1 eV = $1,60218 \times 10^{-19}$ J

³1 MeV = 1000000 eV

⁴1 R_J = 71492 km

Chapter 1

Introduction

Jovian electrons are relativistic electrons, which are assumed to be released continuously via the magnetosphere of Jupiter with an energy range of $\sim 4 - 30$ MeV (Ferreira, 2002). This magnetosphere is the largest magnetosphere in the heliosphere as it expands to ~ 100 radii of Jupiter (R_J) and was discovered in 1973 by the Pioneer 10 spacecraft (Mead, 1974; Morrison and Samz, 1980; Tomás et al., 2004). Later, the Ulysses spacecraft observed that the Jovian magnetosphere releases a quasi-constant source of Jovian electrons in the inner heliosphere (Ferreira, 2002; Dunzlaff et al., 2010). These Jovian electrons are released time dependently due to dynamics within the Jovian magnetosphere and the influence of the Galilean moons, which produce events that release the electrons into the heliosphere (Bagenal et al., 2006). Magnetic flux tubes created in the Jovian magnetosphere from centrifugal forces, release electrons into the heliosphere known as Jovian jets which are dependent on the size of the flux tube (Ferrando et al., 1993; Bandyopadhyay et al., 2022). The magnetosphere produces temporal periodic perturbations of Jovian electron intensities known as the “Jovian clock” which is formed by the rotation of Jupiter (Dunzlaff, 2013). These electrons propagate mainly along the heliospheric magnetic field, but also diffuse perpendicular to the field. Jovian electrons were also recently measured by instruments on the Parker Solar Probe spacecraft (PSP), which captured Jovian electron intensities within 0.5 astronomical units (AU) of the Sun (Mitchell et al., 2022). This research is focused on simulating the propagation of a quasi-constant source of Jovian electrons in the inner heliosphere using the focused transport model from Strauss and Fichtner (2015), originally developed to simulate the propagation of solar energetic particles.

Chapter 2 introduces basic concepts about the heliosphere and the heliospheric magnetic field along which Jovian electrons propagate. Furthermore, the composition, structure, and dynamics of the Jovian system are discussed there.

Chapter 3 introduces the focused transport model used in this work to simulate the anisotropic propagation of Jovian electrons. This chapter focuses on the physical processes included in the two-dimensional focused transport model, some of its numerical aspects, and the optimization of the model.

Chapter 4 discusses the Jovian intensities measured by the PSP spacecraft that is used to yield the best-fitting mean free paths when compared to simulation results from the two-dimensionally focused transport model. The best-fitting mean free paths are used to simulate how Jovian electron intensities propagate through the inner heliosphere.

Chapter 5 presents simulations of the intensities, anisotropy, and pitch-angle distributions of Jovian electrons that propagate in the heliosphere. The Jovian electron intensities are simulated as temporal periodic perturbations to demonstrate a quasi-steady-state solution known as the “Jovian clock”. Jovian jets are also simulated in this chapter to illustrate how electrons released by these jets propagate into the inner heliosphere.

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Chapter 2

Background

2.1 Introduction

This chapter introduces basic concepts about the Sun, the heliosphere, and the heliospheric magnetic field, which particles propagate along. Furthermore, this chapter also introduces Jovian electrons that originate from Jupiter, which is the second-largest magnetic celestial body in the heliosphere. The composition, structure, and dynamics of the Jovian magnetosphere will be briefly discussed.

2.2 The Sun and Heliosphere

The dynamics in the heliosphere are fundamental in understanding how particles propagate. This section introduces the solar wind, co-rotating interaction regions, the inner heliosphere, and the heliospheric magnetic field (HMF).

2.2.1 Solar wind

The solar wind was discovered by Biermann (1957) while observing comet tails that always appeared to be directed away from the Sun, due to plasma flow from the Sun (Biermann, 1957; Ferreira, 2002). The solar wind originates from solar prominences located on the photosphere, such as coronal holes and magnetic flux tubes, which release a magnetic plasma, consisting of energetic particles, into the heliosphere (Leer et al., 1982; Reames, 2013; Wang, 2024). During a solar minimum, fast solar winds are generated near the polar regions of the Sun via open magnetic field lines with a velocity between $\sim 700 - 750$ km/s, whereas slow solar winds are formed closer to the equatorial region of the Sun due to closed magnetic field lines and they travel between ~ 300 to 400 km/s (Zirker, 1977; Fisk and Schwadron, 2001; Carroll and Ostlie, 2007; Priest, 2014). These winds alternate between fast and slow solar winds, which can form co-rotating interaction regions (Gosling, 1995).

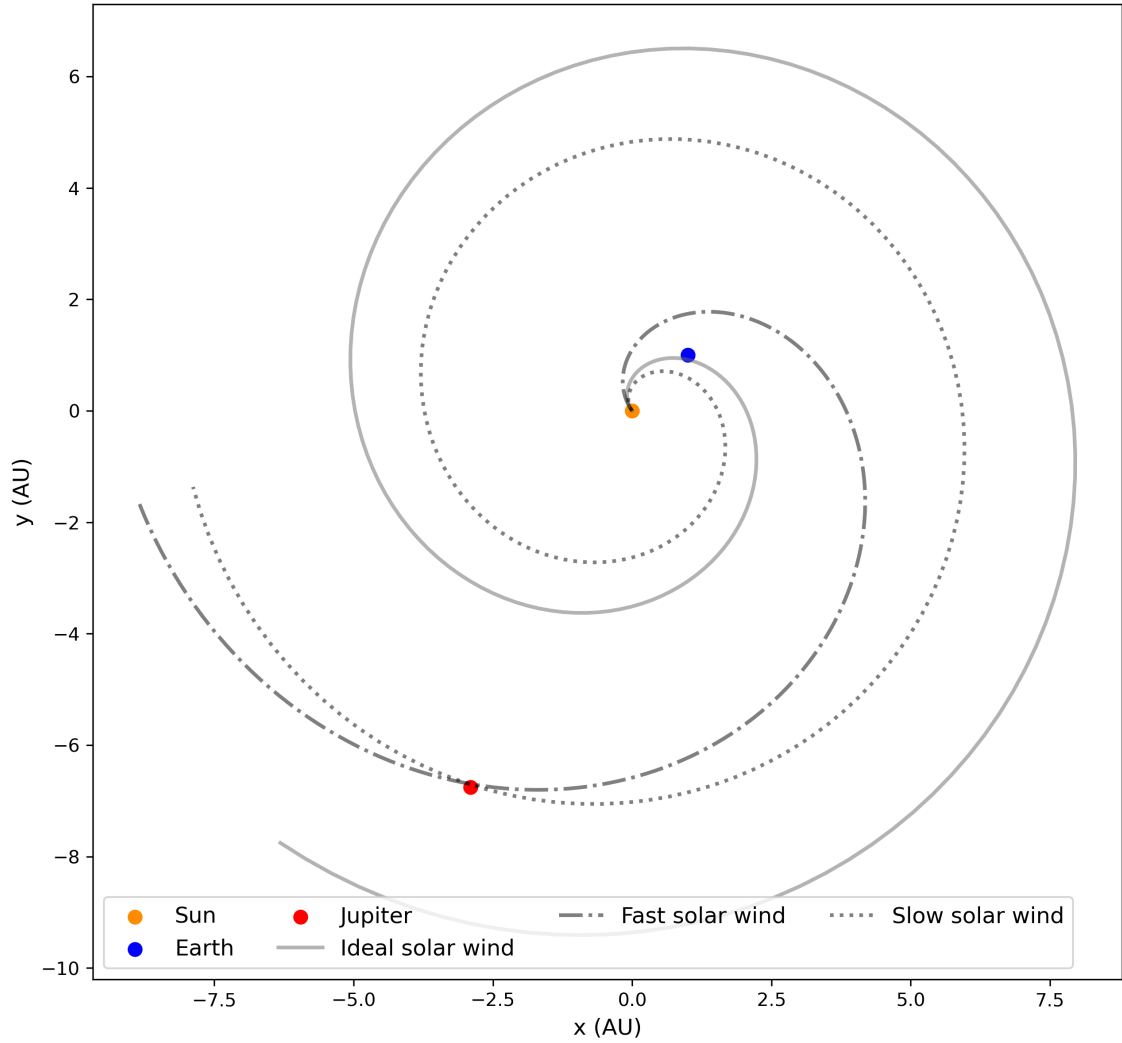


Figure 2.1: The solar wind creates the Archimedean spiral produced by the magnetic field lines of the Sun (Owens and Forsyth, 2013). The nominal solar wind speed is 400 km/s, whereas the fast wind speed is 750 km/s, and the slow wind speed is 300 km/s.

2.2.2 The Parker Field

In a steady state heliosphere it is assumed that the footpoints of a magnetic field are fixed to the photosphere of the Sun, therefore rotating with the Sun to create an Archimedean spiral on which particles transport along, that can be observed in Figure 2.1 (Owens and Forsyth, 2013). This structure is known as the Parker HMF,

$$\vec{B}_{HMF} = AB_0 \left(\frac{r_0}{r} \right)^2 \left[\hat{r} - \tan \psi \hat{\phi} \right], \quad (2.1)$$

which was first described by Parker (1958), where $\hat{\phi}$ is the unit vector in the azimuthal direction, $\hat{r}$ is the unit vector in the radial direction, A is the magnetic field polarity at 1

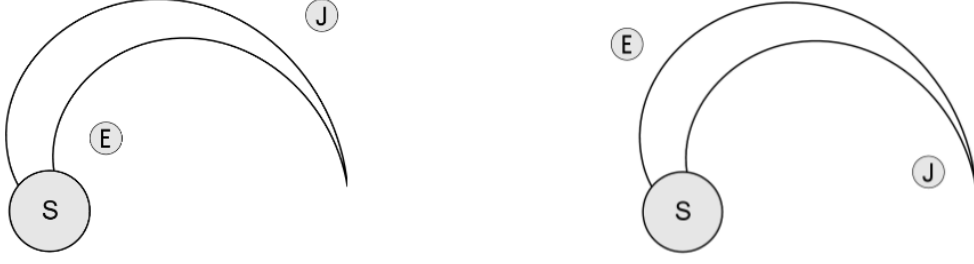


Figure 2.2: Fast solar wind following a slow solar wind produced from the Sun (S), which forms a CIR. The left side demonstrates the CIR reaching Earth (E) before Jupiter (J), whereas the right side represents the CIR reaching Jupiter before Earth (Kühl et al., 2013).

AU, $r_0 = 1$ AU, r is the radial distance, B_0 is the normalization value,

$$B_0 = \frac{B_{\oplus}}{\sqrt{1 + \left(\frac{\omega_{\odot} r_0}{v_{sw}}\right)^2}}, \quad (2.2)$$

and

$$\tan \psi = \frac{\omega_{\odot} (r - r_{\odot}) \sin \theta}{v_{sw}}, \quad (2.3)$$

where v_{sw} is the solar wind speed, $B_{\oplus}$ is the HMF strength at 1 AU, and $\omega_{\odot} \approx \frac{2\pi}{25}$ days is the solar rotation rate (Ferreira, 2002; van den Berg, 2019). Figure 2.1 shows HMF lines from the Sun for different solar winds speeds and how it might affect the transport of particles when Earth and Jupiter are magnetically well connected. The dashed line represents the fast solar wind ($v_{sw} = 700$ km/s), the slow wind speed ($v_{sw} = 300$ km/s) is the dotted line, and the nominal wind speed ($v_{sw} = 400$ km/s) is the solid line.

2.2.3 Co-rotating interaction regions

When the Sun produces a fast solar wind that follows a slow solar wind, the fast solar wind will interact with the slow wind, which creates a phenomenon known as a stream interaction region (SIR) (Gosling and Pizzo, 1999; Kühl et al., 2013). These SIRs usually occur during solar maximum, and as the Sun rotates, it forms co-rotating interacting regions (CIRs) (McComas et al., 1998). These CIRs occur throughout the heliosphere and affect the magnetosphere of multiple planets and particle transport along the HMF as demonstrated in Figure 2.2 (Rutala et al., 2024). These regions cause the slow solar wind to accelerate and the fast solar wind to decelerate. These are known to accelerate particles through a forward and a reverse shock while it also creates a barrier for the propagation of particles (Balogh et al., 1999; Strauss et al., 2016).

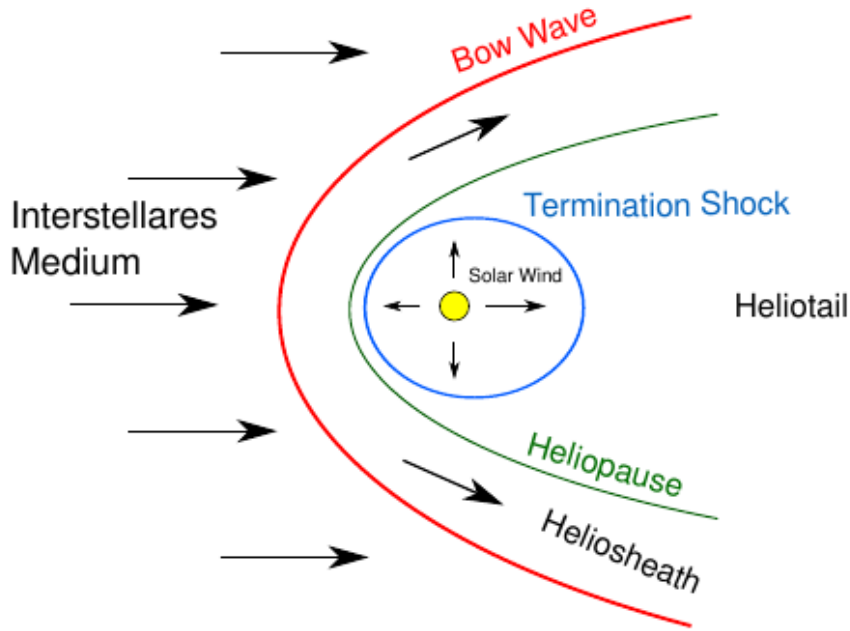


Figure 2.3: A schematic illustration of the heliosphere and structure within (Balogh and Fisk, 2001; Dunzlaff, 2013).

2.2.4 The heliosphere and its boundaries

The heliosphere is a region that expands up to ~ 120 AU, which is where the solar wind, produced by the Sun, interacts with the local interstellar medium (Balogh and Fisk, 2001; Zank, 2015). This region consists of the solar wind, termination shock, heliopause, and the heliosheath as seen in Figure 2.3 (Dunzlaff, 2013). The heliosphere is propagating through the interstellar medium at ~ 25 km/s, which forms the heliospheric elliptical shape (Potgieter, 2010). The solar wind region consists of plasma released by the solar corona, creating a magnetic field that forms Archimedean spirals as the Sun rotates (Richardson, 2018). The termination shock is a discontinuity where supersonic solar wind transforms into the subsonic wind, forming the inner heliosheath which is where the pressure reaches equilibrium with the interstellar plasma (Petelski, 1981; Burlaga and Ness, 2016). The heliopause is considered the outer boundary of the heliosphere as it is where the solar wind has no significant influence (Ferreira, 2002; Potgieter, 2010). The outer heliosheath is a region between the heliopause and the bow shock, where the bow shock is the discontinuity that surrounds the heliosphere (Burlaga et al., 2018). The shape of the heliosphere is affected by the solar cycles; during solar minimum, the outer heliosheath becomes smaller, which allows the interstellar medium to have more effect on the inner heliosphere, whereas, during a solar maximum, the outer heliosheath is more prominent, allowing the solar wind to have more influence on the inner heliosphere (Zank and Müller, 2003).

Physical properties of Jupiter	
Age	~ 4.55 Gyr
Mean density	$1.32 \text{ g} \cdot \text{cm}^{-3}$
Distance from the Sun	5.2 AU
Mass (M_J)	$1.89 \times 10^{27} \text{ kg}$
Radius (R_J)	$71492 \pm 4 \text{ km}$
Equatorial rotation period	11.86 years
Mean temperature	$\sim 102 \text{ K}$
Rotation period	9.92 hours

Table 2.1: Summary of key characteristics of Jupiter (Michaux and Company, 1967; Dunzlaff, 2013).

2.3 The Jovian System

Jupiter is the second largest dynamo in the heliosphere, and it produces an abundance of low-energy electrons. The Jovian magnetosphere consists of three regions with different underlying mechanisms.

2.3.1 Planet Jupiter

Jupiter has mainly been observed in-situ by the Pioneer 10, Pioneer 11, Ulysses, and Voyager spacecraft to provide information about the composition, structure, and dynamics of the Jovian system (Bagenal et al., 2006; Rutala et al., 2024). Jupiter is located at 5.2 AU and consists of heavy elements, mainly hydrogen, methane, ammonia, and helium (Bagenal et al., 2006). Jupiter is not a solid surface; therefore, the interior produces a strong magnetic field (Dunzlaff, 2013). The equatorial orbit period of Jupiter around the Sun is 11.86 years, and the rotation period is 9.92 hours (~ 10 hours) (Michaux and Company, 1967; Donovan and Carr, 1969). Pioneer 10 discovered the Jovian magnetosphere on the 4th of December 1973, and ~ 15 moons orbiting Jupiter during the spacecraft flyby; where Io, Europa, Ganymede and Callisto are the largest moons and named Galilean moons as Galileo discovered them (Mead, 1974; Cruikshank and Morrison, 1976; Ferreira, 2002). The Galilean moons influence the Jovian system, as Io affects the current sheet of the Jovian magnetosphere, and charged particles are absorbed by Europa, Callisto, and Ganymede (Connerney et al., 1981; Pensionerov et al., 2019).

Jupiter is the second largest magnetic celestial body in the heliosphere and has been around for ~ 4.55 Gyr. Table 2.1 summarises the key physical characteristics of Jupiter, including its mass, radius, age, and mean distance from the Sun. Jupiter has a mass (M_J) of $1.89 \times 10^{27} \text{ kg}$, which was determined by the gravitational force (measured by Voyager) of the planet influencing the moons around it (Divine, 1971). The equatorial radius of

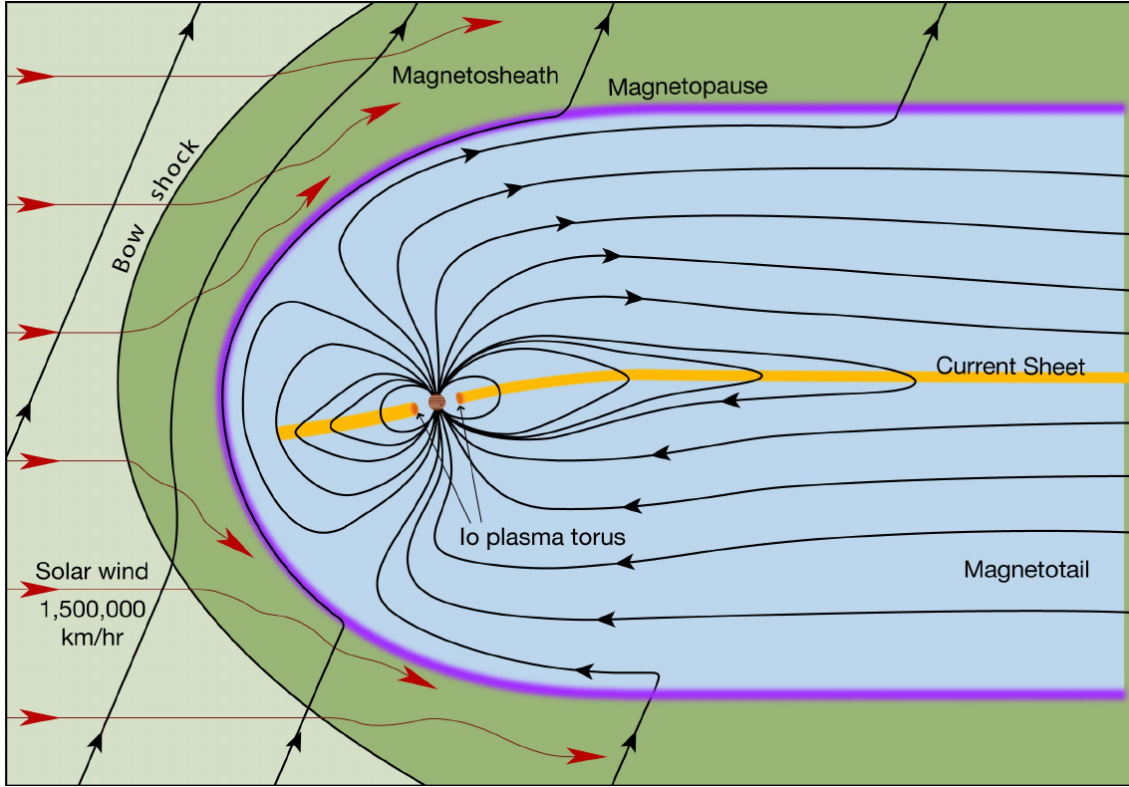


Figure 2.4: Detailed view of the Jovian magnetosphere taken from Dunzlaff (2013). The inner region of the magnetosphere extends until the Io moon (Tomás et al., 2004). The middle magnetosphere contains the current sheet, which is produced from a plasma at Io (Moriguchi et al., 2008). The outer magnetosphere extends to $100 R_J$ and is affected by the solar wind (Morrison and Samz, 1980).

Jupiter (R_J) is 71492 ± 4 km (Seidelmann et al., 2007). The mean temperature of Jupiter is ~ 102 K, although the temperature fluctuates drastically in the core of Jupiter due to the element composition; the temperature affects the element composition of Jupiter (as the elements have different boiling points) giving the characteristic turbulent cloud belts on the surface of the planet (Öpik, 1962).

2.3.2 Jovian magnetosphere

The Jovian magnetosphere is a region that contains a magnetic field between Jupiter and the solar wind; it is the largest planetary magnetosphere and contains plasma with an abundance of sulphur and oxygen ions (Bagenal et al., 2006; Bandyopadhyay et al., 2022). The magnetosphere consists of the inner, middle, and outer regions, which are characterised by the azimuthal equatorial current sheet, auroras, and particle injections; the magnetosphere contains the moons Io, Europa, Ganymede and Callisto that influence the driving dynamics in the magnetosphere (Badman et al., 2015; Nichols et al., 2015).

Flux tubes are created from centrifugal instabilities that produce a plasma that inter-

changes charged particles, which stems from the Io and Ganymede footprints, extends to the magnetotail, and is enclosed in the Jovian magnetosphere (Southwood and Kivelson, 1987; Bagenal et al., 2006; Dumont et al., 2014). The flux tubes form energetic particles in the Jovian plasma, known as injections (Bandyopadhyay et al., 2022). These injections are associated with magnetospheric substorms that correlate with the fast rotation period of Jupiter (See table 2.1 for the Jovian rotation period), where cold plasma convects particles away from the planet; these particles create temporal variations in the outer magnetosphere (Mauk et al., 1997). The hot plasma injections scatter the particles inwards towards the inner magnetosphere, creating Jovian auroras (Dumont et al., 2014).

The magnetosphere consists of three main layers that are seen in Figure 2.4, which will be discussed in this section.

Inner magnetosphere

The inner magnetosphere ranges up until approximately $6 R_J$, which is defined as the orbit of Io (Tomás et al., 2004). A perturbed magnetic field is produced in this region and is located on top of the ionosphere that extends to the orbit of Io (Connerney et al., 1981; Bagenal et al., 2006; Tomás et al., 2004). The Io footprint creates a magnetic flux tube that forms the inner belts, where electron particles propagate along the flux tubes (Connerney et al., 2017; Menietti et al., 2023).

Middle magnetosphere

The middle magnetosphere of Jupiter ranges between $\sim 6 - 60 R_J$, in which Io releases sulphur and oxygen that, when ionised, becomes the current sheet (Moriguchi et al., 2008; Nichols et al., 2015). This region experiences magnetic flux perturbations in the current sheet that correlate with the rotation of Jupiter that was observed by Voyager 1 in 1979 (Connerney et al., 1981). The current sheet creates current density magnetic forces that balance the centrifugal, pressure gradient, and pressure anisotropy forces in the magnetosphere, in which the anisotropic forces spread the current sheet outwards in the equatorial plane (Nichols et al., 2015). The current sheet drags the Jovian magnetic field lines radially outwards, which results in two polarities being experienced near the equatorial region during one Jovian rotation period (~ 10 hrs) (Dunzlaff, 2013). Ganymede, which also has a magnetic field, is located at $\sim 15 R_J$ in the middle magnetosphere, where the current sheet influences the magnetic field of the moon to rotate in the opposite direction to the rotation of Jupiter (called a retrograde rotation) (Bailey, 1971; Connerney et al., 1981; Bagenal et al., 2006).

Outer magnetosphere

The outer magnetosphere extends to $\sim 100 R_J$ and the strong magnetic field of the outer layer is unstable due to the pressure of the solar wind (Morrison and Samz, 1980; Bagenal et al., 2006). The outer part of this region undergoes a bow shock when the Jovian magnetosphere collides with the solar wind, forming the magnetosheath (as seen in Figure 2.4) (Bandyopadhyay et al., 2022). The temporal periodicities are predominantly observed in this region that creates particle injections, which either accelerate particles out of the magnetosphere or scatter them inwards towards the inner magnetosphere (Bagenal et al., 2006).

2.3.3 Jovian electrons

The magnetic flux tubes from Io produce hot and cold plasma injections (refer to section 2.3.2) that contain energetic particles (Thorne, 1982; Nichols et al., 2015). These plasma injections correlate with the Jovian rotation period that produces periodic variation waves in the magnetosphere (Bagenal et al., 2006). The cold plasma injections eject electrons out of the magnetosphere, due to the centrifugal force in the magnetosphere, as electrons have lower density compared to protons (Gopalswamy, 1986; Tao et al., 2011). These electrons have an anisotropic distribution while entering the heliosphere, due to the Jovian rotation period (Woch et al., 2004). These electrons are known as Jovian electrons.

2.4 Jovian events

This section discusses different events that release Jovian electrons into the heliosphere.

2.4.1 First observations

McDonald et al. (1972) observed low energy electrons, with the energy range of $\sim 3 - 12$ MeV, occurring at 1 AU during a solar minimum. Teegarden et al. (1974) discovered an abundance of $\sim 3 - 12$ MeV electrons when Pioneer 10 was ~ 1 AU from the Jovian magnetosphere. Jupiter is considered a constant source of relativistic electrons in the heliosphere. The Jovian electrons are observed to vary every ~ 13 months at 1 AU, which is the synodic period of Jupiter relative to the position of Earth (Chenette et al., 1977).

2.4.2 Pioneer

Pioneer 10 was launched on the 3rd of March 1972 and was the first spacecraft to travel to Jupiter; thereafter Pioneer 11 was launched on the 6th of April 1973 (Soberman et al., 1971; Hall, 1975). Both spacecraft covered a radial distance from the Sun to the outer

heliosphere, where the HMF became weaker further away from the Sun (Ferreira, 2002). The main objectives of the spacecraft were to measure the solar wind, cosmic rays, and large magnetospheres found in the heliosphere (Dunzlaff, 2013). Pioneer 10 and Pioneer 11 were launched in different directions of the heliosphere (Zank et al., 2022). These spacecraft are identical and comprise of similar instruments, such as a magnetometer, plasma analyser, and energetic particle detectors (Hall, 1983; Dunzlaff, 2013; Viso, 2023). The Pioneer spacecraft both observed the acceleration of solar energetic particles, corotating interactive regions, as well as most of the activity in the outer heliosphere (Fisk, 2015). These spacecraft were the first to observe the composition and structure of the Jovian magnetosphere (Connerney, 1993). The Pioneer 10 spacecraft entered the equatorial plane of the Jovian magnetosphere, which observed 10-hour temporal variations that release highly anisotropic electrons with energies between 0.2 – 25 MeV into the heliosphere (Chenette et al., 1974; Ferreira, 2002).

2.4.3 Ulysses

Ulysses was launched on the 6th of October 1990 (Aldhous, 1990). The trajectory of Ulysses differed from previous spacecraft as it was observing the Sun and inner heliosphere from high latitude regions (Marsden and Smith, 1996). The spacecraft consisted of instruments to observe the solar wind, cosmic rays, magnetospheres, and plasma waves (Dunzlaff, 2013). Ulysses was the first spacecraft to observe the Jovian magnetosphere between the ecliptic and polar regions (Wenzel et al., 1992). The high energy telescope (HET) detected anisotropic electrons that were released from the magnetosphere due to temporal variations and bursts in the magnetosphere (Simpson et al., 1992).

2.4.4 Parker solar probe

Launched on the 12th of August 2018, the Parker Solar Probe (PSP) spacecraft explores the inner heliosphere with a trajectory that nears the Sun at each perihelion (as seen in Figure 2.5) (Adhikari et al., 2020). The PSP spacecraft was designed to observe the dynamics and magnetic field, amongst others, of the Sun (Fox et al., 2016). The instruments on board the PSP spacecraft are also used to observe ions and electrons in the solar wind (Case et al., 2020).

2.4.5 Temporal variation

When the Pioneer 10 spacecraft entered the outer Jovian magnetosphere, Chenette et al. (1974) discovered that the solar wind compresses the magnetosphere creating temporal variations where electrons between $\sim 6 - 30$ MeV are released into the heliosphere at ~ 10 hours intervals, which correlates with the rotation rate of Jupiter (Mead, 1974; Connerney et al., 1981; Ferreira, 2002). These periodicities are more prominent at the south pole

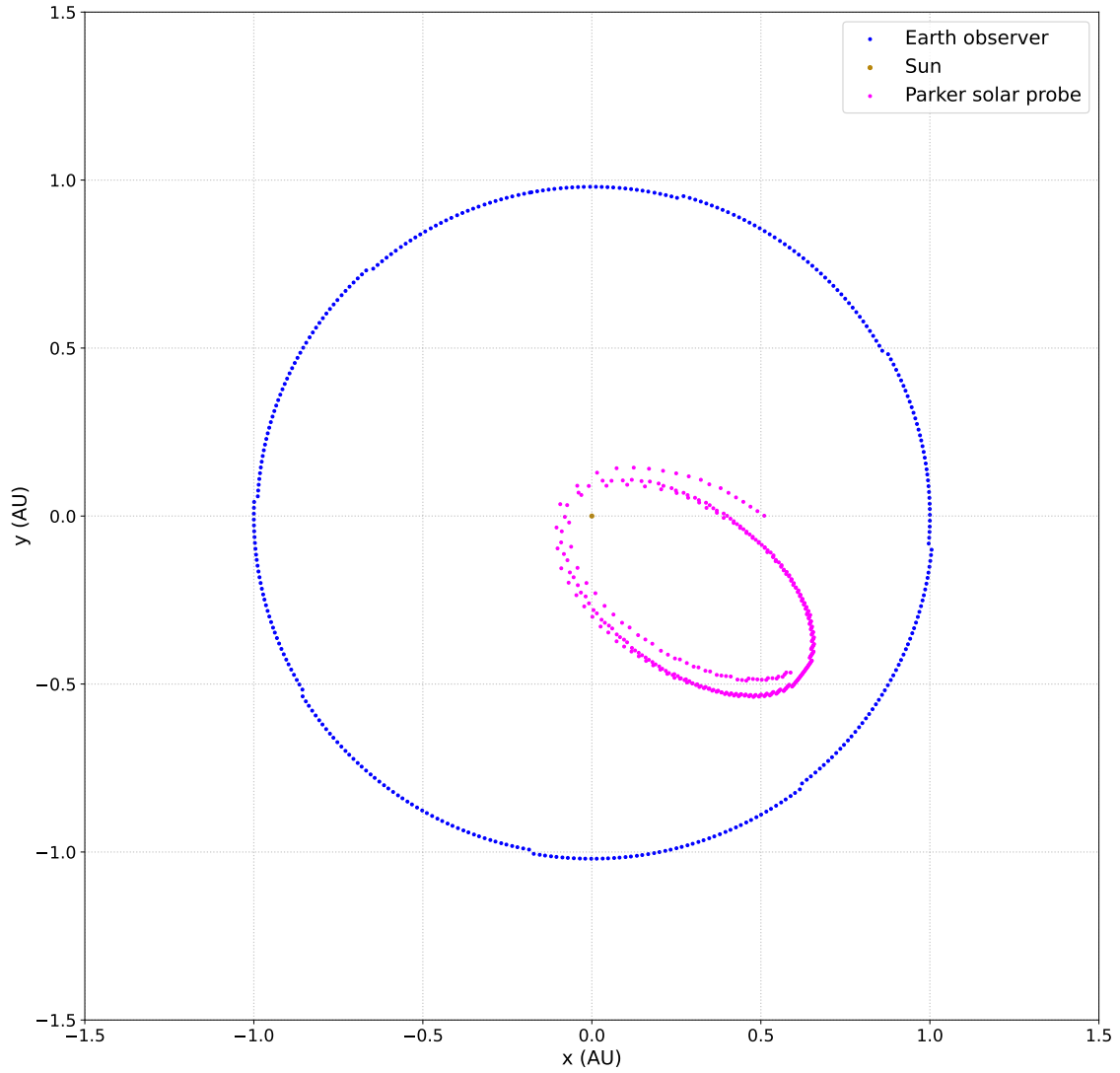


Figure 2.5: Trajectory of the PSP spacecraft around the Sun during 2021.

of Jupiter due to plasma injections in the Jovian magnetosphere (Bagenal et al., 2006; Anagnostopoulos et al., 2023).

2.4.6 Jovian jets

Chenette et al. (1974) describe Jovian electron intensity bursts (also known as Jovian jets) as being more prominent in the outer regions of the Jovian magnetosphere with a significant anisotropic distribution of Jovian electrons observed along well-connected HMF lines between Jupiter and the Sun. These bursts are formed from flux tubes in the magnetosphere, which increases the electron intensity released into the heliosphere (Ferrando et al., 1993). These bursts occur spontaneously compared to the other temporal periodicity (Dunzlaff, 2013).

2.5 Conclusion

This chapter introduced the origin of the solar wind and the HMF lines along which particles propagate throughout the heliosphere. Thereafter, the dynamics of the Jovian magnetosphere were discussed. Jovian electrons are observed to vary in intensity at 1 AU every 13 months due to changing levels of magnetic connectivity. The Jovian magnetosphere releases electrons into the heliosphere that propagate along HMF lines. These electrons are released via events in the Jovian magnetosphere, showing both a well-defined 10-hour periodicity, as well as spontaneous burst events.

Chapter 3

Model

3.1 Introduction

The Strauss and Fichtner (2015) focused transport model is used in this work to simulate anisotropic propagation of Jovian electrons. This chapter focuses on the physical processes included in the two-dimensional focused transport model, some of its numerical aspects, and the optimization of the model.

3.2 The focused transport model

Jupiter is assumed to be a constant source of electrons in the inner heliosphere that has an energy range of $\sim 4 - 30$ MeV (Ferreira, 2002; Dunzlaff et al., 2010). In this section, the focused transport model will be discussed as well as the outputs of the model when the Jovian electron intensity at Jupiter is assumed to be constant.

3.2.1 The focused transport equation

The two-dimensional focused transport equation is given by

$$\underbrace{\frac{\partial f}{\partial t}}_A + \underbrace{\mu \nu \frac{\partial f}{\partial z}}_B + \underbrace{\frac{v}{2L} (1 - \mu^2) \frac{\partial f}{\partial \mu}}_C = \underbrace{\frac{\partial}{\partial \mu} \left(D_{\mu\mu} \frac{\partial f}{\partial \mu} \right)}_D + \underbrace{\nabla \cdot \left(\mathbf{D}_{\perp}^{(x)} \cdot \nabla f \right)}_E, \quad (3.1)$$

and determines how particles are transported in the heliospheric magnetic field (HMF) (Strauss et al., 2017). Here A is the time dependent change of the distribution function f , and B describes the change in the guiding centre position around the magnetic field which drifts parallel to the HMF where μ is the cosine of the particle pitch angle (Strauss and Fichtner, 2015; Bian and Li, 2022). C is the pitch-cosine angle change due to particles moving to different regions in the HMF, which uses the mirroring condition (see van den

Berg et al. (2020) for the mirroring conditions of the focused transport equation) with the focusing length (L) being

$$L = \frac{1}{\Delta \cdot \hat{b}}, \quad (3.2)$$

where $\hat{b}$ is the unit vector along the HMF (Strauss and Fichtner, 2015; van den Berg, 2019). D is the time rate change of the pitch-angle dependence due to collisions, where $D_{\mu\mu}$ is the pitch-angle diffusion coefficient (Chen, 1984). E contains the perpendicular diffusion component $D_{\perp}^{(x)}$ (Strauss et al., 2017).

3.2.2 Numerical solution

The main numerical methods for solving equation 3.1 are the fractional-step and the split-step (see Strauss and Fichtner (2015) and Heita (2019)), which are splitting the partial differential equation along the respective coordinates with a model that assumes constant solar wind and a Parker HMF. The transport quantities in the model are assumed to be independent of ϕ as the Parker HMF (equation 2.1) is independent of ϕ (Strauss and Fichtner, 2015).

The standard parallel isotropic mean free path in D from equation 3.1,

$$\lambda_{\parallel} = \frac{3v}{8} \int_{-1}^1 d\mu \frac{(1 - \mu^2)^2}{D_{\mu\mu}(\mu)}, \quad (3.3)$$

connects the scattering amplitude ($D_{\mu\mu,0}$) and the parallel mean free path ($\lambda_{\parallel}$) (van den Berg et al., 2020; Lang et al., 2024). The pitch-cosine diffusion coefficient in equation 3.1 is assumed to be,

$$D_{\mu\mu} = D_{\mu\mu,0} (1 - \mu^2) (|\mu|^{q-1} + H), \quad (3.4)$$

in the model with $q = 1.67$, $H = 0.05$, and $D_{\mu\mu,0}$ can be calculated from equation 3.3 (Strauss and Fichtner, 2015). In this model, $\lambda_{\parallel} = \frac{\lambda_0}{2} \left(1 + \frac{r}{r_0}\right)$, where r is the radial distance and r_0 is the radial position at 1 astronomical unit (AU), and then the corresponding $D_{\mu\mu,0}$ is calculated.

The focusing coefficient (η) is given as,

$$\eta = v \left(\frac{1 - \mu^2}{2L} \right), \quad (3.5)$$

where L is taken to be,

$$L = \frac{r (v_{\text{sw}}^2 + \omega_{\odot}^2 r^2 \sin^2 \theta)^{3/2}}{v_{\text{sw}} (2v_{\text{sw}}^2 + \omega_{\odot}^2 r^2 \sin^2 \theta)}, \quad (3.6)$$

for a Parker HMF (Heita, 2019).

This work uses the field line random walk pitch-angle diffusion coefficient ($D_{\perp}(\mu)$) in E from equation 3.1, where $D_{\perp}(\mu) = \frac{3v}{2} \lambda_{\perp} |\mu|$, and v is the speed. The perpendicular isotropic mean free path

$$\lambda_{\perp} = \frac{3}{2v} \int_{-1}^1 d\mu D_{\perp}(\mu), \quad (3.7)$$

where it is assumed that $\lambda_{\perp} = \chi \lambda_{\parallel}$ with χ as a constant (Strauss and Fichtner, 2015; van den Berg et al., 2021).

The omnidirectional intensity (j) can be obtained from A in equation 3.1,

$$j = \frac{1}{2} \int_{-1}^1 f(r, \phi, t) d\mu, \quad (3.8)$$

and the first order of anisotropy,

$$A(r, \phi, t) = 3 \frac{\int_{-1}^1 \mu f d\mu}{\int_{-1}^1 f d\mu}, \quad (3.9)$$

(Strauss et al., 2017).

As Jupiter is assumed to be a source of electrons in the heliosphere, the following function is specified at the position of Jupiter,

$$f(r, \phi, \mu, t) = g(t) \cdot \delta(\phi - \phi_0) \cdot \delta(r - r_0), \quad (3.10)$$

and is added to the model to inject pseudo particles with a boundary condition of Jupiter located at $r_0 = 5.04$ AU at $\phi_0 = \frac{323}{180}\pi$. The time independent boundary conditions $g(t) = 100000$ is assumed.

3.2.3 Model outputs

Figure 3.1 demonstrates Jovian electron transport in the heliosphere, where the deep red represents higher Jovian electron intensities. The solid white line represents when Jupiter is well-connected with the Sun, whereas the dashed line is another HMF line from the Sun. The virtual observers, labelled 1 to 12, are distributed in this specific manner as some of them are well-connected between the Sun and Jupiter, whereas some are not well-connected.

Figure 3.2 demonstrates the time profile of the Jovian electrons observed from various positions and coordinates in the heliosphere which appear to fully converge within 100 hours to a steady-state solution.

3.3 Optimization of Model

Parallel computing is widely used today as it increases performance and decreases the runtime; therefore performance optimization is crucial (Brunst et al., 2001). The model used a FORTRAN script to simulate the two-dimensional focused transport. FORTRAN does not have built-in parallel computing although it does have built-in compilation flags, which optimize and control the single instruction/multiple data (SIMD) in the code by optimizing the size, speed, and efficiency of the code (which can be seen in table 3.2) (Celmaster, 1996; Jagasia and Wittig, 2009). As parallel computing increases performance speed, OpenMP uses the same source code script,

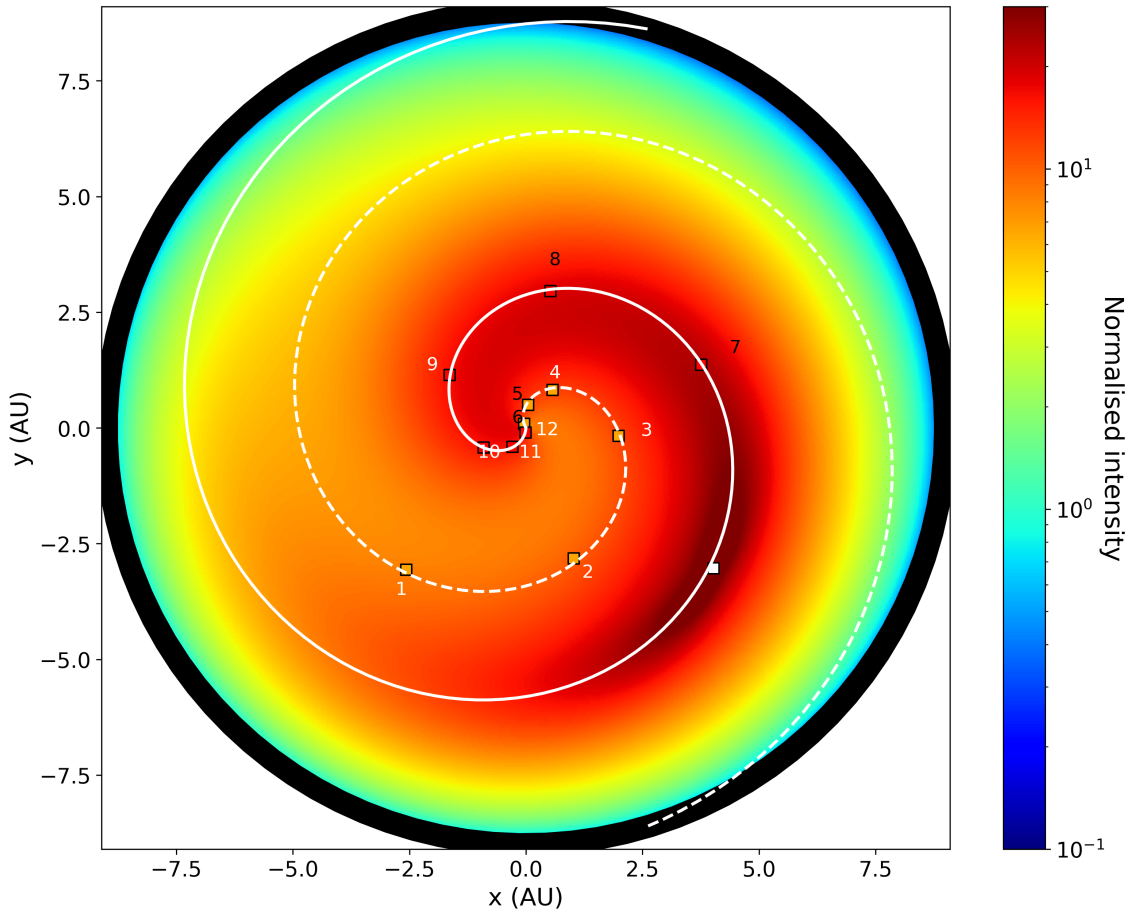


Figure 3.1: Modelled Jovian electron intensities in the equatorial plane of the heliosphere. The white square represents Jupiter, whereas the lines represent HMF lines. The numbered squares are virtual observers in the model.

```
use omp_lib
CALL CPU_TIME ( time_begin )
CALL omp_set_num_threads(13)
!$omp parallel do private(i,j,left_lim,right_lim,limiter)
```

to create parallel regions so that it is possible to run a FORTRAN script on multiple threads running in parallel (Hermanns, 2002; Kiessling, 2009).

In this section, the cluster that was used to run the focused transport FORTRAN model was the Ryzen 5950X PC, which has 16 cores (32 threads) and 128 GB of RAM. The optimal threads in the cluster will be used to yield the best runtime for the model. The runtime for varying threads will be compared to the runtime when the parameters (such as the grid points of ϕ , r , and μ) in the focused transport equation are altered.

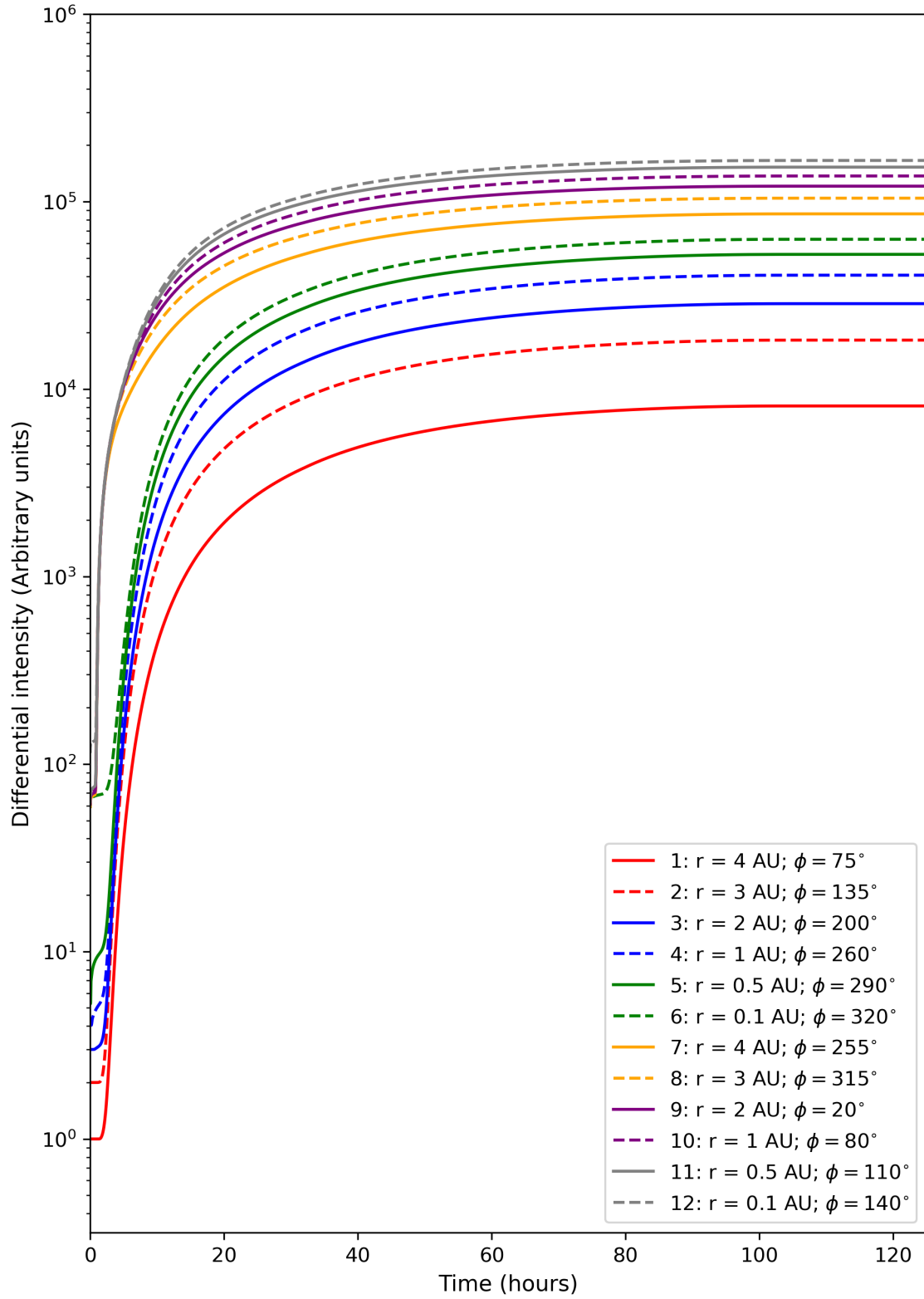


Figure 3.2: The time profile of the simulated Jovian electron intensity for coefficients of $\lambda_{\parallel} = 0.3$ and $\lambda_{\perp} = 0.025\lambda_{\parallel}$. The solution appears to fully converge to a steady-state solution within 100 hours, i.e. the intensities at all positions converge to constant values.

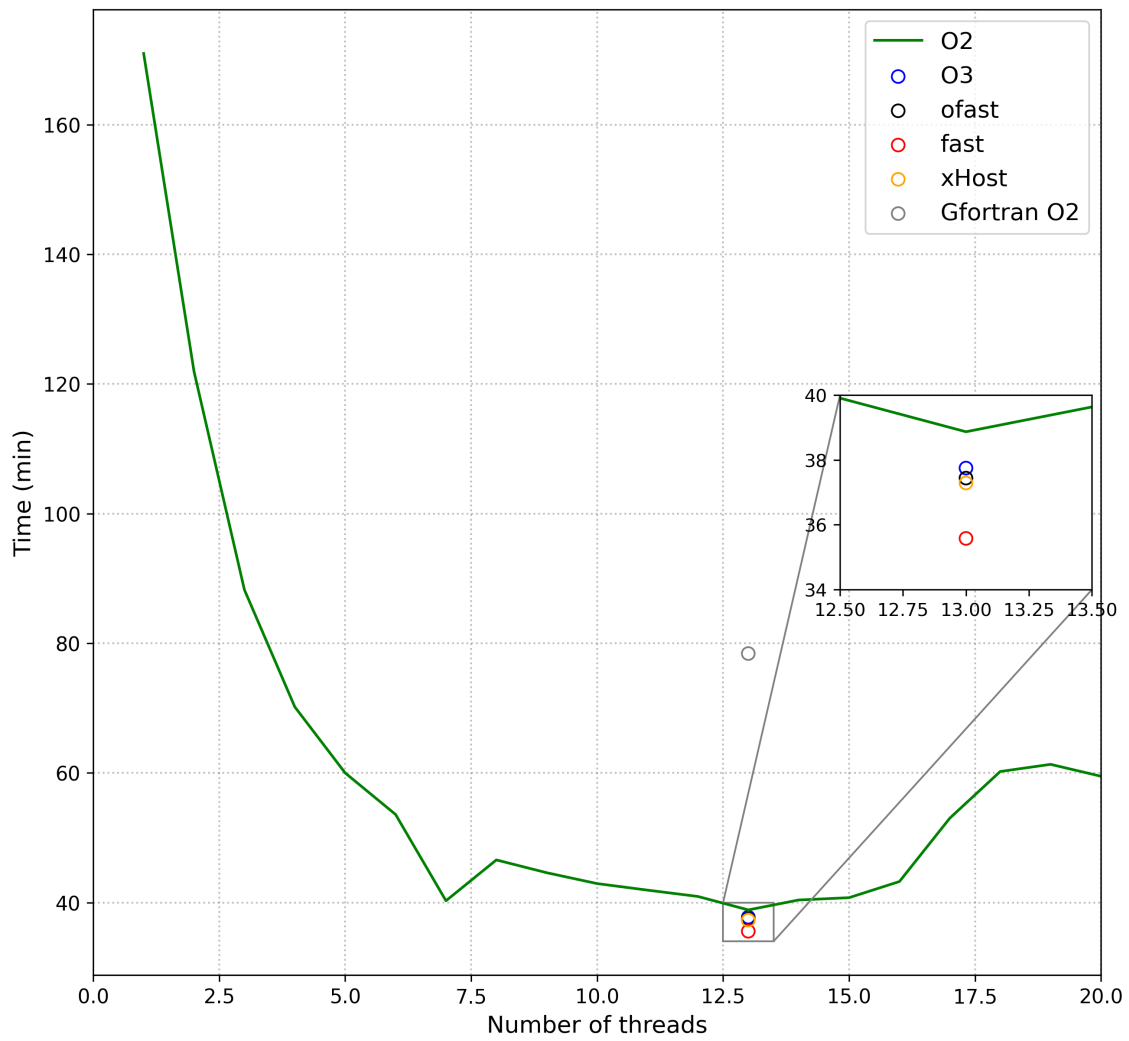


Figure 3.3: Runtimes for 20 threads for the Intel -O2 flag. The runtime quickly decreases until the 6th thread. The runtime then increases until the 8th thread whereafter it has decreased until the 13th thread, which is the lowest runtime. After that, the runtimes increase again.

Table 3.1: Intel FORTRAN versus GFORTRAN flags

Intel FORTRAN	
Flag	Discription
-O2	Is the default flag that maximizes speed as well as uses optimization which includes vectorization (the process of converting an algorithm from operating on a single value to operating multiple values at once)
-O3	Uses the same optimization as -O2 except adds more loop and memory optimizations, which improves the memory and execution speed of the computer
-Ofast	Uses an optimized -O3 with instructions to inform the compiler to use the instruction set architecture (ISA) which controls the central processing unit (CPU)
-xHost	Uses a SIMD (Single Instruction/Multiple Data) instruction based on the CPU running the code
-fast	Uses a combination of -Ofast and -xHost
GFORTRAN	
Flag	Discription
-O0	Is the default flag that debugs the code
-O1	Is optimized, but uses has more run time and uses more memory
-O2	Optimizes run time and increases the performance of the code
-O3	Uses the same optimization as -O2 with except adding more loop and memory optimizations

Table 3.2: Difference between Intel FORTRAN and GFORTRAN compilation flags (Jagasia and Wittig, 2009; Pilla, 2018).

3.3.1 The optimal number of threads

The number of numerical grid points in the ϕ dimension is $M = 100$, the number of numerical grid points r is $N = 300$, and the number of numerical grid points in μ is $NK = 49$ in the focused transport model. Changing the number of threads in the cluster between 1 – 20 and comparing the runtime of each simulation to determine the number of threads; which gives the optimal runtime of the simulation. The solid green line in Figure 3.3 shows the runtime for the Intel -O2 flag, which is the least optimized flag that is used as a baseline for the best-optimized compilation flag (see table 3.2). The runtime decreases until the 6th thread and then slowly increases until the 8th thread, after which it decreases again, giving the minimum runtime at the 13th thread. The increase after the 13th thread could be due to the high-level synchronization points in OPENMP that can

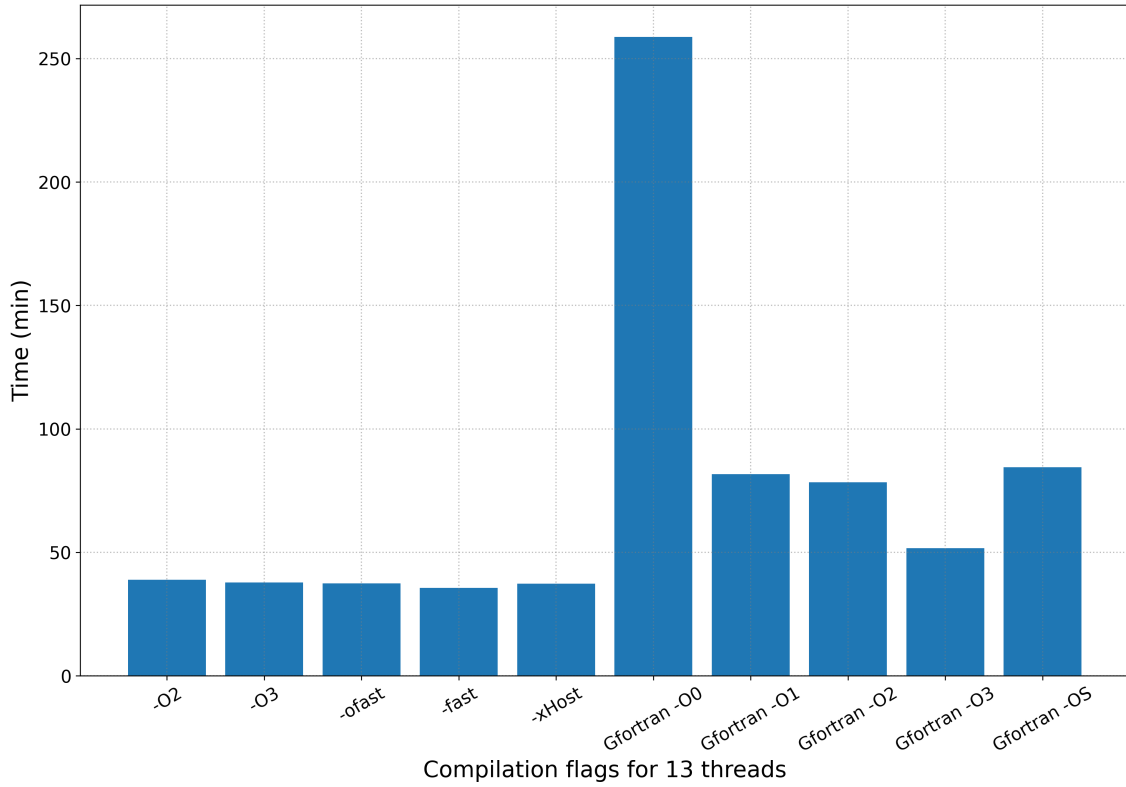


Figure 3.4: The runtime is shorter for the Intel FORTRAN than for the GFORTRAN compiler; the GFORTRAN -O0 flag has the longest runtime, whereas the Intel -fast flag has the smallest runtime for 13 threads.

lead to the same memory location being accessed, therefore decreasing runtime (Atzeni, 2017). The 13th thread was compared to the -O3, -ofast, -fast, and -xhost flags for Intel FORTRAN, as well as the -O2 flag for GFROTRAN. The optimal runtime happens at 13 threads using the -fast compilation flag for Intel FORTRAN.

3.3.2 Intel FORTRAN compared to GFORTRAN

Figure 3.4 demonstrates the different runtimes for all the compilation flags in table 3.2. The best compilation flag for the optimal runtime in Intel FORTRAN is the -fast flag, as it has the optimal speed efficiency of the code. Although most of the Intel FORTRAN compilation flags were more optimal than the GFORTRAN compilation flags which are demonstrated in Figure 3.4. The least optimized compilation flag observed for GFORTRAN is the default optimization flag, whereas the optimal flag is the -O3 flag.

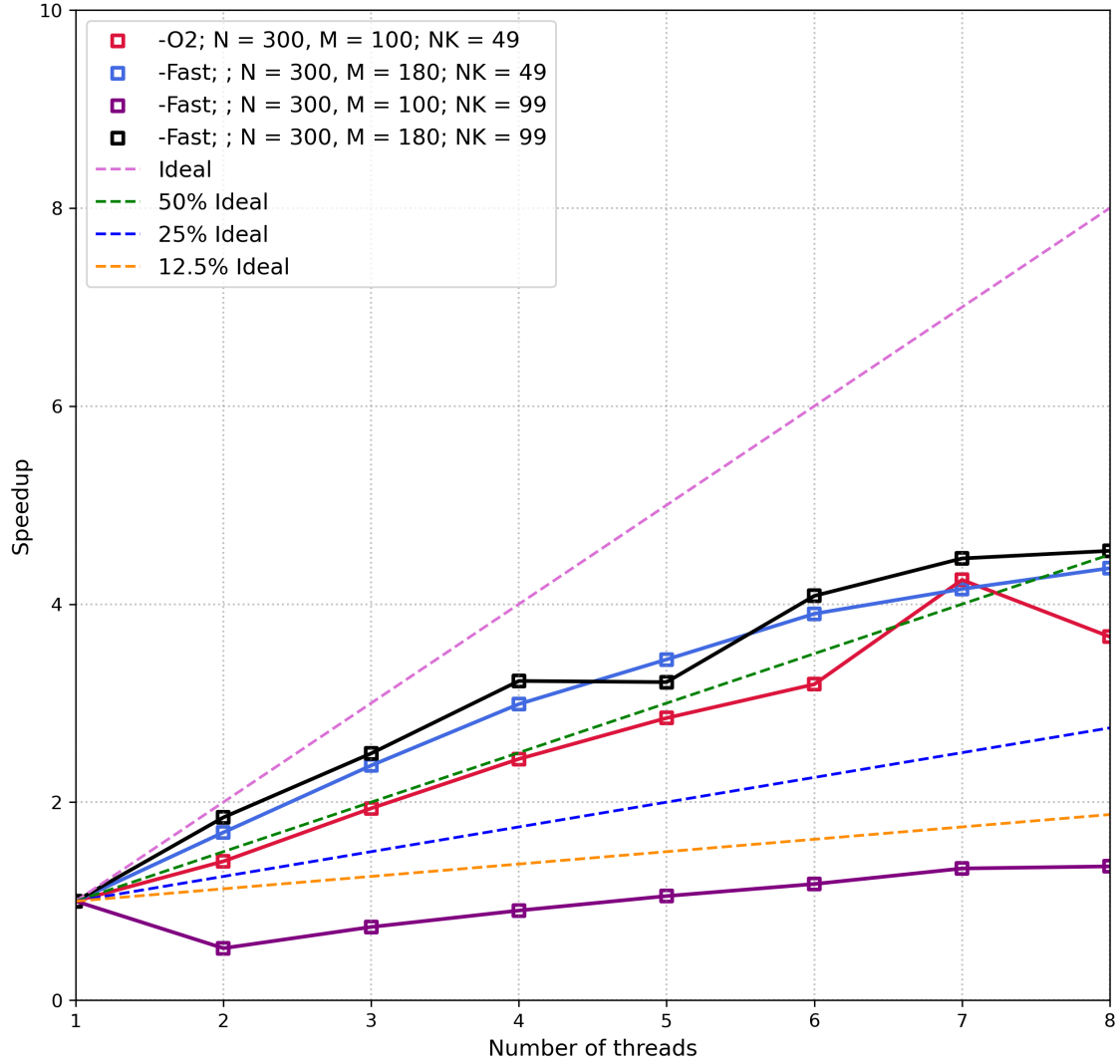


Figure 3.5: M is the number of numerical grid points in the ϕ dimension, N is the number of numerical grid points in the r dimension, and NK is the number of numerical grid points in μ in the focused transport model from section 3.2. The dashed lines represent the ideal relative speedup percentage for 8 threads. The purple, green, blue, and orange dash lines represent the 100%, 50%, 25%, and 12.5% ideal speedup respectively.

3.3.3 Speedup

Relative speedup (S) is the ratio of the elapsed runtime for different amounts of core or threads available in the cluster,

$$S(i) = \frac{T_1}{T_i}, \quad (3.11)$$

where T_1 is the runtime using one thread, and i is the number of threads (where $i \neq 0$) (Eager et al., 1989). Equation 3.11 is often referred to as Gustafson's law as it was first proposed by Gustafson (1988). Relative speedup was assumed to be fixed-time in parallel computing instead of previous assumptions like fixed-sized, where the ideal speedup is when the speedup and the runtime ratio is 1 : 1 (Sun and Ni, 1990). The dashed purple line in Figure 3.5 represents the ideal relative speedup for 8 threads. The green, blue, and orange dash lines represent the 50%, 25%, and 12.5% ideal speedup respectively. The red solid line in Figure 3.5 has the same grid points as in section 3.3.1, which was compiled using the -O2 compilation flag. The rest of the speedup calculation in Figure 3.5 uses the -fast compilation flag (which is more optimized as seen in table 3.2). The blue solid line demonstrates the speedup when M is changed from 100 grid points to 180 grid points, which is above 50% ideal speedup. The purple solid line shows the speedup when NK is changed to higher grid point values, where the speedup is below the 25% ideal speedup. The black solid line has the optimal speedup and occurs when both M and NK grid points are increased, which in Figure 3.5 is observed to be above the blue solid line. However, it dips below the blue line at 5 threads; this could be the same decrease observed in Figure 3.3 as a different optimization flag is used.

3.4 Conclusion

The model solves the two-dimensional focused transport equation which assumes Jupiter to be a constant source of electrons in the heliosphere. The time taken for the model to reach a steady state was determined to be ~ 100 hrs. The model was used to simulate how Jovian electron intensities change in the equatorial plane of the heliosphere.

Optimization for parallel computing is crucial as it increases the performance as well as determines the optimal runtime (Brunst et al., 2001). Compilation flags are built into FORTRAN that control the SIMD in the code. Different numbers of threads were used to determine what was optimal to run the model. Observing the runtimes of various compilation flags from both Intel FORTRAN and GFORTRAN, it was determined that the -fast compilation flag from Intel FORTRAN was the most optimal. The grid points for r , ϕ , and μ were increased to determine how more grid points affected the speedup of the model.

Chapter 4

Jovian electrons in the inner heliosphere

4.1 Introduction

Jupiter’s magnetosphere was shown to be a quasi-constant source of electrons in the inner heliosphere that have an energy range of $\sim 4 - 30$ MeV (Ferreira, 2002; Dunzlaff et al., 2010). Recently, Jovian electrons were measured by instruments on the Parker Solar Probe spacecraft (PSP), which captured Jovian electron intensities within 0.5 astronomical units (AU) of the Sun (Mitchell et al., 2022). In this chapter, observed intensities of Jovian electrons from the PSP spacecraft will be used to yield the best-fitting mean free paths when compared to simulation results from the two-dimensional Strauss and Fichtner (2015) focused transport model. The mean free path values obtained in this chapter will be compared to various mean free paths from different sources as well as to the theoretical estimates. The best-fitting mean free paths will be used to simulate how Jovian electron intensities propagate through the inner heliosphere.

4.2 Observations at Parker Solar Probe

In Figure 4.1, the first four panels show the position for both the PSP spacecraft and Jupiter as obtained from NASA’s heliocentric trajectories website ¹ during 2021. The last panel shows the averaged energetic particles from the instrument for high energy (EPI-HI)/ High energy telescope (HET) electrons. These electrons are between the energy range of $0.9 - 5.7$ MeV as measured by the PSP spacecraft (Mitchell et al., 2022). The EPI-HI is an instrument on the PSP containing three telescopes that respectively measure the spectra, composition, and angular distributions of higher energy particles in the inner heliosphere (McComas et al., 2016). The vertical grey areas in Figure 4.1 are when the

¹<https://omniweb.gsfc.nasa.gov/coho/helios/heli.html>

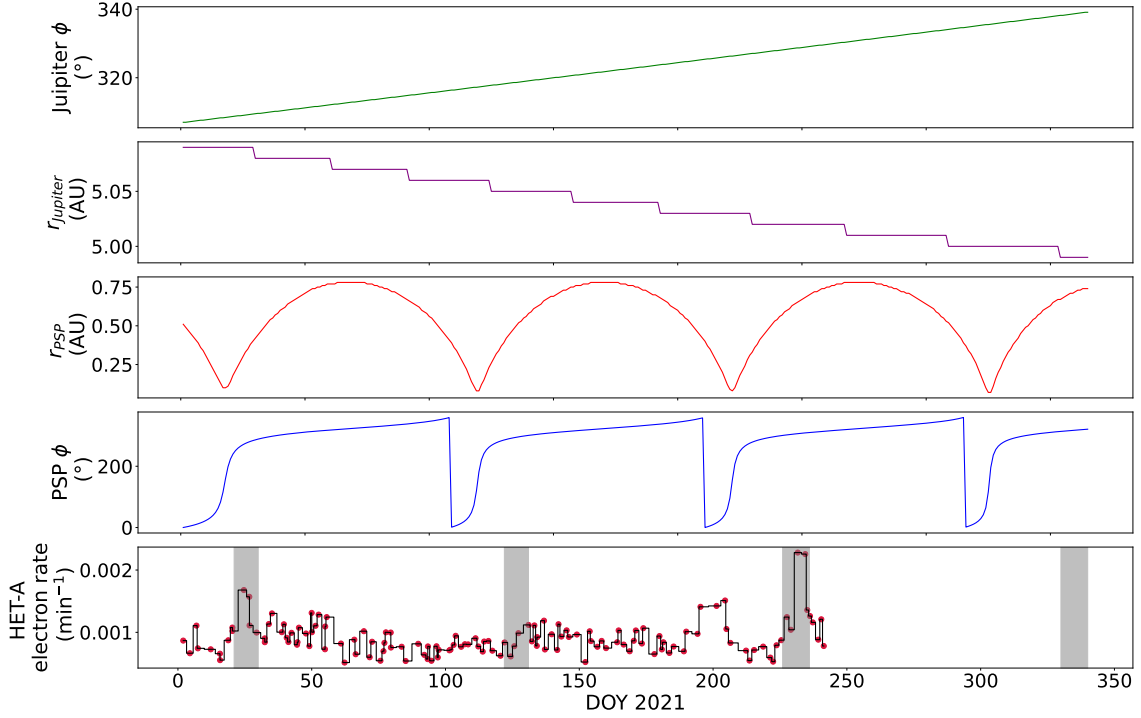


Figure 4.1: The first four panels are the coordinates and position of the PSP spacecraft and Jupiter during 2021. The last panel is the HET-A electron count rate from Mitchell et al. (2022) observed by PSP during 2021. The electron count rate is only consistent for a third of 2021, the rest of the data are sparse, making fitting difficult; subsequently the remainder of 2021 is not plotted. The shaded areas represent the times of good HMF connectivity between the PSP spacecraft and Jupiter during 2021.

PSP spacecraft and Jupiter are magnetically well connected. The first (between 21-30 day of year (DOY)) and third (between 226-236 DOY) magnetic connections show an increase in electrons, and is consistent with the presence of Jovian electrons in the inner heliosphere. The second (between 122-131 DOY) magnetic connection shows a decrease in electrons. The decrease in electrons could be from the solar winds changing (as shown in Figure 2.1) or from co-rotating interacting regions (CIRs).

4.3 The mean free paths

The EPI-HI/HET on the PSP spacecraft measured electrons between the energy range $\sim 0.5 - 6$ MeV. In the model, the geometric mean ($\bar{X}_{geom}$),

$$\bar{X}_{geom} = \sqrt[n]{x_1 x_2 \dots x_n} , \quad (4.1)$$

of the energy channel, $\bar{X}_{geom}$ is ~ 1.7 MeV, is used in the numerical model as it provides a suitable average for particle distributions that usually follow a power law distribution (Mitchell et al., 2022).

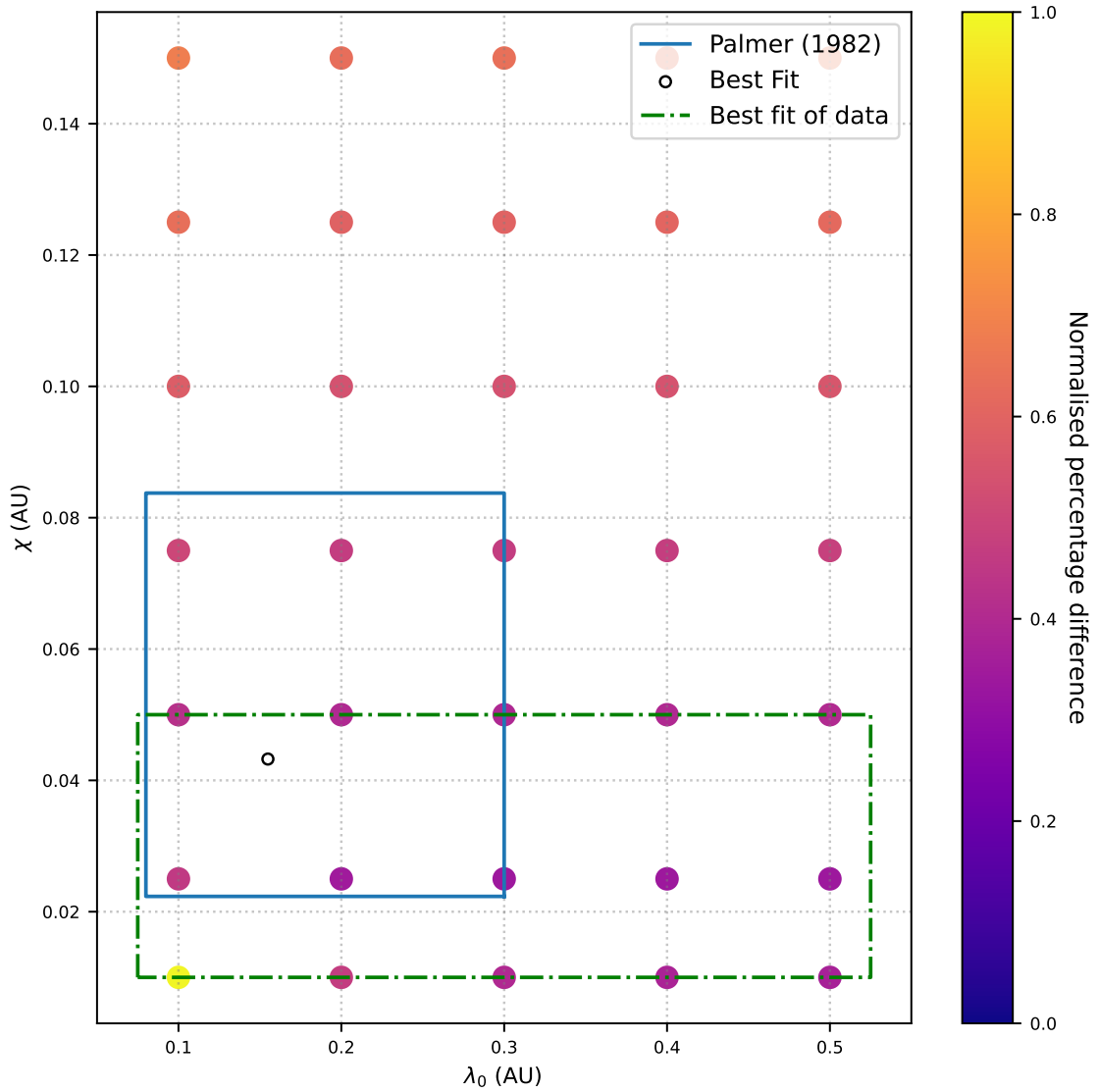


Figure 4.2: Demonstrates the comparison between the simulated 1.7 MeV Jovian electron intensities and the HET-A electron count rate mean to determine the best-fit coefficients, $\lambda_{\parallel}$ and $\lambda_{\perp}$. The blue solid line represents the Palmer (1982) consensus range, and the green dashed line represents the range of best-fitting values. The black annulus demonstrates the coefficients that are assumed for the best-fit to compare to the measurement.

The heliospheric magnetic field (HMF) parallel ($\lambda_{\parallel}$) and perpendicular ($\lambda_{\perp}$) mean free paths,

$$\lambda_{\parallel} = \frac{\lambda_0}{2} \left(1 + \frac{r}{r_0} \right) \quad (4.2)$$

and,

$$\lambda_{\perp} = \chi \lambda_{\parallel} , \quad (4.3)$$

where λ_0 and χ are constants, r is the radial position, and r_0 is the radial position at 1 AU are used in the focused transport model to simulate different Jovian electron intensities that can be compared to the EPI-HI/HET intensities observed by PSP to determine the best-fitting coefficients for the model (Strauss et al., 2013).

Using equation 4.2 and 4.3 in the model with constant values between 0.1 – 0.5 AU for λ_0 , and χ varying between 0.01 – 0.15 for each λ_0 variable to determine the best-fitting coefficients for the Jovian electron intensities. When these intensities are compared to PSP intensities, as quantified by the percentage deviation (Δ),

$$\Delta = \sum_{i=0}^N \frac{\left(\frac{x_i}{\langle x \rangle} - \frac{y_i}{\langle y \rangle} \right)^2}{\frac{x_i}{\langle x \rangle}}, \quad (4.4)$$

with

$$\langle x \rangle = \frac{1}{N} \sum_{i=1}^N x_i, \quad (4.5)$$

where x denotes the intensity of the model, y denotes the PSP intensity, N is the number of data-points, and the $\langle x \rangle$ resembles the mean of the indicated denotations. Equation 4.4 was used to determine the variation between the model and PSP intensities for all the simulated variables. These values were then divided by the highest percentage deviation value to obtain the normalised percentage difference as is seen in Figure 4.2. The best-fitting value for the mean free paths is when Δ is small, which is indicated in Figure 4.2 by the green dashed line.

The optimal normalised percentage difference of the intensities was observed to occur when χ is between 0.01 – 0.05 for all λ_0 values between 0.05 – 0.1 AU. Palmer (1982) provided a baseline for mean free path values by comparing various measurements and theories for cosmic rays, referred to as the Palmer consensus range. The Palmer consensus range was added to give optimal theoretical values for λ_0 and χ of the normalised percentage difference of the Jovian electron intensities.

4.4 Transport of the Jovian electrons in the inner heliosphere

The best-fit range of values from Figure 4.2 was calculated at 1 AU using equations 4.2 and 4.3, where $r = 1$ AU, to give the $\lambda_{\parallel}$ and $\lambda_{\perp}$ mean free paths at Earth. The energy was converted to rigidity (P),

$$P = \frac{A}{Z} \sqrt{T^2 + 2TE_0}, \quad (4.6)$$

where A is the mass number, Z is the atomic number (for electrons this is $A = Z = 1$), T is the kinetic energy, and $E_0 = m_0c^2$ is the rest energy (Moraal, 2013). Most mean free path studies were done in terms of rigidity, therefore converting the energy to rigidity made it easier to compare with the previous estimated mean free path at Earth.

The range of best-fitting mean free paths at 1 AU were compared to the mean free paths of various sources as a function of rigidity which is seen in Figure 4.3 shown as the solid red line for $\lambda_{\parallel}$, the solid grey line for $\lambda_{\perp}$, and the solid purple line for χ . The $\lambda_{\parallel}$ values were compared to values at 1 AU from Bieber et al. (1994), Bieber et al. (2002), Dröge

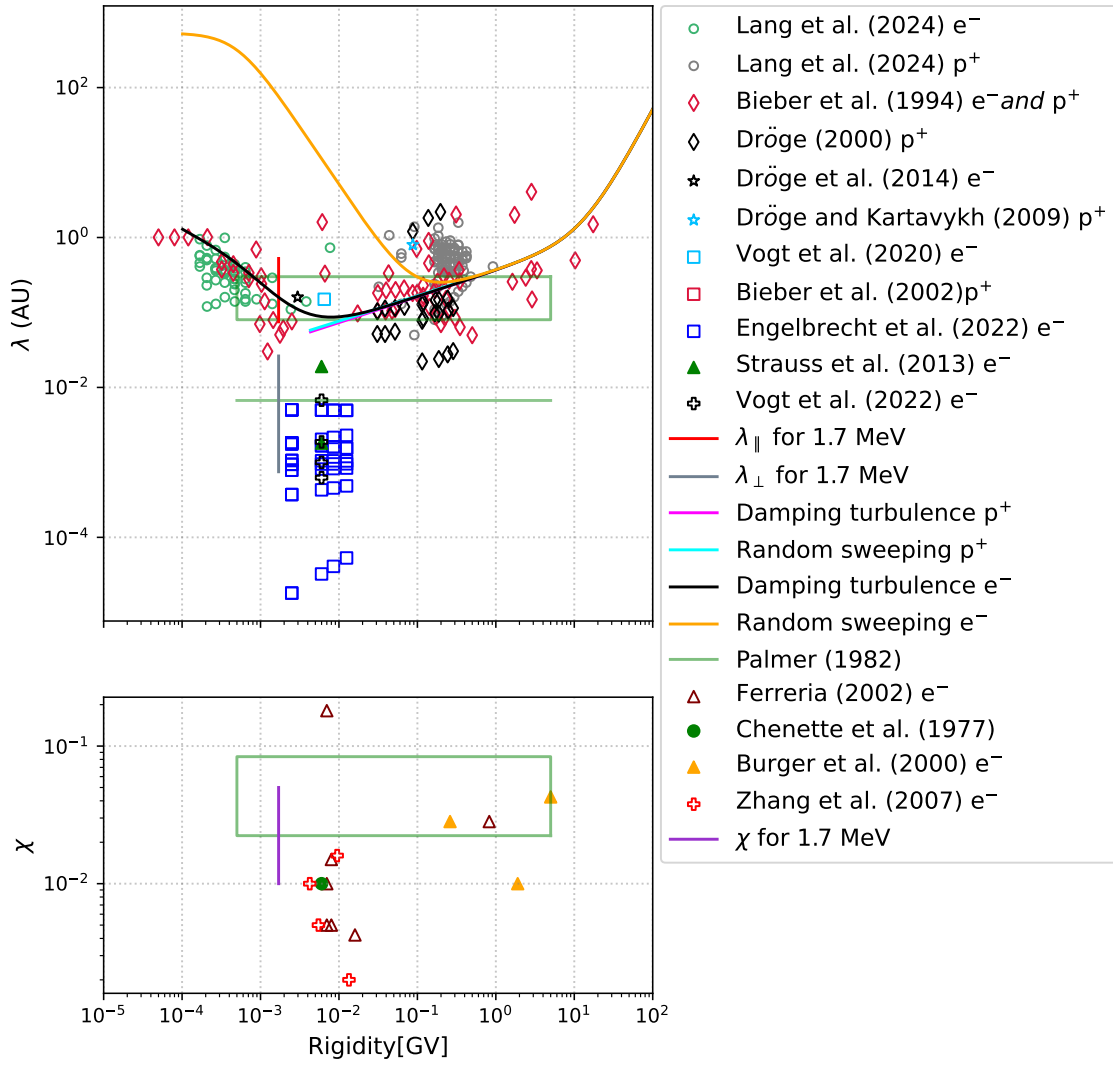


Figure 4.3: Comparison of various sources' mean free paths of both electrons and protons at 1 AU, as a function of rigidity. The top panel contains both the best-fitting values for $\lambda_{\parallel}$ (which is represented by the red solid line) and $\lambda_{\perp}$ (represented by the grey solid line) values. The bottom panel contains the best-fitting χ values (represented by the purple solid line). These values were compared to the Palmer (1982) consensus range (represented by the solid green line), as well as the damping turbulence (which is represented by the black solid line for electrons and the pink solid line for protons) and random sweeping (represented by the orange solid line for electrons and the light blue solid line for protons) theoretical estimations.

(2000), Dröge and Kartavykh (2009), Dröge et al. (2014), Vogt et al. (2020), and Lang et al. (2024). As there is a large spread in $\lambda_{\parallel}$ values at 1 AU, it does not determine if the simulated best-fit values are optimal. The best-fit simulated values are consistent with $\lambda_{\parallel}$ values as seen in Figure 4.3, as the best-fitting simulated values are among the mean free paths from previous studies. The $\lambda_{\perp}$ values were compared to the mean free paths taken from Strauss et al. (2013), Vogt et al. (2020), and Engelbrecht et al. (2022). The best-fit simulated values for $\lambda_{\perp}$ are consistent with the previous estimated mean free paths. The

best-fit of χ from Figure 4.2 is compared to previous estimates at 1 AU, such as Chenette et al. (1977), Burger et al. (2000), Ferreira (2002), and Zhang et al. (2007). The range of best-fitting χ values was determined from Figure 4.2 where the normalised percentage difference was small; a trend was observed that the majority of the range of best-fitting χ values were between 0.01 – 0.05 for all λ_0 values.

Teufel and Schlickeiser (2002) determined the $\lambda_{\parallel}$ mean free path approximations for realistic Kolmogorov-type slab turbulence present in the HMF,

$$\lambda_{\parallel} = \frac{3sR_L^2 k_{min}}{\pi(s-1)} \left(\frac{B_0}{\delta B_{slab}} \right)^2 \left[\frac{1}{4} + \frac{2}{(2-s)(4-s)} \frac{1}{R^s} + \frac{\kappa_{DT/RS}}{Q^{p-s}R^s} \right]; \quad (4.7)$$

$$\kappa_{DT} = {}_2F_1 \left(1; \frac{1}{p-1}; \frac{p}{p-1}; -\frac{a}{f_1 Q} \right) \frac{a}{f_1}, \quad (4.8)$$

$$\kappa_{RS} = \left(\frac{\sqrt{\pi}}{\Gamma(p/2)} + \frac{1}{p-2} \right) \left(\frac{a}{2} \right)^{p-2}, \quad (4.9)$$

referred to as damping turbulence (DT) and random sweeping turbulence (RS) models, where

$$f_1 = \frac{2(p-s)}{\pi(p-2)(2-s)}; \quad a = \frac{v}{\alpha_D V_A}; \quad R = R_L k_{min}; \quad Q = R_L k_d; \quad v = \frac{Pc}{T + E_0}; \quad R_L = \frac{P}{B_0 c}.$$

Here R_L is the Larmor radius, c is the speed of light, B_0 is the background magnetic field strength, k_{min} is the inertial range onset wavenumber, k_d is the dissipation range onset wavenumber, s is the initial spectral index, p is the dissipation spectral index, v the speed of the particle, V_A is the Alfvén speed, Γ is the standard Gamma function, and ${}_2F_1$ is the Gauss hyper-geometric function (Engelbrecht and Burger, 2013; Engelbrecht et al., 2022; Lang et al., 2024). The damping turbulence and random sweeping turbulence models were added to compare if the simulated mean free paths corresponded to theoretical mean free path values at 1 AU for cosmic rays in the inner heliosphere. Figure 4.3 shows the damping turbulence intersecting the Palmer consensus range as well as the range of best fitting $\lambda_{\parallel}$ values. The simulated χ and $\lambda_{\perp}$ also intersect the Palmer consensus range. Therefore the best-fitted simulated values for $\lambda_{\parallel}$ is between 0.08 – 0.3 AU and χ is between 0.02 – 0.05 which also falls within the Palmer consensus range.

4.5 Comparison with best-fit model results

In the first panel of Figure 4.4 the red symbols represents the EPI-HI/HET electron intensity observed on the PSP spacecraft and the lines are simulated results from the two-dimensional focused transport model. The solid blue line is the model of the best-fitting $\lambda_{\parallel}$ and $\lambda_{\perp}$ values, in this case taking $\lambda_{\parallel} = 0.155$ AU and $\lambda_{\perp} = 0.043$ AU (which is demonstrated in Figure 4.2) which was determined by calculating the geometric mean of the Palmer consensus range. The best-fit model is compared to an ill-fitting model (which is the green dashed line in Figure 4.4) where $\lambda_{\parallel} = 0.2$ AU and $\lambda_{\perp} = 0.01\lambda_{\parallel}$ AU,

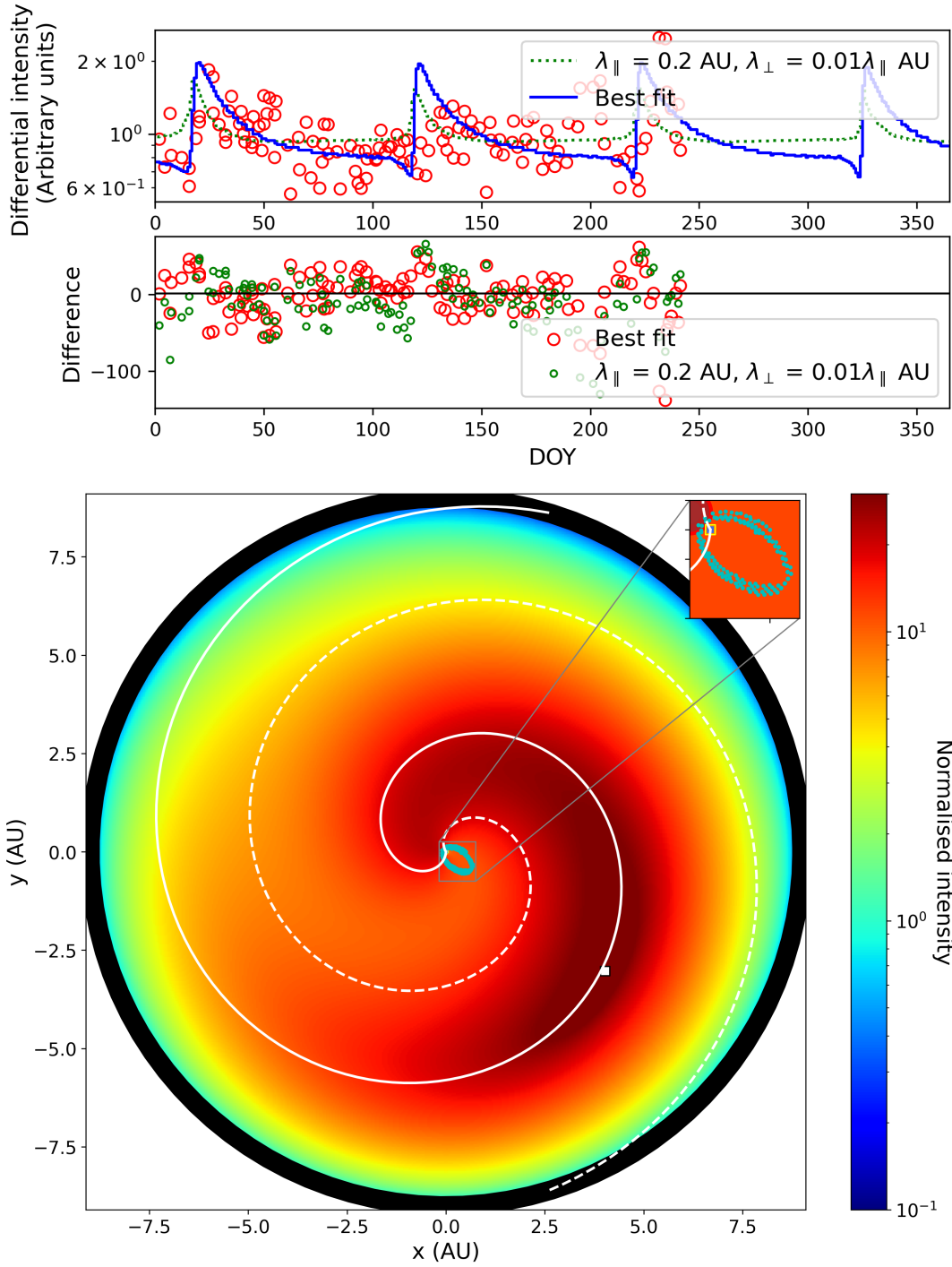


Figure 4.4: The top panel demonstrates the differential intensities observed at PSP, which was compared to the model $\lambda_{\parallel} = 0.2$ AU and $\lambda_{\perp} = 0.01\lambda_{\parallel}$ AU, as well as the best-fit values. The middle panel demonstrates the difference between the observed intensities and the simulations' best-fit intensities. The bottom panels show the modulation of 1.7 MeV Jovian electron intensities in the equatorial plane of the heliosphere, including the PSP trajectory around the Sun (which is zoomed in). The white square represents Jupiter, whereas the solid and dashed lines represent Parker HMF lines. The darker colours indicate where more of the Jovian electrons are present in the heliosphere.

to demonstrate how the best-fit model conforms to the observed data.

The second panel from Figure 4.4 represents the difference,

$$\text{Difference} = \frac{x_i}{\langle x \rangle} - \frac{y_i}{\langle y \rangle}, \quad (4.10)$$

between the best-fit model and the observed PSP data (represented by the red dots), as well as the ill-fitting model and the observed PSP data (represented by the green dots) during the duration of 2021. The observed difference of the intensities is close to 0 with few outliers, indicating that the best-fit mean free paths of the model are favourable.

The last panel demonstrates the modulation of normalised 1.7 MeV Jovian electron intensities in the equatorial plane of the heliosphere. The intensity is more prominent at Jupiter (indicated as a white square), and is also prominent along the magnetic connection (the solid white line) to the Sun. Figure 4.4 also includes the PSP trajectory around the Sun (which is zoomed in), to demonstrate how the PSP spacecraft and Jupiter are magnetically connected in Figure 4.1 during certain periods of 2021. The darker colours indicate where most of the Jovian electrons are present in the heliosphere.

4.6 Conclusion

When Jupiter is magnetically connected to the PSP spacecraft, there is an observed increase of Jovian electrons. To determine the best-fitting mean free paths of Jovian electrons during 2021, Jovian electrons were simulated using the two-dimensional focused transport model. The mean free path coefficients were varied between $0.1 - 0.5$ AU for λ_0 and $0.01\lambda_0 - 0.15\lambda_0$ to obtain χ . The percentage deviation between the simulated intensities and the observed intensities at PSP was determined and normalised. The range of best-fitting mean free path values was compared to various previous estimates at 1 AU, as well as theoretical values such as the Palmer consensus range, damping turbulence, and random sweeping turbulence models for $\lambda_{\parallel}$; the best-fit mean free paths coefficients for Jovian electrons at 1 AU were assumed to be where $\lambda_{\parallel}$ and χ overlapped the Palmer consensus range. The best-fit model used was where $\lambda_{\parallel} = 0.155$ AU and $\lambda_{\perp} = 0.0432$ AU. The simulations using the best-fitting coefficients were then compared to both an ill-fitted simulated model as well as the observed data from the PSP spacecraft, respectively, to demonstrate how preferable the best-fit model is to the observed data. The best-fit mean free paths were used to simulate how Jovian electron intensities behave in the equatorial plane of the heliosphere.

Chapter 5

Jovian electron events in the heliosphere

5.1 Introduction

In this chapter, the best-fitting mean free paths from Chapter 4 are used to simulate the intensities, pitch-angle distributions, and anisotropy of Jovian electrons that propagate in the heliosphere. The Jovian electron intensities are simulated as temporal periodic perturbations to demonstrate a quasi-steady-state solution known as the “Jovian clock” (Chenette et al., 1974). Jovian jets are also simulated in this chapter to illustrate how Jovian jets affect the Jovian electron distribution in the inner heliosphere.

5.2 Ulysses observations of Jovian periodicities

Figure 5.1 shows data from Dunzlaff (2013) between 34 – 36.5 day of the year (DOY) of 1992 when Ulysses was located in the middle magnetosphere near the current sheet in the equatorial plane. The electron count rate from the energy channel H3 in the high energy telescope (HET), which measured Jovian electrons ≥ 1.5 MeV (Simpson et al., 1992) is shown. The data indicate a prominent 10-hour Jovian electron periodicity as well lesser 5-hour Jovian electron periodicity. The 10-hour periodicity correlates to the fast rotation period of Jupiter (see table 2.1), and the 5-hour periodicity correlates to half of the rotation period, these are referred to as the Jovian clock (Simpson et al., 1992; Dunzlaff et al., 2013). The model added to the data in Figure 5.1 is a wave function used to reproduce the temporal periodicities that will be added to the Jovian electron source in the focused transport model and used later in the chapter.

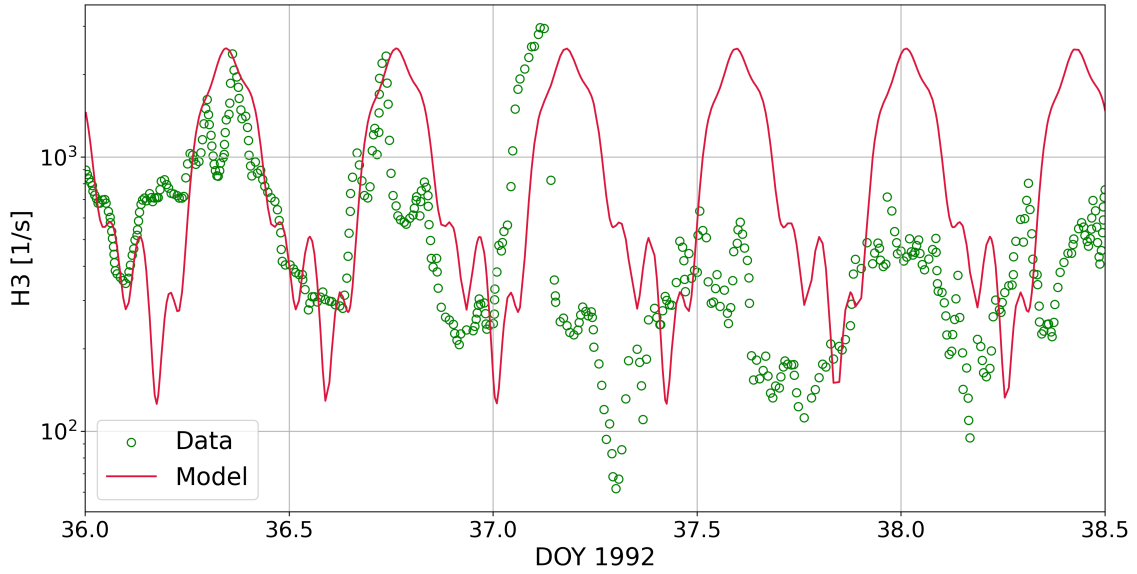


Figure 5.1: The data are obtained from Dunzlaff (2013) and show the electron count rate from the HET H3 channel onboard the Ulysses spacecraft. These electron count rates were observed between 36 – 38.5 day of year (DOY) in 1992, when Ulysses passed through the Jovian magnetosphere. The temporal periodicity model was fitted to the data.

5.3 Jovian clock simulations

The periodicities observed in section 5.2 can be simulated by changing the time independent boundary condition to the following,

$$g(t) = C \cdot \left(\sin \left(\frac{2\pi t}{P_{(10 \text{ hour})}} \right) + 2 + \frac{1}{2} \sin^3 \left(\frac{2\pi t}{P_{(5 \text{ hour})}} + P_{(5 \text{ hour})} \right) + g_0 \right), \quad (5.1)$$

to demonstrate the Jovian clock, which correlates with the fast rotation of Jupiter, where t is the time, g_0 is the background intensity, $P_{(10 \text{ hour})} = 10$, $P_{(5 \text{ hour})} = 5$, and C is a constant. The time dependent boundary condition of the Jovian clock was added to the transport model discussed in section 3.2. This section uses equation 5.1 in the focused transport model to observe how the intensity of the Jovian clock behaves differently in the heliosphere compared to a steady-state solution.

5.3.1 Time dependence of Jovian electrons for the clock model

Figure 5.2 shows the time profile of the differential Jovian electron intensities observed by observers at various positions and coordinates in the heliosphere (as shown in Figure 3.1). These differential intensities appear to converge until a quasi-steady-state solution is obtained, which occurs at ~ 100 hrs. Temporal periodicities are also seen on HMF lines that are not well-connected, although not as predominantly compared to the well-connected HMF lines. The anisotropies in Figure 5.2 also demonstrate quasi-steady-state perturbation at positions that are magnetically well-connected between the Sun and Jupiter,

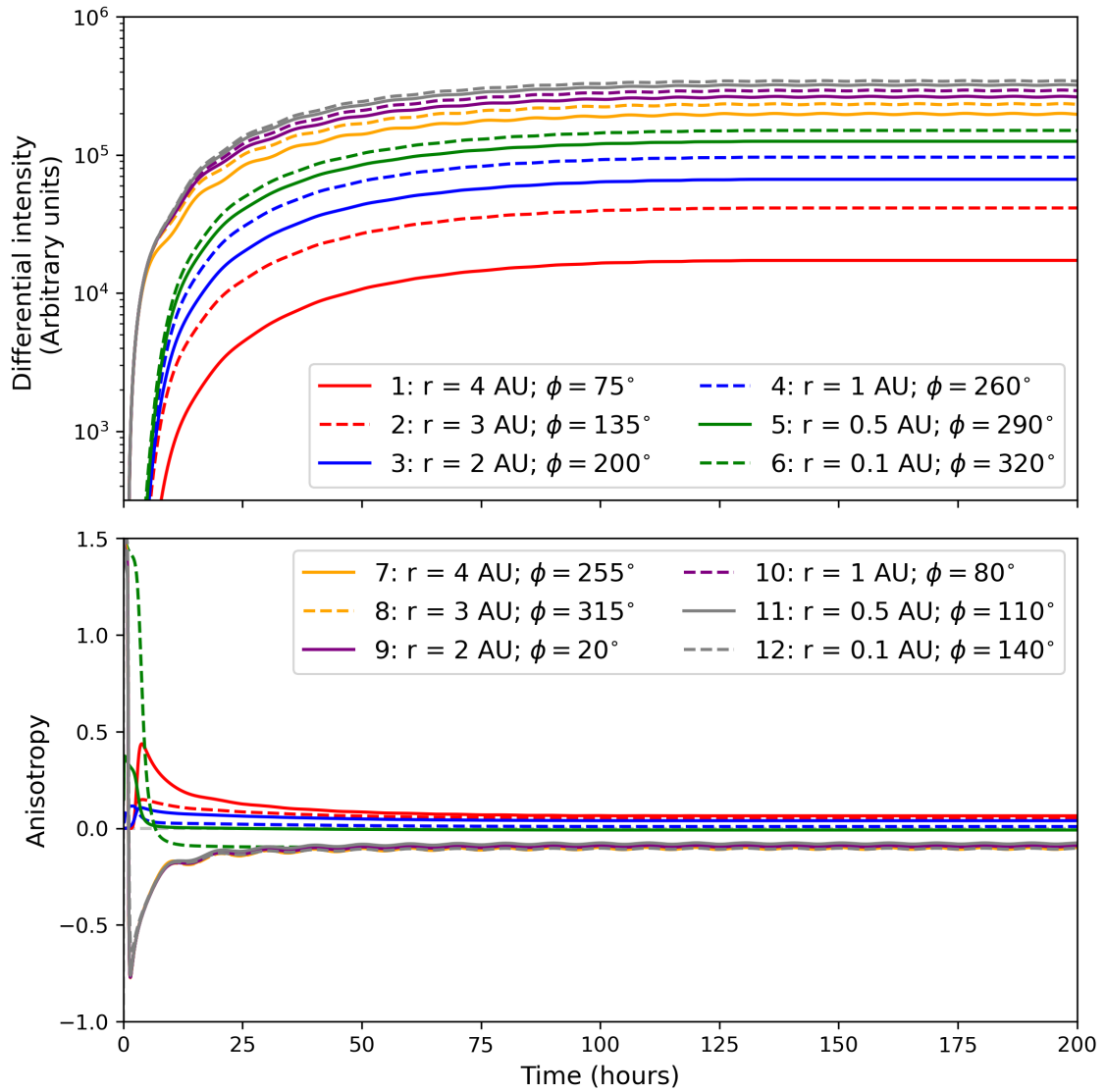


Figure 5.2: The zoomed-in time profile of the simulated 10 hr and 5 hr temporal periodicities of Jovian electron intensities for the best-fit coefficients discussed in Chapter 4. The solution fully converges to a quasi-steady-state solution within ~ 100 hours, i.e. the intensities at all positions converge until a constant perturbation is reached. The bottom panel shows the time profile for the anisotropy.

whereas the anisotropies converge to a constant value when electrons are propagating on the HMF lines that are not magnetically well-connected. The anisotropies appear to have an inverse correlation with the differential intensity, that indicates that Jovian electrons on the magnetically well-connected HMF line propagate towards the Sun. In contrast, Jovian electrons on the HMF lines that are not well-connected appear to propagate away from the Sun.

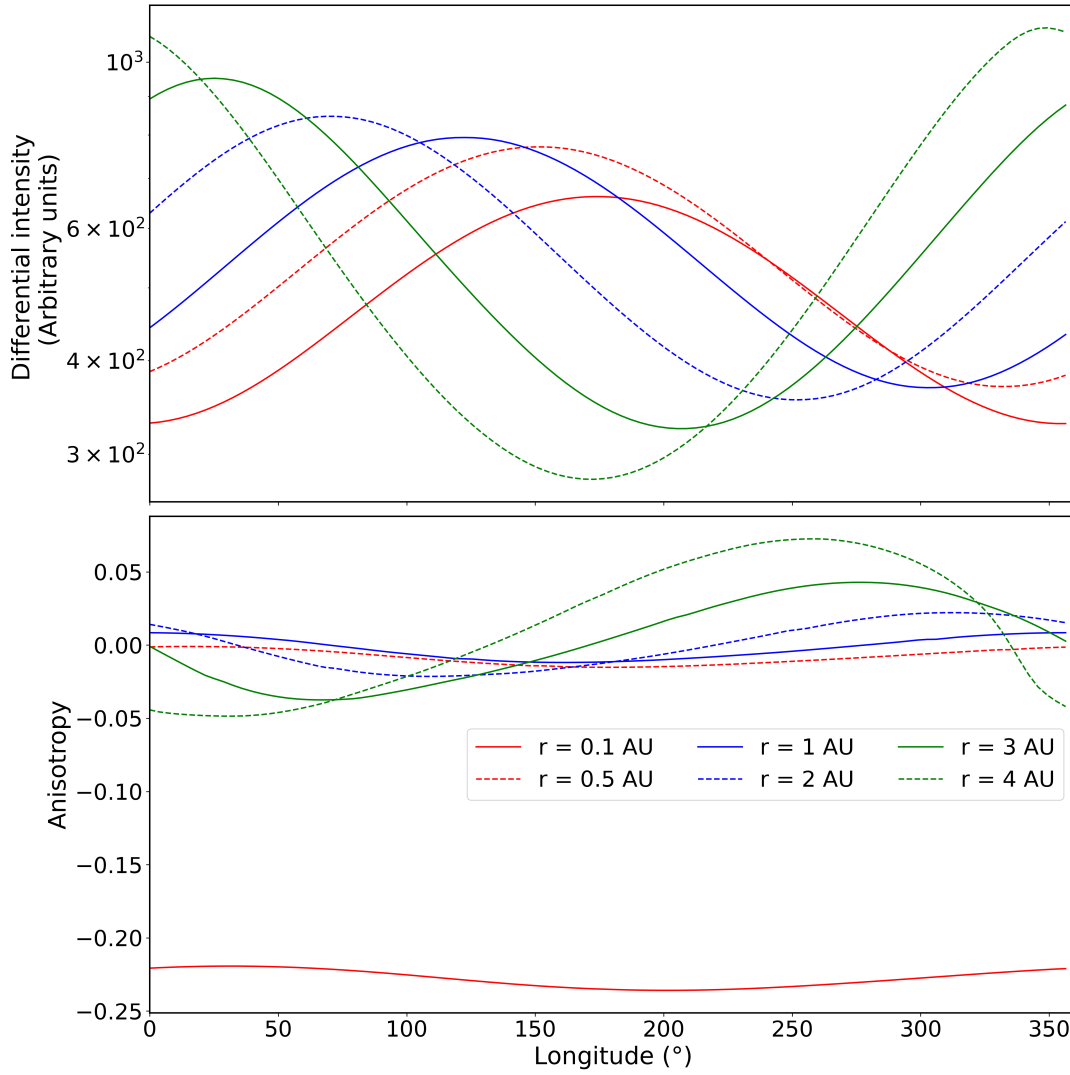


Figure 5.3: The top panel shows the differential intensities as a function of longitude for temporal periodicities of Jovian electron intensities observed at different radial positions in the heliosphere at 200 hrs. The bottom panel shows the anisotropy of Jovian electron intensities as a function of longitude.

5.3.2 Electron diffusion in the azimuthal direction

Figure 5.3 shows the differential intensity of Jovian electrons in a quasi-steady-state (from Figure 5.2) as a function of the azimuthal angle (longitude) at different radial positions at 200 hrs. The Jovian electron differential intensity decreases the further away from Jupiter that the electrons propagate. Figure 5.3 also shows the anisotropy of Jovian electrons in a quasi-steady-state as a function of the azimuthal angle at the same radial positions as the differential intensity. The anisotropy is apparently anti-correlated to the differential intensity, where positive anisotropy indicates that particles are predominantly transported away from the Sun, and a negative anisotropy indicates that particles propagate in the direction of the Sun with respect to the HMF lines (Strauss and Fichtner, 2015). Figure 5.3 shows Jovian electrons that are propagating both towards and away from the Sun,

depending on where the observer is located along the magnetic field lines. At 2, 3, and 4 astronomical units (AU) the anisotropies fluctuate. In contrast, at 0.1 and 0.5 AU the anisotropies fluctuate less; that shows the Jovian electrons are propagating towards the Sun. At 0.1 AU, the Jovian electrons show strong anisotropic propagation toward the Sun.

5.3.3 Electron pitch-angle scattering

Figure 5.4 shows the pitch-angle distribution of Jovian electrons at the different observers in the heliosphere. These pitch-angle distributions are expressed with respect to the HMF line, where $\mu = 1$ (at 0°), which indicates that Jovian electrons are propagating away from the Sun. In contrast, $\mu = -1$ (at 180°) indicates that the Jovian electrons propagate towards the Sun. The black regions are where the pitch-angle distributions are near the boundaries of the model. The pitch-angle distributions at observers 1 and 2 (from Figure 5.4) indicate isotropic transport of Jovian electrons on the HMF line, as these anisotropies are asymmetric. The pitch-angle distributions at observer 6 show significantly strong anisotropic propagation away from Jupiter as they form an asymmetrical distribution. The pitch-angle distributions observed in Figure 5.4 at observers 3, 4, and 5 are isotropic, as the Jovian electrons seem to propagate uniformly in all directions.

5.4 Jovian jets

Jovian jets are characterised by a sharp increase in Jovian electrons in the heliosphere with strong anisotropies; these jets emerge from the Jovian magnetosphere and can be observed up to 0.8 AU away from Jupiter (Ferrando et al., 1993; Dunzlaff, 2013). Jovian jets can be simulated by changing the time dependent boundary condition when the intensities reach an initial steady-state (~ 100 hrs) where equation 3.10 becomes

$$g(t) = \begin{cases} g_0 & \text{if } t < 100 \text{ hrs} \\ g_0 + C & \text{if } 100 \text{ hrs} < t < 100 \text{ hrs} + \Delta t \\ g_0 & \text{if } t > 100 \text{ hrs} + \Delta t \end{cases}, \quad (5.2)$$

where C is the additional Jovian electrons released during the jet event and Δt is the time durations of the burst simulated to represent a Jovian jet. This section focuses on how Jovian jet electron intensity behaves differently in the heliosphere compared to a steady-state and quasi-steady-state solution.

5.4.1 Time dependence of Jovian electrons for jets

Figure 5.5 shows the time profile of differential intensities with a Jovian jet simulated at 100 hrs where in equation 5.2 Δt is set to 30 min and C is 1000. The differential intensity

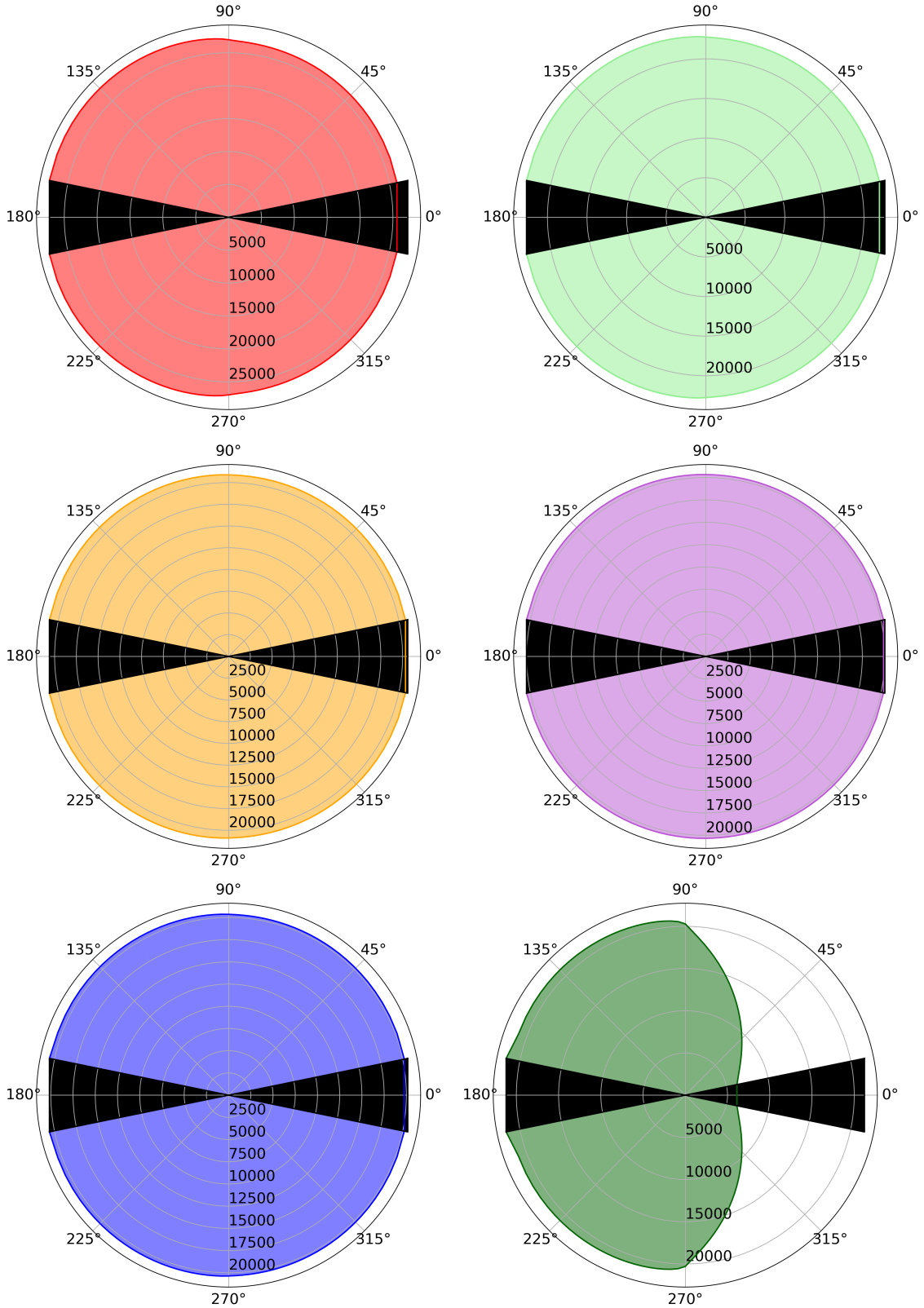


Figure 5.4: The pitch-angle distribution of the Jovian electrons at observers 1 (red), 2 (light green), 3 (orange), 4 (purple), 5 (blue), and 6 (dark green), as seen in Figure 3.1.

of the burst is observed by the observers (seen in Figure 3.1) at various radial positions and coordinates in the heliosphere; although the intensity will revert to the same intensity before the jet. However, there appear to be significantly weak anisotropies on HMF lines

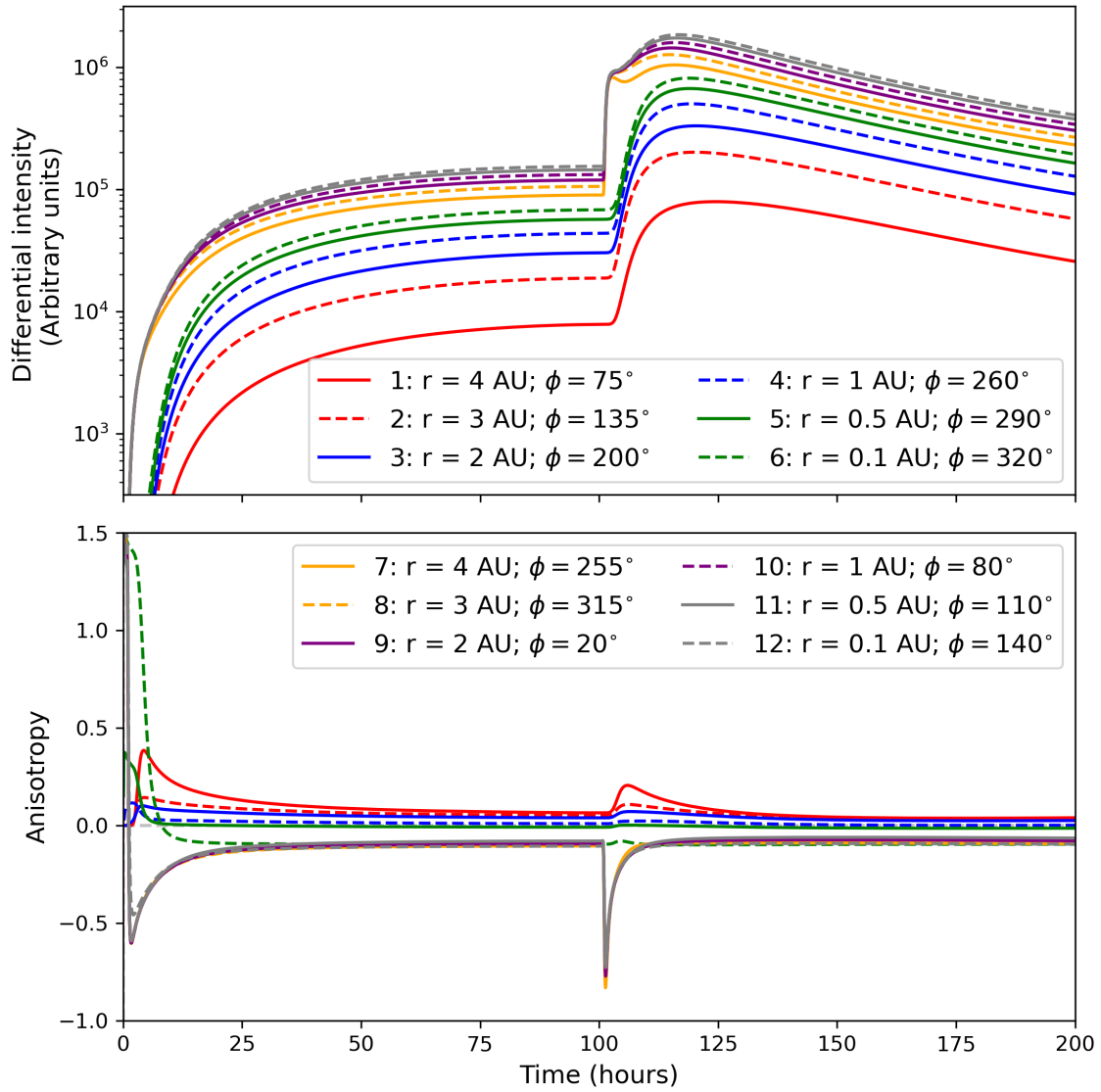


Figure 5.5: The top panel is the time profile of a simulated Jovian jet occurring at 100 hrs using the best-fit mean free paths discussed in Chapter 4. The bottom panel shows the time profile of the anisotropy for the above Jovian jet intensities.

that are not well-connected between the Sun and Jupiter. The anisotropies appear to have an inverse correlation with the differential intensity. As the Jovian jet is injected, a negative anisotropic peak is observed. The negative anisotropies are mainly observed along the magnetically well-connected HMF line, indicating that Jovian electrons are propagating towards the Sun.

Figure 5.6 shows the time profile of varied injected differential intensities with various time durations for the Jovian jets. When the Jovian jet occurs over a longer duration, the Jovian electron intensity increases slowly, and the simulation takes longer to start decreasing. When the Jovian jet occurs over a shorter duration, the Jovian electron intensity increases sharply. The intensity of the Jovian electrons injected in to the Jovian jets affect the size of the Jovian jet in the simulation. The observers located on HMF lines that are

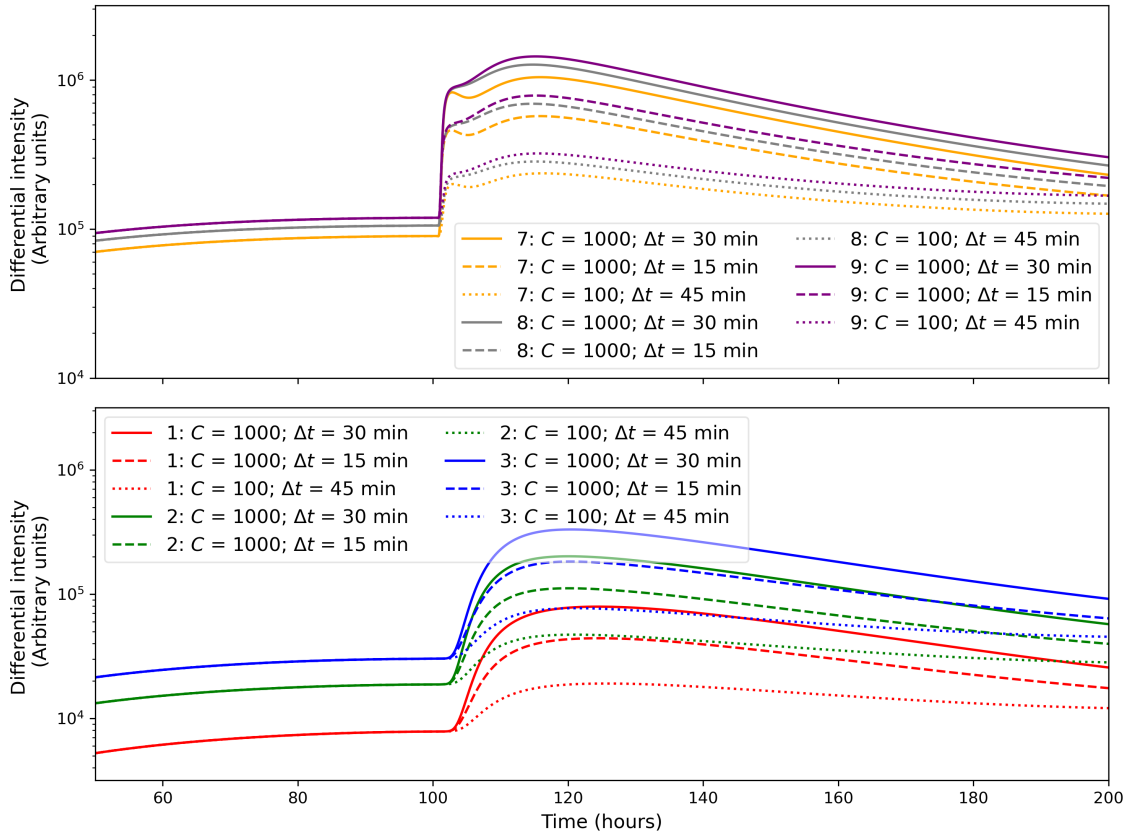


Figure 5.6: The time profile of different injection intensities with different time durations of the Jovian jets. The top panel is for the observers 7, 8, and 9 (from figure 5.5) that are located on the well-connected HMF line between the Sun and Jupiter. The bottom panel shows results at observers 1, 2, and 3 (from figure 5.5) that are located on HMF lines that are not well-connected to Jupiter.

not magnetically well-connected observe a slight increase in Jovian electrons, indicating that Jovian electrons propagate primarily along well-connected lines.

5.4.2 Electron diffusion in the azimuthal direction

Figure 5.7 shows the differential intensity of Jovian electrons during a Jovian jet from Figure 5.5 at 101.39 hours as a function of the azimuthal angle observed at different radial positions in the heliosphere. The intensities appear to increase near Jupiter (at 4 and 3 AU) around 0° and 360° , where the HMF line is magnetically well-connected. The intensities observed furthest from Jupiter appear to remain constant.

The anisotropy of Jovian electrons shown in Figure 5.7 indicates that the Jovian electrons are propagating towards the Sun around 0° and 360° and propagating towards Jupiter at $\sim 50^\circ - 250^\circ$ for 3 and 4 AU. These anisotropies appear to be inversely proportional to the differential intensities.

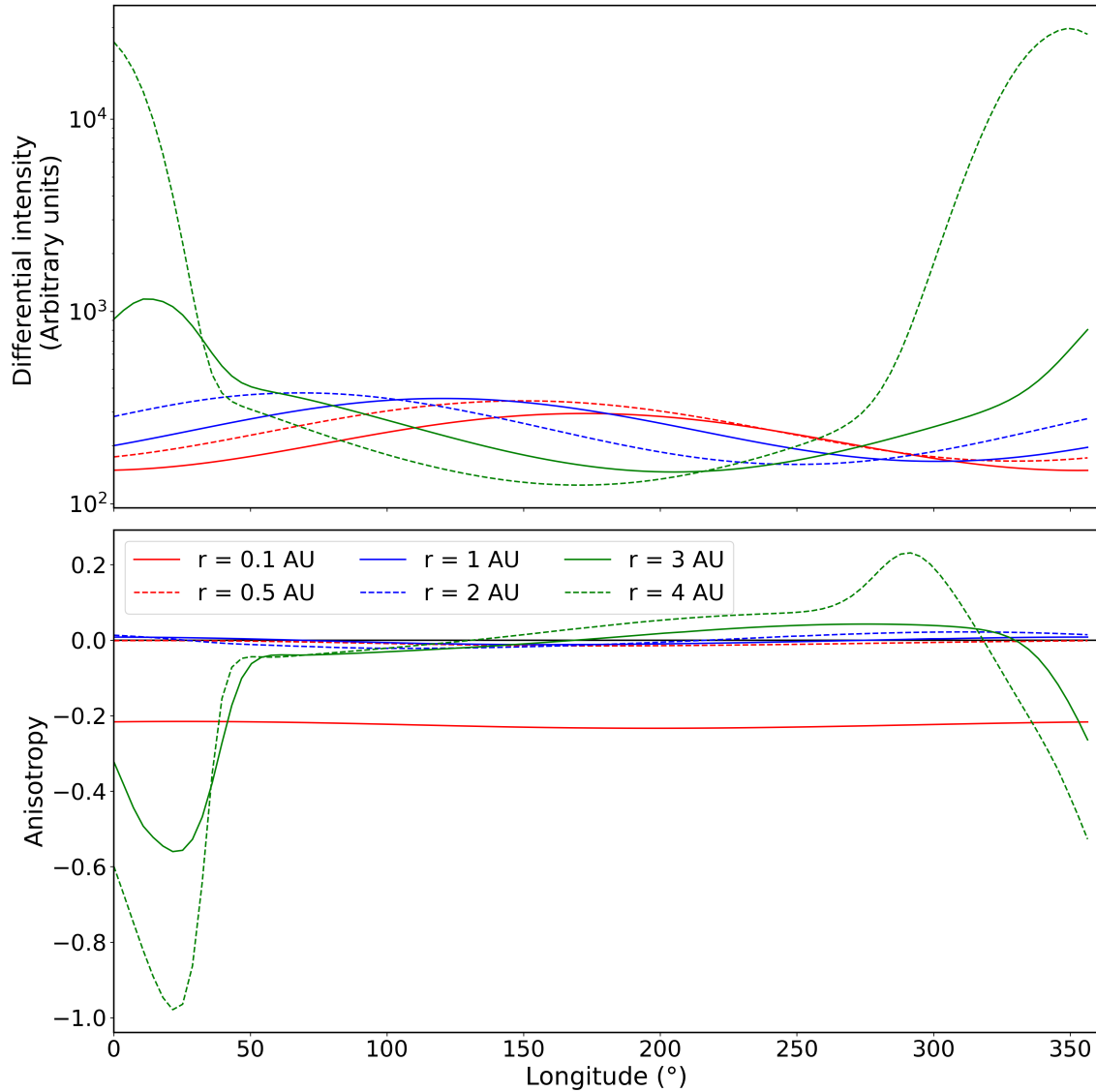


Figure 5.7: The top panel shows the same differential intensities as Figure 5.5 but at 101.39 hrs, just after the Jovian jet is injected into the simulation. The panel below shows the anisotropies of the above differential intensities as a function of longitude.

5.4.3 Pitch-angle scattering for electrons

The pitch-angle distributions shown in Figure 5.8 are taken at 1.39 hrs after the jet occurred. The pitch-angle distributions observed at observers 1 and 2 show weak anisotropic behaviour of Jovian electrons propagating along HMF lines, whereas the distribution at observer 6 shows significantly strong anisotropic behaviour; these electrons are predominantly moving away from Jupiter. These anisotropies are shown in Figure 5.8 as asymmetric. The pitch-angle distributions at observers 3, 4, and 5 appear to be nearly isotropic, as the Jovian electrons propagate uniformly in all directions.

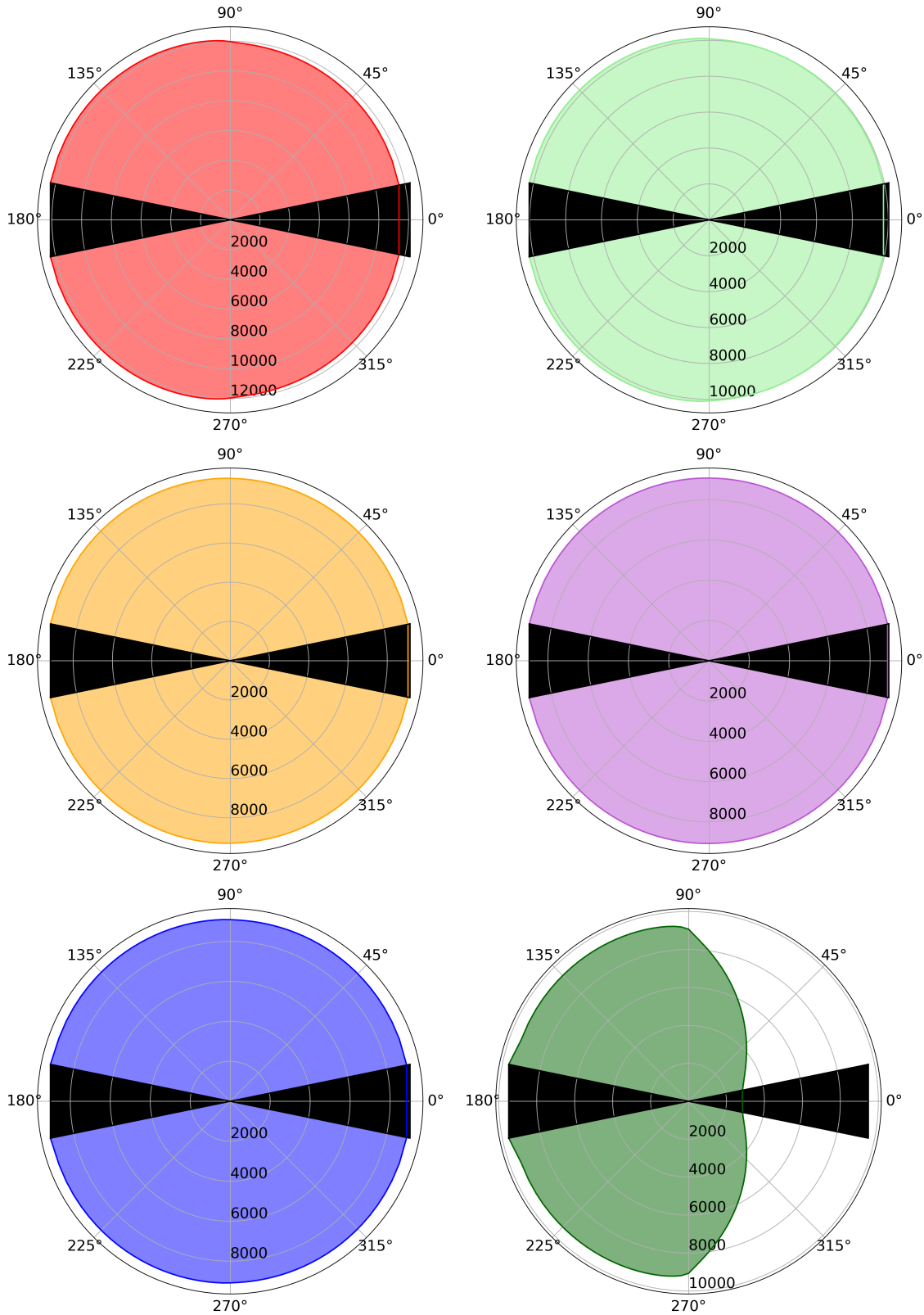


Figure 5.8: The pitch-angle distribution of the Jovian electrons 1.39 hrs at observers 1 (red), 2 (light green), 3 (orange), 4 (purple), 5 (blue), and 6 (dark green), as seen in Figure 3.1.

5.5 Conclusion

The Ulysses spacecraft observed both 10-hour and 5-hour periodicities when entering the Jovian magnetosphere, which correlates with the Jovian rotation period. These periodic variations are known as the Jovian clock and consistently release Jovian electrons into the heliosphere. Another Jovian event that releases particles into the heliosphere is Jovian jets. To simulate the propagation of the Jovian electrons in the heliosphere, these Jovian events were added to the time independent boundary condition used in the two-dimensional focused transport model.

The Jovian clock produces differential intensities that reach a quasi-steady-state solution after ~ 100 hrs. These periodicities are mainly observed along a well-connected HMF line and become smaller as the electrons propagate further away from Jupiter. Jovian jets were added once the Jovian electron intensities initially reached a steady-state solution (~ 100 hrs). The Jovian jets demonstrated drastic increases in Jovian intensities over a short duration, which was observed to increase near Jupiter (at 4 and 3 AU) along a magnetically well-connected HMF line. The anisotropies of both Jovian events appear to contain positive anisotropy, which indicates Jovian electrons are predominantly transported away from the Sun, as well as negative anisotropy, which indicates propagation of Jovian electrons in the direction of the Sun along HMF lines.

The pitch-angle distributions of Jovian electrons at the observers from Chapter 3 are also shown. Both Jovian events show similar pitch-angle distributions. Observers 1 and 2 show weak anisotropic behaviour of Jovian electrons, whereas observer 6 show significantly strong anisotropic behaviour, that is, propagating away from Jupiter towards the Sun. Observers 3, 4, and 5 show near isotropic behaviour.

Chapter 6

Conclusion

This research summarised the basic physics underlying the propagation of Jovian electrons and simulated the propagation of the Jovian electrons using a two-dimensional focused transport model.

Chapter 2 summarised the origin of the solar wind and the heliospheric magnetic field (HMF) along which particles propagate throughout the heliosphere. The dynamics of the Jovian magnetosphere were also discussed. Jovian electrons are observed to vary in intensity at 1 AU every 13 months due to changing levels of magnetic connectivity between Earth and Jupiter. These electrons are released via events on the Jovian magnetosphere, showing both a well-defined 10-hour periodicity, as well as spontaneous burst events.

Chapter 3 discussed the two-dimensional focused transport model and how it is solved, which assumes Jupiter to be a constant source of electrons in the heliosphere. The time taken for the model to reach a steady state was determined to be ~ 100 hrs. The model was used to simulate how Jovian electron intensities change in the equatorial plane of the heliosphere. The optimization for parallel computing was investigated as it increases the performance of the model, as well as determines its optimal runtime.

In **Chapter 4** data obtained from the Parker Solar Probe (PSP) spacecraft during 2021 were used to determine the best-fitting mean free paths for the two-dimensional model. The best-fitting mean free paths were compared to various previous estimates at 1 AU, as well as theoretical values such as the Palmer consensus values, damping turbulence, and random sweeping turbulence models for parallel diffusion to demonstrate that the best-fit model is much preferable to the observed data. The best-fit mean free paths were used to simulate how Jovian electron intensities behave in the equatorial plane of the heliosphere.

Chapter 5 investigated two types of Jovian events: The first event was the Jovian clock where data were obtained from the Ulysses spacecraft in Dunzlaff (2013). The second was the Jovian jets, which releases a sporadic increase of Jovian electron intensities into the heliosphere. These Jovian events were added to the time independent boundary condition used in the two-dimensional focused transport model to simulate the propagation

of Jovian electron intensities in the heliosphere. Higher Jovian electron intensities are mainly observed along a well-connected HMF line and become lower as the electrons propagate further away from Jupiter and perpendicular to the HMF. The anisotropies of both Jovian events appear to contain negative anisotropy, which indicates Jovian electrons are predominantly transported away from Jupiter towards the Sun, as well as positive anisotropy, which indicates propagation of Jovian electrons in the direction away from the Sun primarily along HMF lines that are not well magnetically connected to Jupiter.

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