

Chapter 6

Jovian Electrons

6.1 Introduction

In this chapter, the Jovian magnetosphere, as source of the Jovian electron component, is incorporated into the SDE model discussed in Chapter 4. From a modulation standpoint, the study of Jovian electrons presents a well-defined transport problem: Various *in-situ* observations of Jovian electrons in the inner heliosphere, as well as accompanying plasma measurements are available. Moreover, as these particles are relativistic, their tempo of fractional energy loss becomes energy independent (see Chapter 5). These factors, as well as the proximity of their source to Earth, make it possible to study Jovian electron propagation times; both from a modelling and observational point of view. Results from the model are shown, illustrating the validity of the model in reproducing Jovian intensities. Then, the propagation time of Jovian electrons to Earth is calculated and compared to observational values in order to constrain the diffusion tensor. Lastly, using these diffusion coefficients, the 6 MeV Jovian intensity at Earth is calculated.

Results from this chapter are presented by *Strauss et al.* [2011a, 2013a]

6.2 Incorporating Jovian Electrons into the Stochastic Transport Model

The Jovian magnetosphere is incorporated in the model as a second *boundary condition* and not explicitly as a source. This is done by specifying the volume of the magnetosphere V_J . Starting at (x_i^0, s^0) and tracing the pseudo-particles until $(x_i^e, s^e) \in V_J$, the pseudo-particle is then defined to be of Jovian origin. The total electron intensity is calculated by making use of Eq. 4.28, where Ω_b indicates the galactic CR boundary (i.e. beyond the HP) and $\Omega'_B = V_J$. The model is therefore able to calculate galactic and Jovian electron intensities simultaneously, or only one species at a time. For the Jovian source function, f'_b , the parametrized function of *Ferreira et al.* [2001a] is adopted. The Jovian magnetosphere is approximated as a solid angle (in spherical coordinates), centred at a radial distance of 5.2 AU and at varying azimuthal positions in the equatorial plane. The magnetosphere is assumed to be $100 R_J$ wide in the

solar direction (with the Jovian radius $R_J = 71492$ km), $200 R_J$ in latitudinal and azimuthal extent and $200 R_J$ long in the tail direction. The modelled intensities are, however, insensitive to the actual volume (size) of the magnetosphere as long as it remains reasonable.

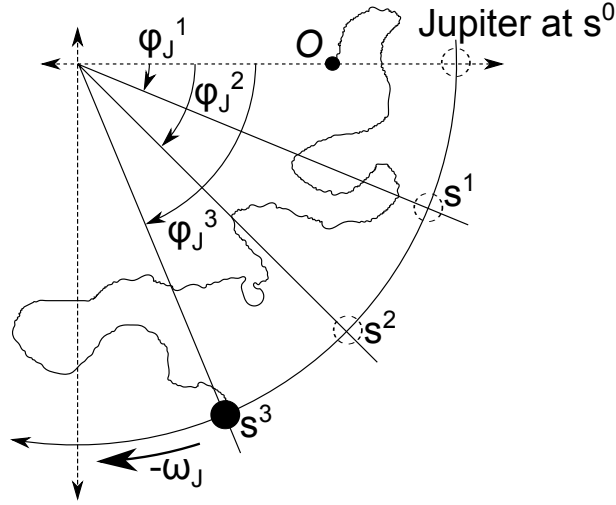


Figure 6.1: A schematic illustration (not to scale) in the equatorial plane of how the azimuthal position of the Jovian magnetosphere is varied time-dependently in the model. At s^0 both the observational point (represented by the small filled circles at O) and the Jovian magnetosphere (represented by the dashed circle) are located at the same azimuthal position, e.g. $\phi^0 = \phi_J^0 = 0$. During the integration process, the azimuthal position of the Jovian magnetosphere changes with an angular frequency of $-\omega_J$, while the position of the observation point remains unchanged. The pseudo-particle enters the Jovian magnetosphere at the time s^3 at an azimuthal position ϕ_J^3 , with $\Delta\phi_J = |\phi_J^3 - \phi_J^0|$.

A time dependence in the position of V_J , because of Jupiter's relative position with respect to an observer located at $(r^0, \theta^0, \phi^0, s^0)$, is also incorporated. This is illustrated schematically in Fig. 6.1. The integration process is started at s^0 with the Jovian magnetosphere located at $(r_J, \theta_J, \phi_J^0)$. The azimuthal position of V_J is then varied as

$$\phi_J^{j+1} = \phi_J^j - \omega_J \Delta s, \quad (6.1)$$

with $\omega_J = 2\pi/4333$ days the orbital angular velocity of Jupiter. A pseudo-Jovian electron will thus encounter Jupiter at a different azimuthal position ϕ_J^e , after Jupiter has moved a finite distance

$$\Delta\phi_J = |\phi_J^e - \phi_J^0|. \quad (6.2)$$

At least 3000 pseudo-particles are integrated for every phase space position, for both galactic, N_G , and Jovian electrons, N_J . As the fraction of pseudo-particles reaching Jupiter is much less than those reaching the HP (about 1-10%), generally $N_G > N_J > 3000$.

6.3 Electron Intensities in the Inner Heliosphere

The modelling results shown in this section include both the galactic and Jovian electron populations in the modulation model. In the following figures, galactic and Jovian intensities are shown separately, while the total electron intensity, which is a linear combination of the separate components, is also shown. Jovian electrons dominate the galactic component at low energies and, because the effects of drifts are small or even negligible at these low energies, computed intensities are only shown for the $A > 0$ polarity cycle. For the next section, where only Jovian electrons are investigated, drifts are neglected in the model. The parallel mean free path is assumed to be given as

$$\lambda_{\parallel} = \begin{cases} \lambda_0 \left(\frac{P}{P_0} \right) \left(1 + \frac{r}{r_0} \right) & : P \geq P_0 \\ \lambda_0 \left(1 + \frac{r}{r_0} \right) & : P < P_0, \end{cases} \quad (6.3)$$

where $\lambda_0 = 0.15$ AU, $P_0 = 1$ GV and $r_0 = 1$ AU, along with isotropic perpendicular diffusion, $\lambda_{\perp} = 0.01\lambda_{\parallel}$. The heliopause is located at $r_{HP} = 140$ AU.

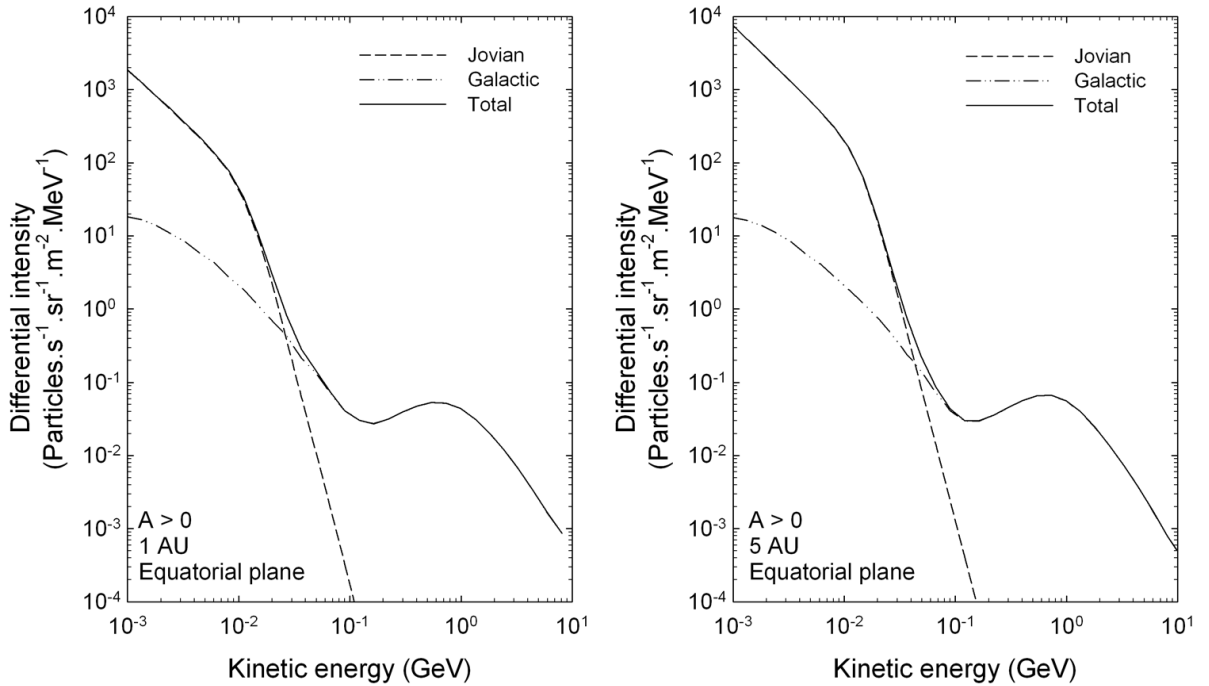


Figure 6.2: Computed galactic electron (dashed-dotted lines), Jovian electron (dashed lines) and combined electron (i.e. a linear combination of the galactic and Jovian intensities, solid lines) spectra at Earth (left panel) and at 5 AU (right panel) for the $A > 0$ cycle.

Fig. 6.2 shows computed energy spectra, with the inclusion of both galactic and Jovian electrons into the model. The left panel shows the galactic contribution (dashed line), the Jovian contribution (dash dotted line) and the linear combination of these components (total, solid

line) at Earth in the equatorial plane. For these computations, the observer was taken to be located at an azimuthal position of $\phi^0 = 0$, while Jupiter's position was initially located at $\phi_J = 0$, but allowed to vary time dependently during the integration process, as discussed previously. The right panel is similar, but for an observer located at 5 AU. For both computations, the $A > 0$ cycle is assumed. The results show the same qualitative behaviour as discussed previously by *Potgieter and Ferreira [2002]*, with Jovian electrons dominating the combined energy spectrum below ~ 10 MeV.

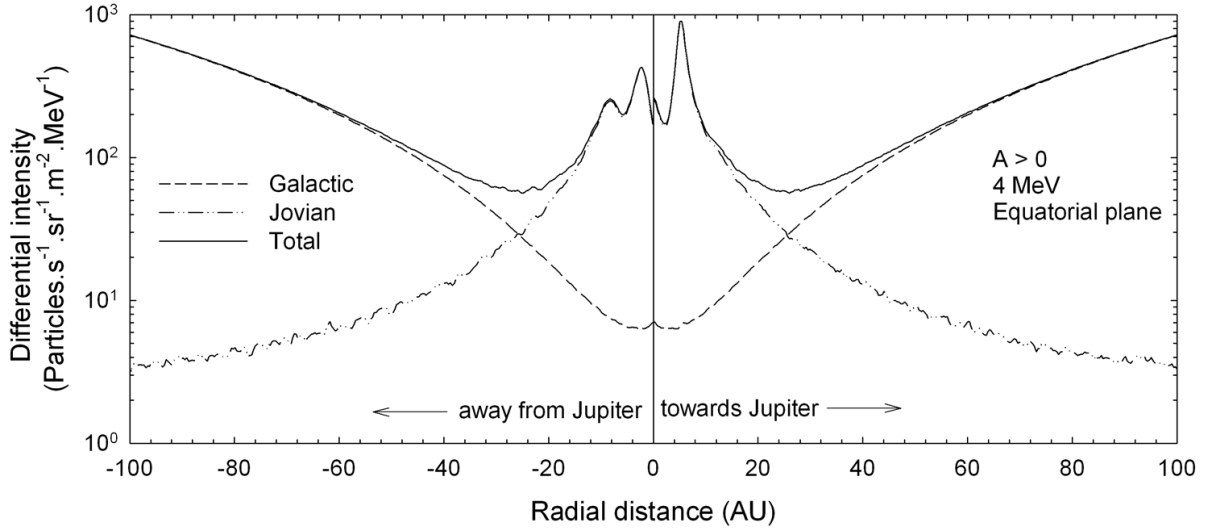


Figure 6.3: Combined computed galactic and Jovian electron intensities at 4 MeV as a function of radial distance from the Sun, located at the origin. The initial position of the Jovian magnetosphere is kept at $\phi_J^0 = 0$, while radial cuts at $\phi = 0$ (towards Jupiter) and $\phi = \pi$ (away from Jupiter) are shown.

In Fig. 6.3 the computed total electron intensity is shown as a function of radial distance at an energy of 4 MeV. For all simulations, Jupiter's initial position is kept fixed at $\phi_J^0 = 0$, while the right panel shows a radial cut at $\phi = 0$ (towards Jupiter) and the left at $\phi = \pi$ (away from Jupiter). Jovian electrons dominate the total electron intensity in the inner heliosphere up to ~ 20 AU in the equatorial plane. This value is however not unique, but depends on the diffusion tensor assumed in the modulation model. In the inner heliosphere, four distinctive peaks in electron intensities are evident: The highest one corresponds to the actual position of Jupiter, while the three lower peaks correspond to HMF crossings of field lines connecting the observational point and Jupiter. At $r > \sim 40$ AU, the Jovian electron intensities are no longer smooth, but exhibit a wavy behavior. This is caused by the relative motion of Jupiter (discussed next), allowing different field lines to connect the observational point to the Jovian magnetosphere during the integration process.

To further emphasize the spatially 3D nature of Jovian electron transport in the inner heliosphere, Fig. 6.4 shows modelled intensity contours in the equatorial (top panel) and merid-

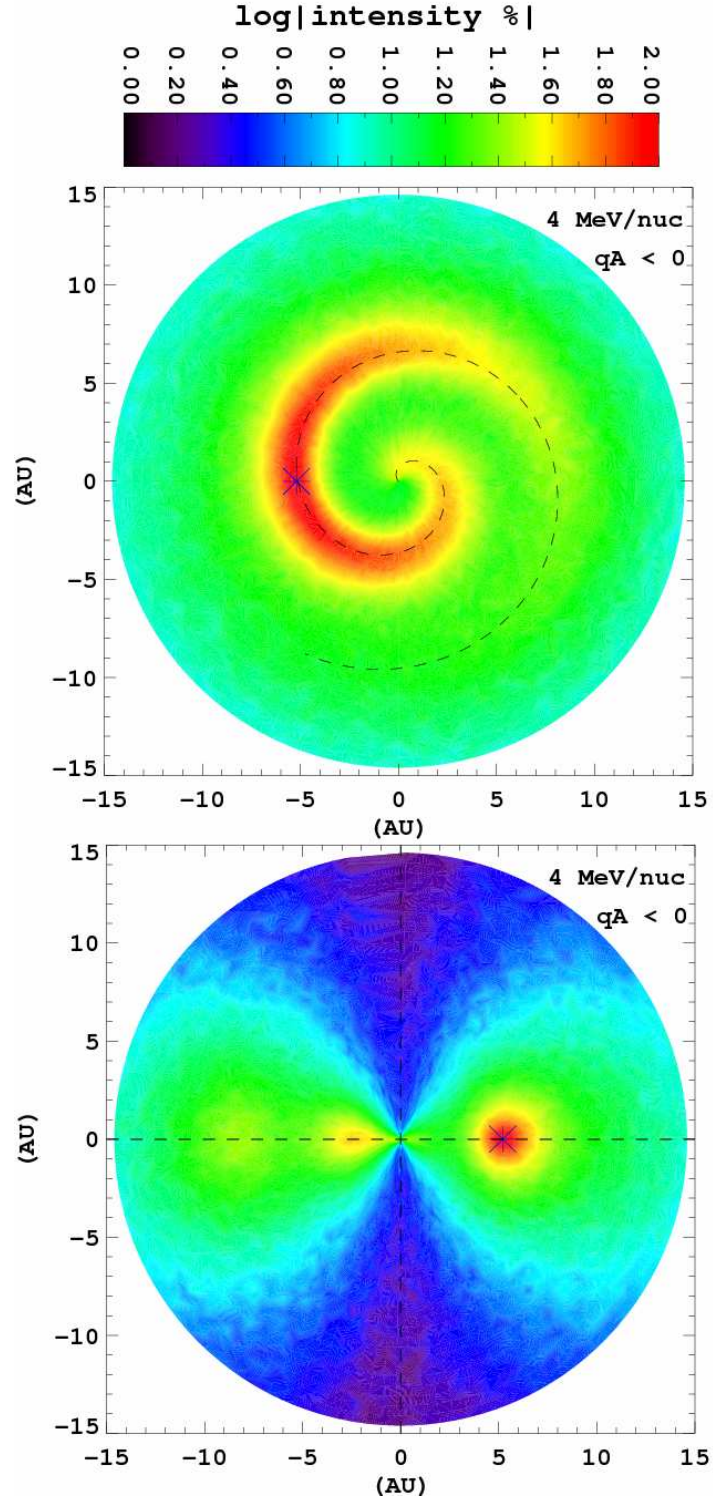


Figure 6.4: Modelled Jovian electron intensities in the equatorial (top panel) and meridional (bottom panel) planes at an energy of 4 MeV. The blue asterisk shows the position of Jupiter, while the dashed line in the top panel shows an HMF line connecting Jupiter to the Sun.

ional (bottom panel) planes at an energy of 4 MeV. The position of the Jovian magnetosphere is indicated by the blue asterisk (not to scale), while intensities are normalized to 100% at Jupiter.

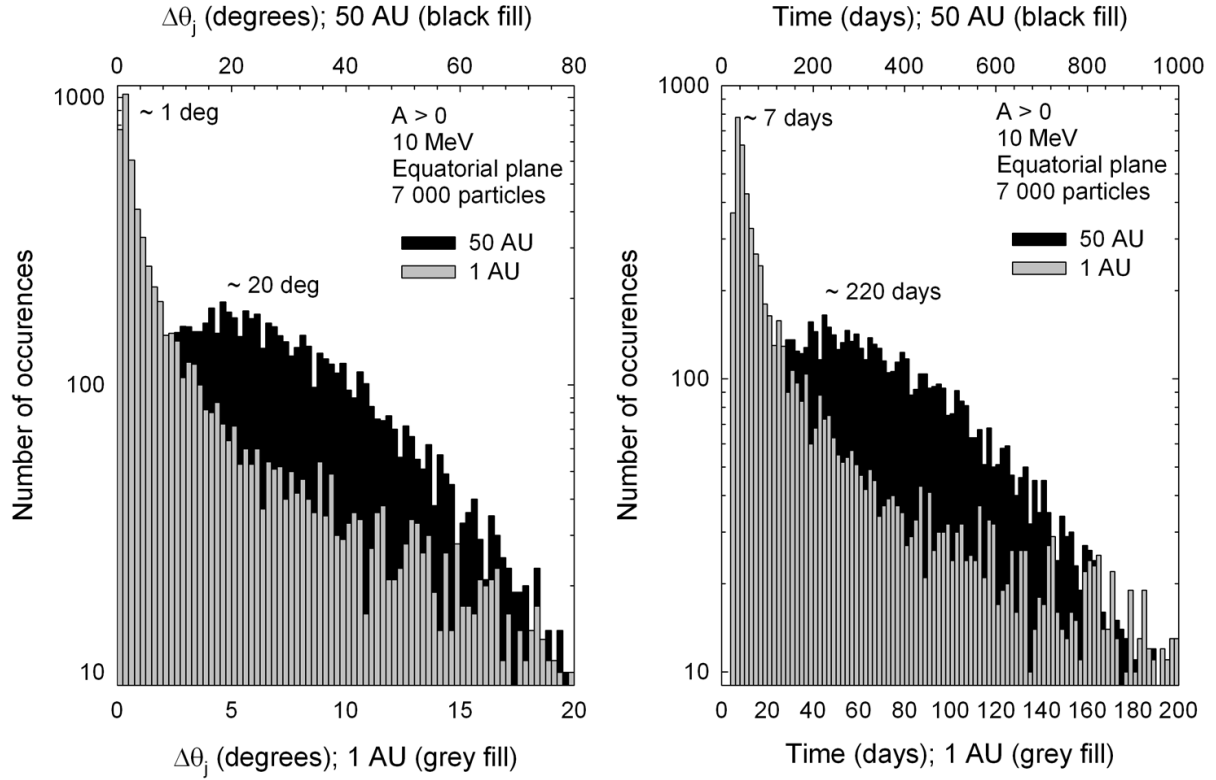


Figure 6.5: The left panel shows the relative azimuthal motion of Jupiter $\Delta\phi_J$, when 10 MeV electrons are traced time backwards from an observational point at Earth (grey histogram, bottom axis) and from an observational point located at 50 AU in the equatorial plane (black histogram, top axis) to the Jovian magnetosphere. The right panel shows the corresponding propagation times. At Earth, the relative motion of Jupiter is small, $\Delta\phi_J \sim 1^\circ$, and so is the propagation time of ~ 7 days. For an observer at 50 AU however, the relative motion of Jupiter is large $\Delta\phi_J \sim 20^\circ$, and the propagation time increases to ~ 220 days.

In Fig. 6.5, the relative motion of the Jovian magnetosphere during the integration process is illustrated, as well as the propagation time of Jovian electrons. The left panel of Fig. 6.5 shows the relative azimuthal motion $\Delta\phi_J$ of the Jovian magnetosphere when Jovian electrons of 10 MeV are traced time backwards from Earth (grey histogram; bottom axis) to the Jovian magnetosphere. This azimuthal motion is due to the finite time a Jovian electron will spend in the heliosphere while propagating from Jupiter to Earth. At these small radial separations between the observational point and the source (i.e. ~ 5 AU separation between Jupiter and Earth), the relative motion of Jupiter is small $\sim 1^\circ - 2^\circ$ during the propagation process and can be neglected, as has been done in traditional modulation models. At larger radial separations, for an observational point located at 50 AU as an example (black histogram; top axis), the effect of a moving source however becomes larger, $\sim 20^\circ$, and contributes to the varying electron intensities shown in Fig. 6.3. The expectation value is $\langle\Delta\phi_J\rangle = 4^\circ$ for an observational point located at 1 AU, but increases to $\langle\Delta\phi_J\rangle = 31^\circ$ for an observational point at 50 AU. The propagation times for Jovian electrons, for the same scenarios as in the left panel, are shown in the right panel. No Jovian electrons reach Earth in less than 5 days, with the propagation

time peaking at ~ 7 days. These relatively short propagation times make convection and diffusion the effective modulation processes for Jovian electrons in the inner heliosphere, because these particles don't reside long enough in the heliosphere to undergo significant adiabatic energy changes, while drift effects are negligible at these low energies. A more detailed study of Jovian propagation times follow in the next section.

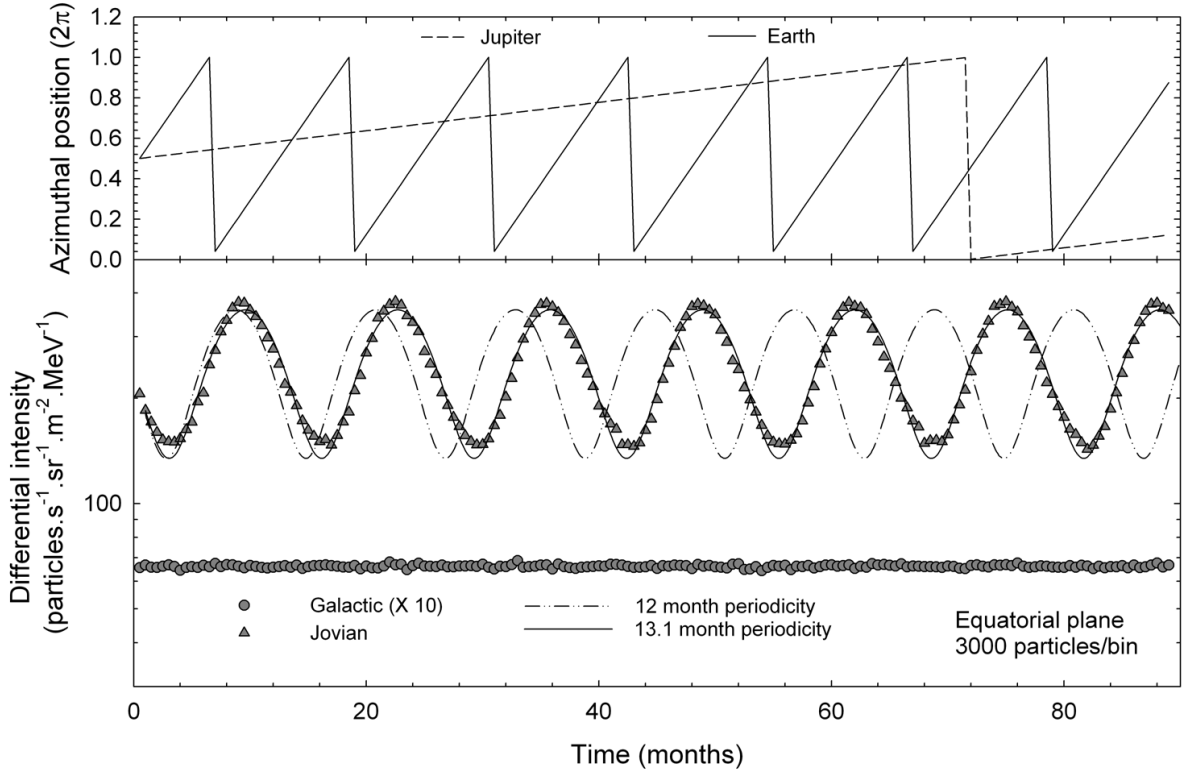


Figure 6.6: The top panel shows the assumed time dependent azimuthal positions of Earth and Jupiter in the modulation model, while the bottom panel shows the effect thereof on electron intensities at 4 MeV in the equatorial plane. Jovian intensities are indicated by the triangles and galactic (multiplied by a factor of 10) by the filled circles. The solid and dashed lines show sinusoidal fits to the Jovian intensities, with periods of 13.1 and 12 months respectively.

Next, the geometrical effect of changing the azimuthal separation of Earth (as the observational point) and Jupiter on electron intensities is modelled. The resulting Jovian and galactic intensities are shown in Fig. 6.6. For these simulations the azimuthal position of Earth is varied in accordance with its orbital period of $2\pi/365.25 \text{ days}^{-1}$ and Jupiter with its orbital period of $2\pi/4333 \text{ days}^{-1}$. Both Earth and Jupiter are initially located at $\phi = \pi$, as shown in the top panel of the figure. In the bottom panel the resulting electron intensities at Earth are shown. For galactic electrons this changing geometry has no effect, as the Parker HMF is azimuthally symmetric. For the Jovian electrons on the other hand, a clear sinusoidal variation with time is found. If the azimuthal position of Jupiter would remain constant over time, a sinusoidal variation with a period of 12 months is expected due to the movement of Earth (shown as the dash dotted line), but varying the azimuthal separation realistically, a period of 13.1 months (solid line) is found. This is in accordance with the observations of e.g. *Moses* [1987] and the

ADI modelling done previously by *Ferreira et al.* [2004].

6.4 Jovian Electron Propagation Times

Later in this section, it will be shown how CR observations can be used to derive values for the different diffusion coefficients. Before attempting this, the concept of degeneracy as related to CR modelling studies must be briefly discussed. By degeneracy it is meant that more than one set of transport parameters lead to the same modelling results, e.g. the computed CR flux. In other words, the choice of transport parameters is not always unique. This concept is illustrated with an example, and the 1D diffusion-convection approximation is chosen. Neglecting temporal changes of f , no energy losses, and assuming spherical symmetry, the TPE reduces to

$$V_{sw}f - \kappa_{rr} \frac{\partial f}{\partial r} = 0, \quad (6.4)$$

and CR transport reduces to a diffusion-convection problem. The solution of Eq. 6.4 is simply

$$f(r) = f(r_b)e^{-M(r)}, \quad (6.5)$$

where

$$M(r) \equiv \int_r^{r_b} \frac{V_{sw}}{\kappa_{rr}} dr' \quad (6.6)$$

is sometimes referred to as the modulation function. Here, r_b is the radial distance to the spherical boundary and κ_{rr} is the effective radial diffusion coefficient. This is an example of a three-fold degenerate system; different combinations of κ_{rr} , V_{sw} and dr' lead to the same value of $f(r)$ when $M(r)$ is unchanged. Without any additional information (e.g. observations), it is impossible to distinguish which equivalent combination of parameters best describe the transport process.

6.4.1 A Modelling Approach to a Theoretical Test Case

In this section, some characteristics are shown of the average propagation time $\langle \tau \rangle$ when it is calculated for 6 MeV Jovian electrons propagating from Jupiter to Earth. Unless otherwise stated, a constant value of $V_{sw} = 600 \text{ km.s}^{-1}$ is adopted throughout this chapter for illustrative purposes unless otherwise stated, while the parallel and perpendicular mean free paths are assumed to scale as

$$\lambda_{\parallel} = \frac{\lambda_0}{2} \left(1 + \frac{r}{r_0} \right) \quad (6.7)$$

and

$$\lambda_{\perp} = \chi \lambda_{\parallel}, \quad (6.8)$$

where χ is a constant (the ratio of the perpendicular to parallel diffusion coefficients), λ_0 is the magnitude of $\lambda_{\parallel}$ at a radial position of $r_0 = 1$ AU (i.e. Earth) and any rigidity dependence neglected, as the focus is on low energy electrons. Fig. 6.7 shows $\langle \tau \rangle$, for 6 MeV electrons released from the Jovian magnetosphere and *observed* at Earth, as a function of $\Delta\phi$. Here, $\Delta\phi = \phi_J - \phi_E$ is the angular separation between Jupiter (ϕ_J , as source of the electrons) and Earth (ϕ_E , where they are *observed*). For this example, $\lambda_0 = 1$ AU and $\chi = 0.01$. It is clear that the modelled $\langle \tau \rangle$ (filled circles) exhibits a sinusoidal variation with changing values of $\Delta\phi$. This is expected because different choices of $\Delta\phi$ correspond to different levels of magnetic connection between the two planets. For $\Delta\phi = 180^\circ$ the two planets are relatively well connected by the same HMF line, so that Jovian electrons can propagate more easily (and quicker!) from their source to the observer. As a result, $\langle \tau \rangle$ will be shorter, as indicated by the arrow labelled (b) on the graph. The bottom panel (b) shows pseudo-particle traces for three different Jovian electrons using the same modulation conditions, illustrating the effective transport of these particles to Earth for this value of $\Delta\phi$. At $\Delta\phi = 0^\circ$ however, the magnetic connectivity is much worse and the modelled $\langle \tau \rangle$ is much longer. The corresponding particle traces, shown in Panel (a), illustrate the difficulty of these particles in propagating to Earth. During times of good magnetic connection, Jovian electrons propagate to Earth mainly through parallel diffusion, while perpendicular diffusion is the *dominant diffusion* process during times of poor magnetic connection.

In Fig. 6.8 the values of V_{sw} (left panel) and χ (right panel) are varied in the modulation model to examine the effect thereof on the calculated $\langle \tau \rangle$. The red solid line in both cases correspond to the *reference solution* shown in the previous figure. The results shown here can be understood when considering the analytical approximation derived in the previous chapter

$$\langle \tau \rangle = \frac{R^2}{6\kappa_{rr} - V_{sw}R}. \quad (6.9)$$

Although this expression is over-simplified to be applied to the present scenario, where Jovian electrons propagate in 3D from a point-like source, insight can be gained into the behaviour of $\langle \tau \rangle$. Eq. 6.9 predicts longer values of $\langle \tau \rangle$ when V_{sw} is increased. This is seen in the left panel of Fig. 6.8, where the $V_{sw} = 800 \text{ km.s}^{-1}$ solution has $\langle \tau \rangle$ larger than the reference case for e.g. $\Delta\phi \sim 0^\circ, 250^\circ$. This solution is, however, below the reference solution at $\Delta\phi \sim 120^\circ$, because, by increasing V_{sw} , the Parker spiral HMF is stretched out, so that the length of the HMF line connecting Jupiter and Earth decreases. This leads to a smaller value of $\langle \tau \rangle$ when Jovian electrons reach Earth mainly via parallel diffusion, i.e. in regions of good magnetic connectivity between source and observer.

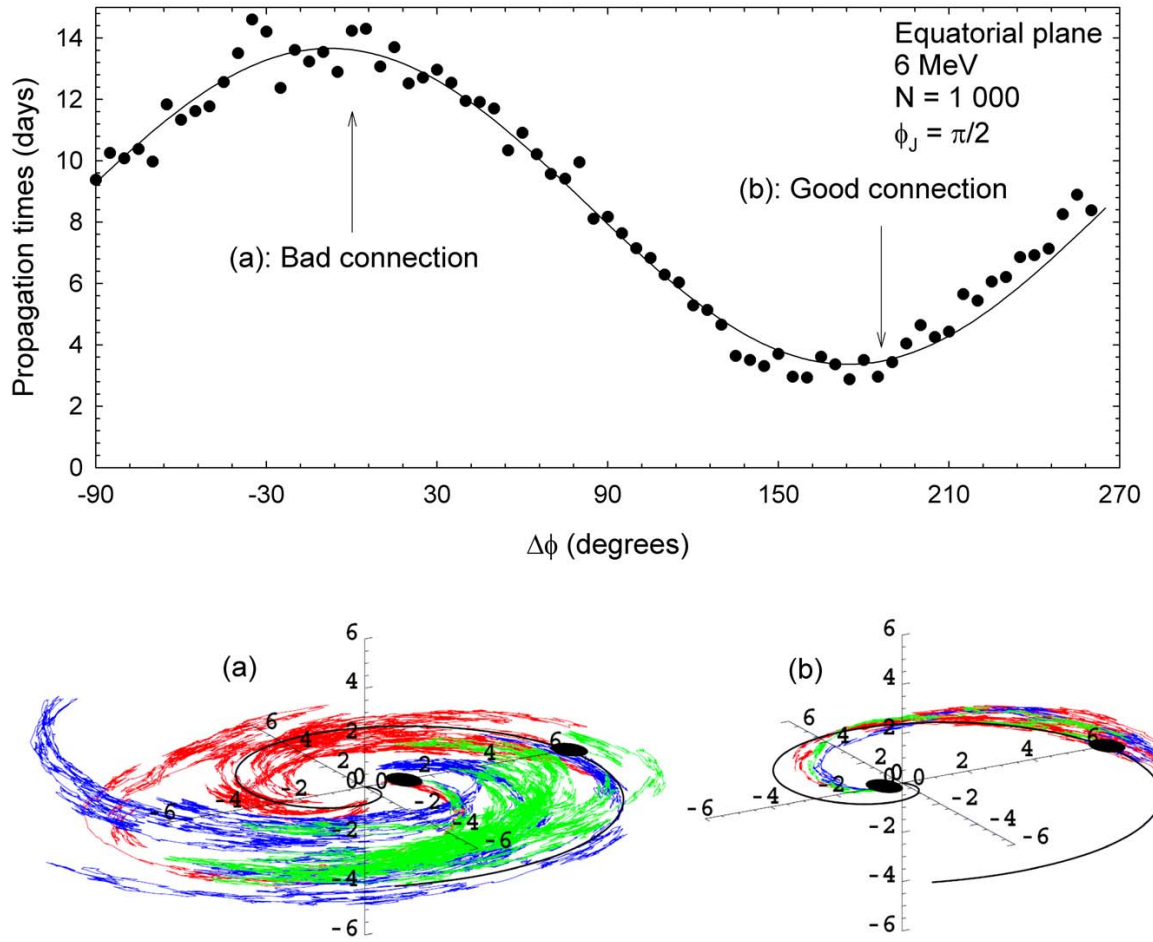


Figure 6.7: The top panel shows the computed average propagation time $\langle\tau\rangle$ for 6 MeV Jovian electrons as a function of the azimuthal separation between Jupiter and Earth $\Delta\phi = \phi_J - \phi_E$ (filled circles). The solid line is a sinusoidal fit to the results and is shown for illustrative purposes. For each simulated data point, $N = 1\,000$ pseudo-particles were solved. The bottom panel shows pseudo-particle traces (blue, red and green lines) for the scenarios indicated by (a) and (b) in the top panel. The black solid line shows the HMF line connecting Jupiter and Earth (the two planets indicated by the two large discs). All axes are labelled in AU.

In the right panel of Fig. 6.8, the value of χ is varied in the SDE model. When χ is increased, $\langle\tau\rangle$ decreases, in agreement with Eq. 6.9 when the diffusion coefficient increases. It is however not so simple when considering the interplay between $\lambda_{\parallel}$ and $\lambda_{\perp}$. For the case when $\chi \rightarrow 1$ (isotropic diffusion with $\lambda_{\parallel} = \lambda_{\perp}$), $\langle\tau\rangle$ becomes independent of $\Delta\phi$. This is because the diffusion process is independent of the geometry of the HMF (i.e. there is no preferred diffusion direction) for this scenario.

Next, consider the use of $\langle\tau\rangle$ for parameter estimation. Say, for illustrative purposes, that the filled circles in Fig. 6.7 are actually measurements of $\langle\tau\rangle$. Furthermore, consider only two of these *measurements*: (1) $\langle\tau\rangle = 3.25$ days at $\Delta\phi = \pi/2$ and (2) $\langle\tau\rangle = 7.8$ days at $\Delta\phi = \pi/4$. These two *data points* can be used to constrain the values of two unknown parameters (keeping in mind that in order to uniquely define n parameters, at least n independent data points are

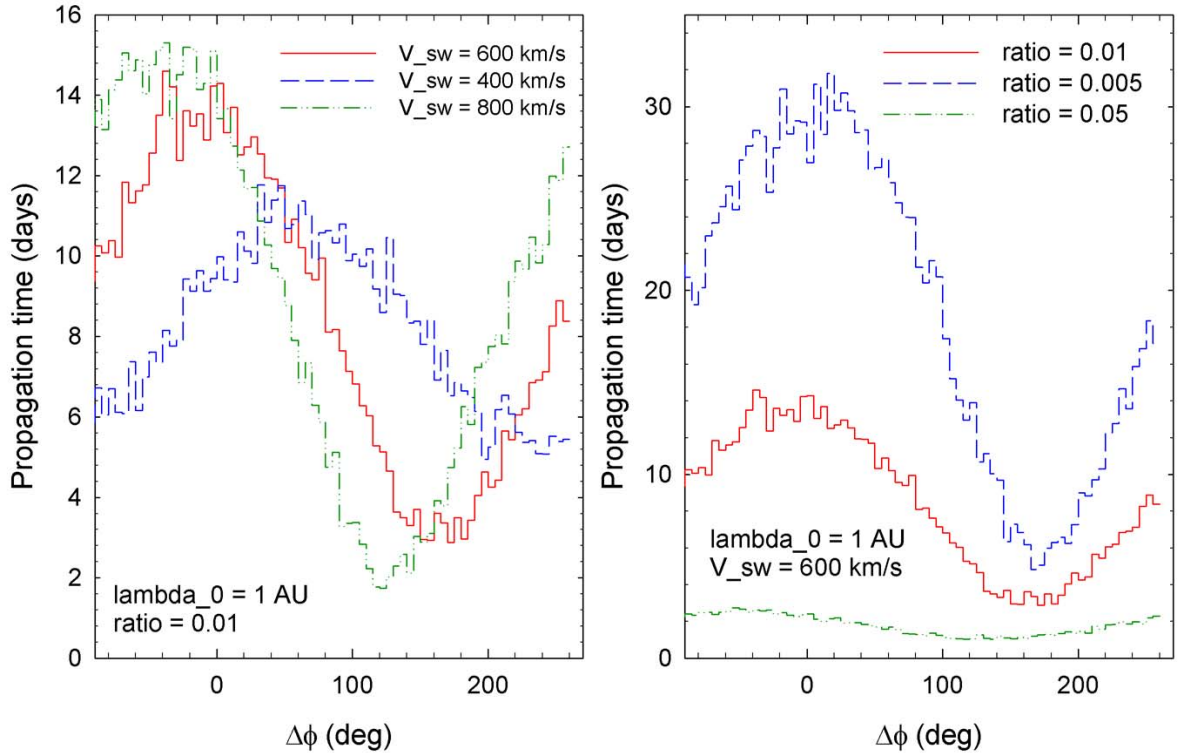


Figure 6.8: The response of the calculated $\langle \tau \rangle$ as a function of $\Delta\phi$ to changing values of V_{sw} (left panel) and χ (the ratio of the perpendicular to parallel diffusion coefficients, right panel) in the modulation model. See Eqs. 6.7 and 6.8.

needed). The two unknown quantities are chosen as λ_0 and χ and a parameter scan in the ranges $\lambda_0 \in [0.1, 10]$ AU and $\chi \in [0.001, 0.1]$ is performed. The results are shown in the top row of Fig. 6.9, where the resulting $\langle \tau \rangle$ is shown as a contour plot. The left panels are for $\Delta\phi = \pi/2$ and the right panels for $\Delta\phi = \pi/4$. As expected, smaller mean free paths lead to longer propagation times. In the bottom panels, the calculated error function

$$\epsilon(\lambda_0, \chi) = \frac{|\langle \tau \rangle_{\text{modelled}} - \langle \tau \rangle_{\text{observed}}|}{\langle \tau \rangle_{\text{modelled}}} \times 100\%, \quad (6.10)$$

is shown, using the two pseudo-measurements discussed above. It is intriguing that the best fit solutions form straight lines (on the log-log plot) in the parameter space, as indicated by the solid white lines. It is thus clear that the process is two-fold degenerate; different combinations of λ_0 and χ combine in such a way as to produce the same values of $\langle \tau \rangle$ at a given point in space. The red asterisk in each panel shows the values of (λ_0, χ) used to generate the pseudo-measurements. In Fig. 6.10, the results of Fig. 6.9 are combined into a single error function, also showing the separate best fit solutions. The intersection of the two white lines once again correspond well with the values of (λ_0, χ) used to generate the pseudo-measurements (indicated by the red asterisk). This theoretical case illustrates the methodology used in the rest of the paper where actual observations of $\langle \tau \rangle$ are used.

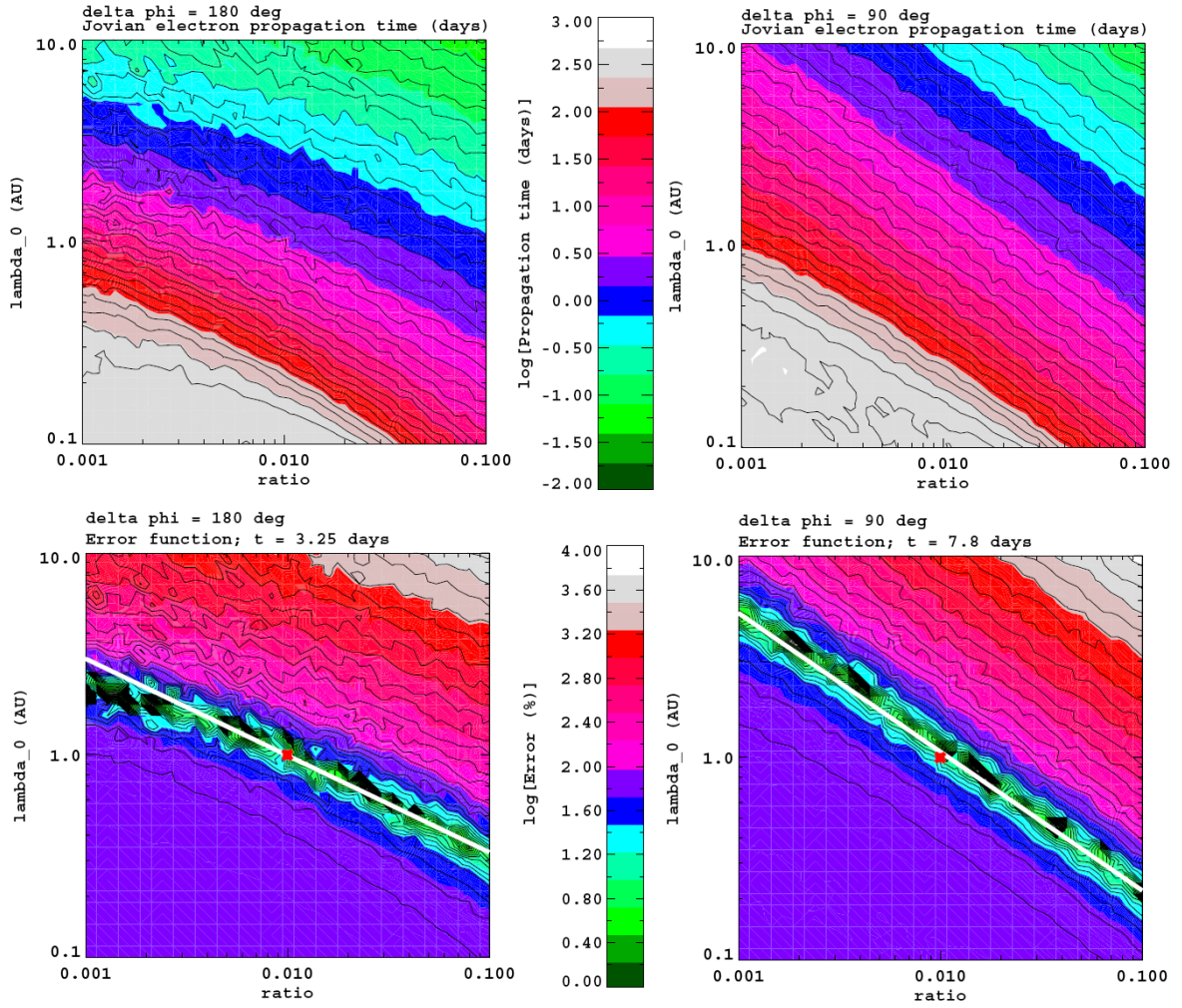


Figure 6.9: The top panels show the calculated $\langle \tau \rangle$ for $\Delta\phi = \pi/2$ (left panel) and $\Delta\phi = \pi/4$ (right panel) as a function of λ_0 and χ as in Eqs. 6.7 and 6.8. The bottom panels show the corresponding error function, calculated using the *observed* values of $\langle \tau \rangle = 3.25$ days (left panel) and $\langle \tau \rangle = 7.8$ days (right panel). The solid white lines indicate the best fit solutions, while the two red asterisks show the values of these parameters as used for the simulations in Fig. 6.7.

6.4.2 Observing Jovian Electron Propagation Times

Before considering how Jovian electron propagation times can be observed (or rather, be derived from observations), first consider the temporal distribution of this quantity at Earth (chosen throughout as an *observational* point). Fig. 6.11 shows this normalized distribution for a certain choice of parameters as an example. Up till now, only the average value of this quantity $\langle \tau \rangle$ has been considered, whereas, from now on, also $\tau_{\max}$, the most probable propagation time (i.e. where the distribution peaks) is considered. Depending on the choice of transport parameters, $\langle \tau \rangle$ and $\tau_{\max}$ can differ by up to a factor of ~ 100 if the distribution tends to be Poisson-like. If the distribution becomes more Gaussian-like, $\langle \tau \rangle \approx \tau_{\max}$; a scenario not encountered in any of the simulations performed here.

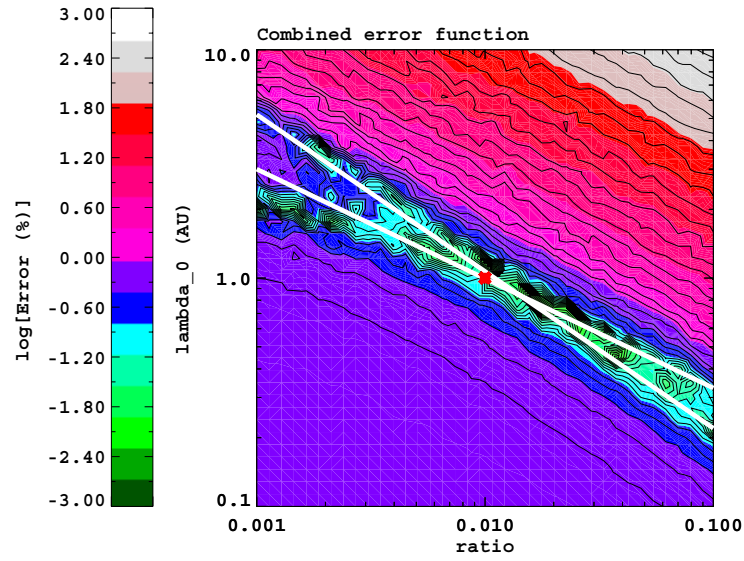


Figure 6.10: Combining the error functions, shown separately in the bottom panels of Fig. 6.9, onto a single contour graph.

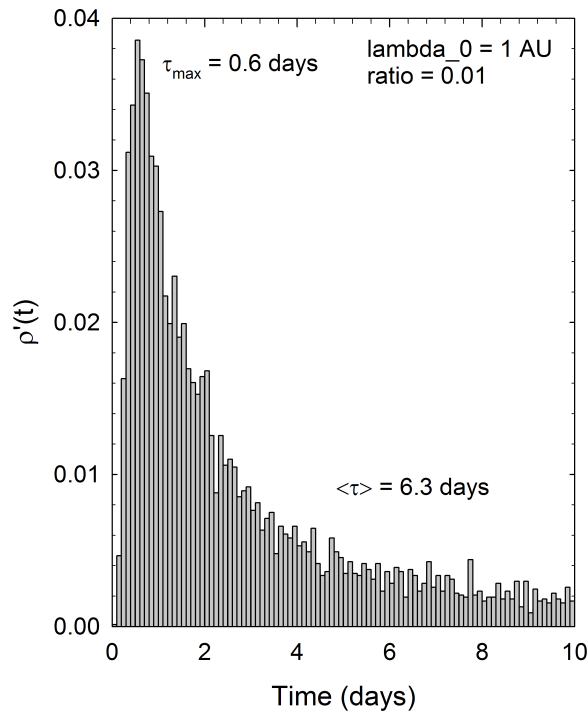


Figure 6.11: The normalized probability density of the propagation time of 6 MeV Jovian electrons reaching Earth with $\lambda_0 = 1$ AU and $\chi = 0.01$. Two time-scales are indicated on the figure, namely the most probable propagation time $\tau_{max} = 0.6$ days, and the average propagation time $\langle \tau \rangle = 6.3$ days.

It is probably impossible to measure the propagation time of galactic CRs in the heliosphere. However, the proximity of the Jovian magnetosphere to Earth, as well as the myriad of space-

craft making plasma and particle observations in the inner heliosphere, make it possible to do so for Jovian electrons. The methodology behind such an observation is quite complex and discussed below.

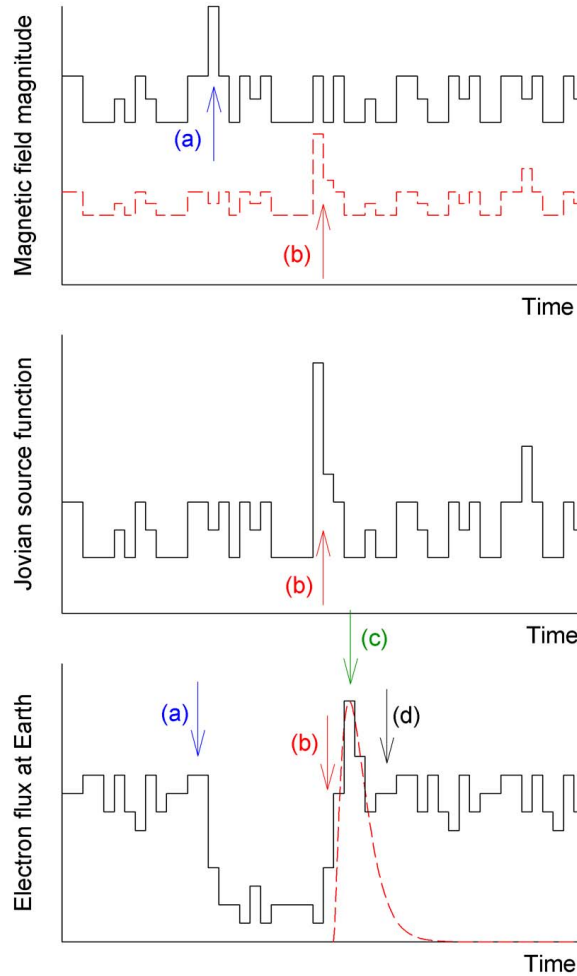


Figure 6.12: A schematic illustration of how an electron QTI is believed to occur using arbitrary units. The top panel shows the simulated HMF magnitude at Earth (solid line) and at Jupiter (dashed line). The middle panel shows the relative flux of Jovian electrons accelerated and released from the Jovian magnetosphere, while the bottom panel shows the resulting flux at Earth. The different time labels (a), (b), (c) and (d) are discussed in the text.

Since the 1960's [e.g. *Cline et al.*, 1964], a variety of electron variations on short time-scales have been observed at Earth. Of interest here are the so-called quiet-time increases (QTIs), discussed by e.g. *McDonald et al.* [1972]. These QTIs are observed as increases in the low energy electron flux, seemingly anti-correlated with solar energetic particle events (transient solar events). During a QTI, the observed electron energy spectrum is also much harder, implying additional acceleration. After the discovery that low energy electrons are accelerated in the Jovian magnetosphere, it was realized that the QTIs occur due to a transient solar event (e.g. a coronal mass ejection or co-rotating interaction region) interacting with the Jovian mag-

netosphere and the plasma environment between Jupiter and Earth [see the discussion by e.g. *Chenette*, 1980]. Fig. 6.12 shows a schematic illustration of how a QTI is believed to form, and how the detection of such an event can be used to infer a propagation time for the Jovian electrons themselves. The top panel shows the HMF magnitude at Earth (solid line) and at Jupiter (dashed line), the middle panel the relative flux of electrons directly at the Jovian magnetosphere (from a modelling point of view referred to as the Jovian source function or input spectrum) and the bottom panel shows the electron flux at Earth. Assume a transient is released from the Sun at a time $t < t_a$, then at $t = t_a$, the transient passes Earth. The passage of a transient is usually observed by a compression of the HMF due to the forward propagating shock wave and a decrease in the CR flux observed at Earth. This drop in flux is due to the diffusion barrier (a stronger HMF and more turbulence lead to a decrease in the mean free paths) that is essentially located between Earth and Jupiter [see the modelling done by e.g. *Kissmann et al.*, 2004]. At $t = t_b$, the transient passes Jupiter while the electron flux at Earth has started to recover to *normal* or undisturbed quiet time levels. A second process however occurs when a transient interacts with the magnetosphere of Jupiter: The magnetosphere becomes more compressed, additional energy is deposited into the magnetosphere [see e.g. *Smith et al.*, 1978], and Jovian electrons are accelerated more efficiently (a higher absolute flux and a harder energy spectrum). This is indicated in the middle panel of Fig. 6.12: The Jovian source function is essentially comprised of two distinct components; a quiet time level, with an additional spike when a transient passes the magnetosphere. The resulting flux at Earth should mirror this two-component input spectrum: The red line in the bottom panel indicates the contribution from only the *spikey* part (the Poisson shape of the curve based on the modelling shown in Fig. 6.11), while the solid dashed line shows the total flux. At $t = t_c$, the electron flux should reach a maximum, whereafter it drops back to quiet time levels at $t = t_d$. The connection between the propagation time and the electron flux will be discussed again later in this paper. The most probable propagation time is calculated as

$$\tau_{\max} \equiv t_c - t_b, \quad (6.11)$$

independent of the actual electron flux and only on the temporal distribution.

There are two possible drawbacks when using this method to calculate $\tau_{\max}$. Firstly, transient events usually do not occur at precise solar minimum conditions, but rather at moderate to maximum solar activity conditions. Secondly, multiple spacecraft observations are needed to calculate t_b , i.e. to determine exactly when the transient passes the Jovian magnetosphere.

Two QTIs from *Chenette* [1980] are selected for study in the rest of the work and are shown in Fig. 6.13. The value of t_b is also taken from the same paper. The two events are selected so that their values of $\Delta\phi$ are sufficiently different when using the observations for parameter estimation. It is debatable whether these observations actually represent solar minimum conditions, as they were taken during the historic 1970's mini-cycle that was observed predominantly in

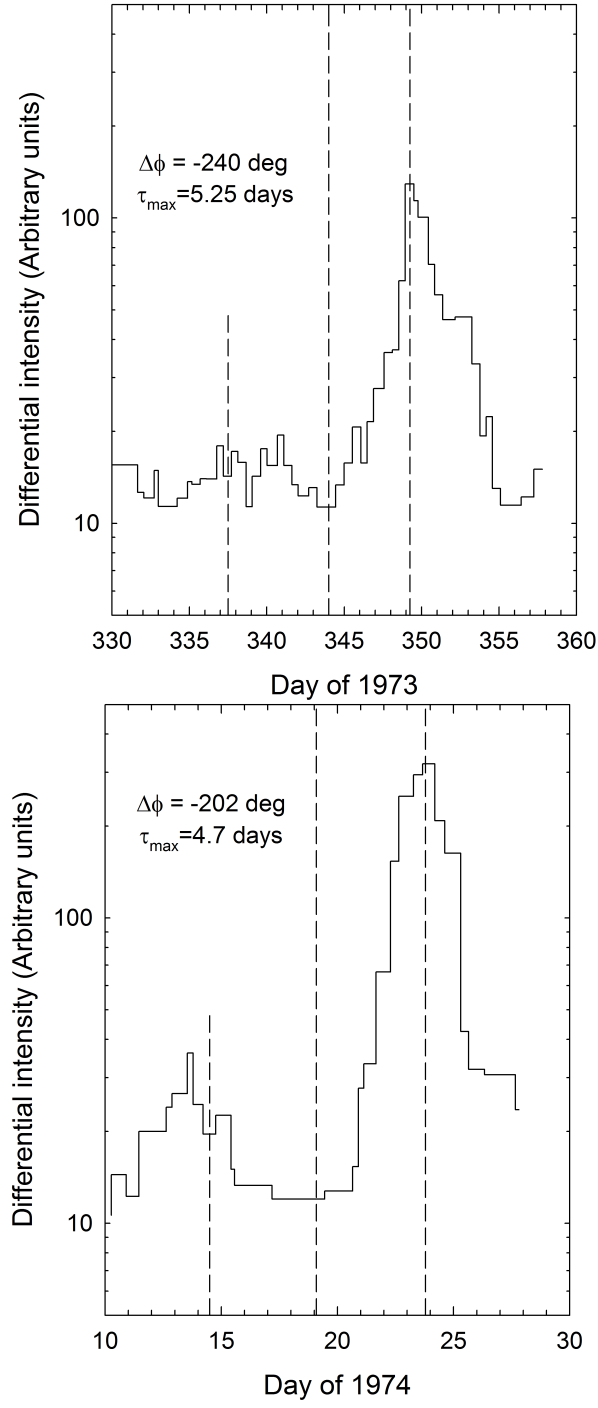


Figure 6.13: Two observed QTIs, selected from *Chenette* [1980], and used to calculate observational values of $\tau_{\max}$.

CR observations [see e.g. *Garcia-Munoz et al.*, 1977; *Wibberenz et al.*, 2001]. The two data points used further in this study are thus

$$\begin{aligned}
\tau_{\max} &= 5.25 \text{ days at } \Delta\phi = -240^\circ \\
\tau_{\max} &= 4.70 \text{ days at } \Delta\phi = -202^\circ.
\end{aligned} \tag{6.12}$$

6.4.3 Probing the Diffusion Coefficients

Using the same technique described in Section 6.4.1, the actual observed values of $\tau_{\max}$ are used to find an estimate of (λ_0, χ) that is representative of these observations. It should be noted that in the simulations only $\Delta\phi$ is changed in the transport model, whereas all other interplanetary conditions are kept constant. The resulting combined error function is shown in Fig. 6.14 as a contour plot in parameter space. The best fit solution is then simply where the error function is at a minimum, namely at $(\lambda_0, \chi) = (0.019 \text{ AU}, 0.095)$, indicated by the red asterisk on the figure. The values obtained here are dependent on the assumed radial and energy dependence of the mean free paths, with different profiles leading to different values of these quantities at Earth (again a degenerate scenario). The values obtained are, however, quite reasonable: *Bieber et al.* [1994] revisited the Palmer consensus values of $\lambda_{\parallel}$ at Earth, and found that $\lambda_{\parallel} \approx 0.1 \text{ AU}$, although this value will have a significant spread between individual events, up to a factor of ~ 10 [see also *Dröge*, 2000]. In order to reproduce Jovian electron intensities along the Pioneer 10 spacecraft trajectory, *Ferreira et al.* [2001a] used a value of $\lambda_0 \sim 0.04 \text{ AU}$ at Earth; again comparable to our estimates. *Giacalone and Jokipii* [1999] derived a range of $\chi \in (0.02, 0.04)$, which is about a factor of ~ 2 smaller than the estimate made here. None of the perpendicular transport parameters used here have, however, been enhanced at off-ecliptic latitudes; *Ferreira et al.* [2001b] needed a factor of up to ~ 16 increase in $\lambda_{\perp}$ to reproduce Ulysses observations, while *Zhang et al.* [2007] found similar results closer to the Jovian magnetosphere. This can account for the larger value of χ found here. Also note that the parameters estimated here depend on the assumed radial and energy dependencies of the diffusion coefficients, and as such, will change when these profiles are changed.

Using the best fit values of λ_0 and χ derived in the previous section, Fig. 6.15 shows the modelled $\tau_{\max}$ as a function of $\Delta\phi$ in the left panel. The scatter points are the observations used to gauge the values of the transport parameters. The behaviour of $\tau_{\max}$ is, however, very complex due to its dependence on the distribution function of the propagation times. It is therefore more intuitive to examine the corresponding behaviour of $\langle\tau\rangle$, as is done in the right panel of the figure.

The values of $\langle\tau\rangle$ shown in this figure are a factor of ~ 30 longer than those shown previously in Fig. 6.7. This is because the diffusion coefficients, as derived from observations in this section, are much smaller in magnitude than the ones used to produce the results of Fig. 6.7. Also note in Fig. 6.15 that $\langle\tau\rangle$ is much longer than the corresponding $\tau_{\max}$ because the distribution of the calculated propagation times has a very long tail at longer times. However, it should be remembered that the bulk of the particles would have a propagation time in the vicinity of

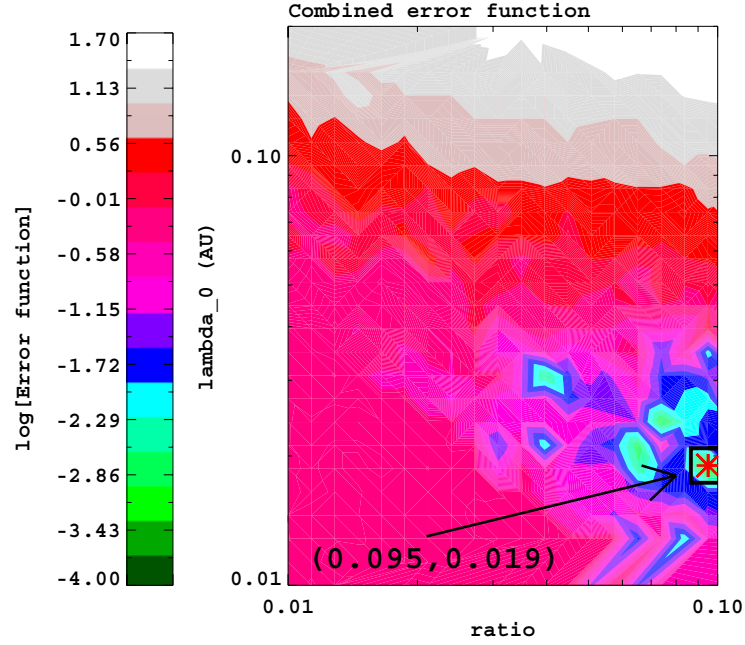


Figure 6.14: The resulting error function, in terms of the parameters λ_0 and the ratio χ , when modelled and observed values of $\tau_{\max}$ are compared. The red asterisk indicates where the error function is at a minimum at $(\chi, \lambda_0) = (0.095, 0.019 \text{ AU})$.

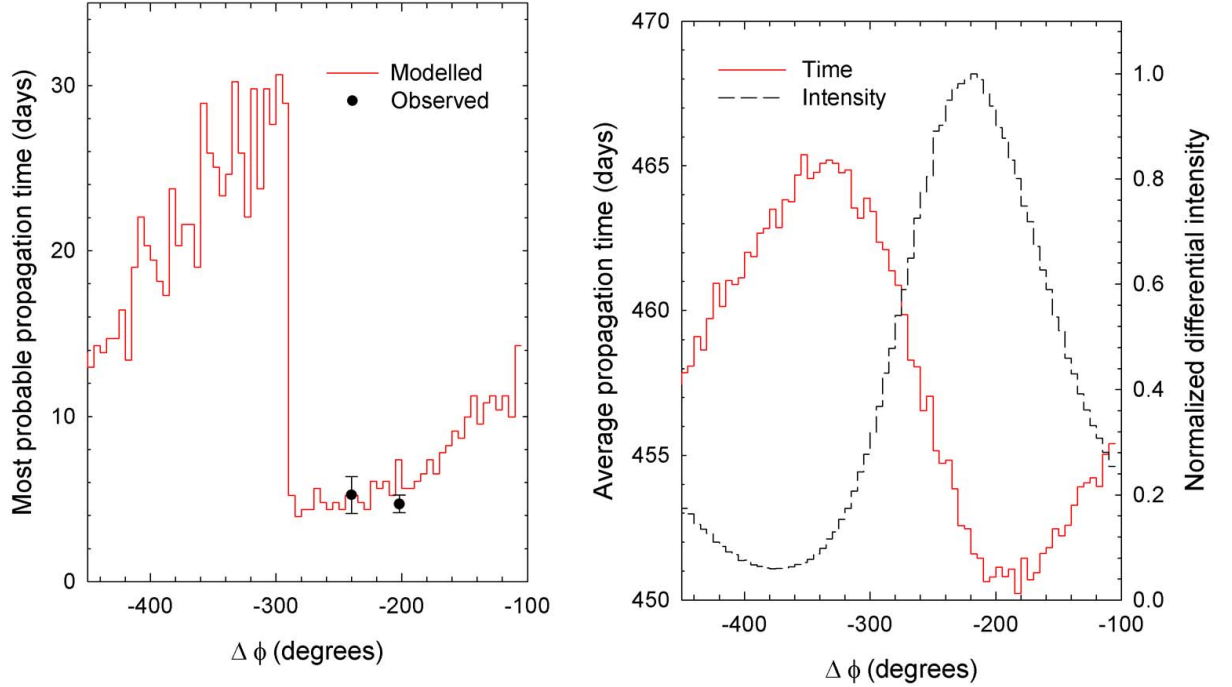


Figure 6.15: The solid red line in the left panel shows the modelled $\tau_{\max}$ as a function of $\Delta\phi$, while the two points show the observed values. The right panel shows the modelled Jovian flux at Earth (dashed line) and $\langle\tau\rangle$ (solid line) for the same set of transport parameters.

$\tau_{\max}$, so that $\tau_{\max}$ is, from an observational point of view, more relevant than $\langle\tau\rangle$. Moreover, the best-fit solutions shown here are based on a comparison with only two data points. It remains uncertain whether or not these two data points accurately describe the quantitative behaviour of $\tau_{\max}$.

As expected, Fig. 6.15 shows that $\langle\tau\rangle$ obtains its maximal value when the magnetic connectivity between Jupiter and Earth is at its worst, $\Delta\phi \approx -30^\circ$. During times of good magnetic connectivity, $\Delta\phi \approx -180^\circ$, $\langle\tau\rangle$ is at a minimum. Also shown in the right panel is the corresponding differential electron intensity at Earth (dashed line), normalized to unity where the intensity is a maximum. As could be expected, the electron flux is anti-correlated with $\langle\tau\rangle$, reaching its highest levels when $\langle\tau\rangle$ is at a minimum (this would correspond to the case when the energy loss is at a minimum; see Chapter 5). A roughly sinusoidal variation of the differential intensity with $\Delta\phi$ is characteristic of Jovian electron observations at Earth and leads to the well-known ~ 13 month periodicity observed at Earth [e.g. *Moses, 1987*]. The calculations show that the 6 MeV electron flux at Earth varies by a factor of ~ 10 during a ~ 13 month period, in good agreement with the observed factor of $\sim 10 - 15$ [e.g. *Chenette, 1980*].

6.4.4 An Estimate of the Jovian Flux at Earth

Before the differential intensity of Jovian electrons at Earth is calculated, the Jovian electron source function, the differential intensity directly at the Jovian magnetosphere, must be specified as a boundary condition. The source function as derived by *Ferreira et al. [2001a]* is used, where the differential intensity scales as $\sim E^{-1.5}$ below ~ 10 MeV, while softening to $\sim E^{-6}$ above this energy. This two component power law spectrum is based on observations near/at the Jovian magnetosphere [*Baker and Van Allen, 1976*] and also at Earth [*Moses, 1987*]. The left panel of Fig. 6.16 shows this assumed Jovian source function as the solid line, together with the (normalized) observations used to derive its spectral form. The fact that the spectral shapes of both sets of observations are similar, suggests that: (1) The diffusion parameters are energy independent in this energy range and (2) by keeping in mind that the rate of fraction energy loss is energy independent for relativistic electrons, both the propagation time and the fractional energy loss of these particles should be roughly energy independent. This last fact was also demonstrated by *Moses [1987]*. Moreover, the first point validates the assumption of an energy independent mean free path in this energy range. In order to normalize the Jovian source function to observed levels, the maximum intensity of 16 MeV electrons measured during the Pioneer 10 Jovian encounter (the red square on the figure), is used.

Using the Jovian source function discussed above, as well as the best fit transport parameters discussed in the previous section, the resulting Jovian electron differential intensity is calculated and presented in the right panel of Fig. 6.16. The red bands show the minimum and maximum intensities during a ~ 13 month cycle in the magnetic connectivity between Earth and Jupiter (i.e. the minimum and maximum levels during a complete cycle of $\Delta\phi$), with the red star showing the average. The solid line again shows the assumed Jovian source function,

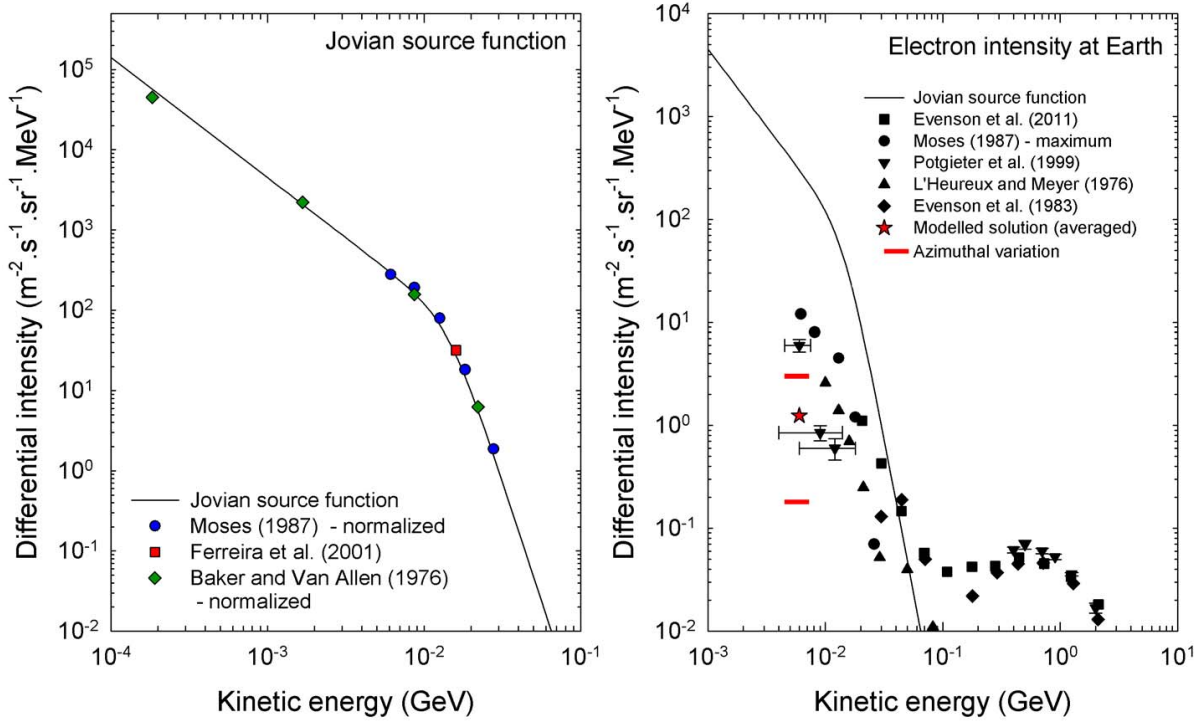


Figure 6.16: The left panel shows the Jovian source function as used in this work, together with the observations [Baker and Van Allen, 1976; Moses, 1987; Ferreira et al., 2001a] that were used to derive this spectrum. The right panel shows the observed electron intensities at Earth [with data from L’Heureux and Meyer, 1976; Evenson et al., 1983; Moses, 1987; Potgieter et al., 1999; Evenson and Clem, 2011], compared to our modelled solution: The horizontal red lines show the intensities during best and worst magnetic connectivity, while the red star shows the ~ 13 month averaged value.

while the scatter points show various observations of electrons at/near Earth. Note that all of these measurements were made during times of relatively good magnetic connectivity, and as such, should be compared to the maximum prediction. When comparing this modelled value with the observed levels at 6 MeV, the calculation is found to be $\sim 50\%$ lower than observed. This suggests that roughly half of the 6 MeV electrons observed at Earth are of Jovian origin, while the rest are of galactic origin. This estimate is similar (although lower) than the 60 – 75% Jovian contribution suggested by Ferreira et al. [2001a]. This result should, however, be interpreted cautiously. Although the calculation of the best fit transport parameters from the observed propagation times is robust, the calculation of the absolute Jovian flux at Earth, as well as the resulting galactic electron contribution, is based on two observational assumptions. Firstly, the absolute flux of the Jovian source function is scaled to observed electron intensities in the Jovian magnetosphere. It is however still unknown what fraction of these particles actually escape the magnetosphere before being transported to Earth. Secondly, to infer a value for the galactic electron contribution, the modelled flux has to be compared to low energy electron observations. Propagation times can however only be calculated during times of CIR interaction, resulting in a variable electron flux at Earth, making this comparison

difficult. In this study, quiet time electron observations were used, suggesting that our estimate of 50% should perhaps be interpreted as a lower limit. An in-depth investigation into these *unknowns* is needed before further conclusions can be made. See also the discussion by Potgieter and Nndanganeni [2013].

6.5 Summary and Conclusions

Jovian electrons were incorporated into the SDE model as a second CR electron species, after which their transport in the inner heliosphere was investigated. Energy spectra, as well as radial intensity profiles, with the inclusion of both galactic and Jovian electrons into the modulation model, were shown in Figs. 6.2 and 6.3. The same qualitative behaviour as noted in previous modulation studies was found, with Jovian electrons dominating the galactic contribution at low energies in the inner heliosphere. Notable from Fig. 6.3 is the wavy behavior of the Jovian intensities at large radial distances because of the relative motion of the Jovian magnetosphere included in the present model and shown in Fig. 6.5. For Jovian electrons observed at Earth, the motion of the Jovian magnetosphere, $\sim 4^\circ$, is negligible, while for Jovian electrons reaching 50 AU, this effect can become quite pronounced, $\sim 31^\circ$. In essence, this effect is due to the difference in propagation times between the two scenarios. The results of this section are qualitatively similar to those of previous studies using more traditional finite differences numerical schemes. Because of the numerical stability of the SDE method, more detailed (realistic) descriptions of the heliospheric environment can however be included in the model, e.g. including the relative motion of Jupiter.

For the first time, the propagation time of Jovian electrons from Jupiter to Earth was calculated and results presented here. The basic characteristics of the modelled $\langle\tau\rangle$ were shown and discussed. Amongst others, it was shown how $\langle\tau\rangle$ depends on the level of magnetic connectivity between Jupiter and Earth, as well as on the magnitude of selected transport parameters. Qualitatively, it is concluded that $\langle\tau\rangle$ is anti-correlated with the magnetic connectivity, so that $\langle\tau\rangle$ becomes larger when the level of magnetic connectivity worsens. It was shown how observational constraints may be placed on τ_{max} by making use of observed QTIs of the Jovian electron flux at Earth. These observational values were then used to gauge the magnitude of the transport parameters used in the modulation model. These *best fit* transport parameters were then used to calculate the absolute flux of Jovian electrons reaching Earth. It is confirmed, by using a completely independent analysis to that of Ferreira *et al.* [2001a], that a very significant fraction of the low energy electrons observed at Earth are of Jovian origin. This is in contrast to the suggestion made by Evenson and Clem [2011] that these observations are dominated by a galactic component.