The transport of galactic and jovian cosmic ray electrons in the heliosphere

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Abstract

An overview is given on what we know about the cosmic ray diffusion process from the modelling of low-energy (MeV) electron transport in the heliosphere. For energies below \( \sim 300 \) MeV, these electrons give a direct indication of the average mean free paths because they do not experience large adiabatic energy changes and their modulation is largely unaffected by global gradient and curvature drifts. Apart from galactic cosmic ray electrons, the jovian magnetosphere at \( \sim 5 \) AU in the ecliptic plane is also a relatively strong source of MeV electrons, with energies up to \( \sim 30 \) MeV. Therefore, when modelling the transport of these particles in the inner heliosphere, a three-dimensional treatment is essential. By comparing these models to observations from the Ulysses, Pioneer and Voyager missions, important conclusions can be made on e.g., the relative contributions of the galactic and jovian electrons to the total electron intensity, the magnitude of the parallel and perpendicular transport coefficients, and the time dependant treatment thereof.

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1. Introduction

In this paper, an overview is given on what we know about the cosmic ray diffusion process from the modelling of low-energy (MeV) galactic and jovian electron transport inside the heliosphere. The heliosphere is created by the Sun of which the turbulent plasma atmosphere constantly blows radially away from its surface (e.g., Parker, 1958) and called the solar wind. Imbedded in the solar wind is the Sun’s magnetic field wound up in a spiral and as it is transported into space it forms the heliospheric magnetic field (HMF). It is this HMF which determines the transport of charged particles, such as cosmic ray electrons, where it changes their intensities with time as a function of energy and position. This process is known as the heliospheric modulation of cosmic rays. Largely contributing to cosmic ray modulation is the diffusion process, resulting from irregularities in the HMF which scatters particles so that they effectively undergo a diffusive random walk along and across the HMF lines.

Cosmic ray electrons differ from other cosmic ray species: They are less massive, oppositely charged, and much less abundant, making it more difficult to measure their intensities. However, for energies below \( \sim 300 \) MeV, cosmic ray electrons (and positrons) give a direct indication of the diffusion transport because they do not experience large adiabatic energy changes and their modulation is unaffected by global gradient and curvature drifts. This aspect is shown in Fig. 1 (from Ferreira, 2002) where a numerical modulation model is utilized (see discussion below) to compute electron spectra at 1, 5, 60 and 90 AU in the equatorial plane. Results are shown in Fig. 1(a) for both the \( A > 0 \) and \( A < 0 \) polarity cycles. Fig. 1(b) shows the...
ratio of the computed intensities for the $A > 0$ and $A < 0$ polarity cycles. Shown here is that for energies $<30$ MeV and for all distances shown the spectra, corresponding to different polarity cycles, converge indicating that drift effects become less important. Also, the slope of the spectra follows the local interstellar spectra (LIS) due to a constant rigidity dependence of the diffusion coefficients assumed in the model, indicating that at these energies the transport is mostly diffusive in nature. This is in contrast to protons which experience adiabatic cooling. Discussed below is what we can learn of the electron diffusive process at low energies by using modulation models and compare results to spacecraft observations in particular.

2. Sources of cosmic ray electrons

Concerning their origin, galactic cosmic ray electrons originate from far outside our solar system (see e.g., Casadei and Bindi, 2004; Kobayashi et al., 2004). They are accelerated during supernova explosions (e.g. Axford et al., 1977; Bell, 1978; Blandford and Ostriker, 1978) and distributed in the form of a power law $j \propto E^{-\gamma}$, with $\gamma = 2.6$ the spectral index, $E$ the kinetic energy in MeV/nucleon and $j = R^2 f$, the differential intensity typically in units of particles m$^{-2}$ s$^{-1}$ sr$^{-1}$ MeV$^{-1}$ with $f$ the distribution function (as in Eq. (1)); $R$ is rigidity where $R = p q / c$ with $p$ the particle's momentum, $q$ the charge and $c$ the speed of light. The total electron relativistic energy is given by $E + E_r$ with $E_r \approx 0.511$ MeV the rest mass energy of electrons. In terms of relativistic momentum this can be expressed as $E + E_r = \sqrt{c^2 p^2 + E_r^2}$ and in terms of rigidity $E + E_r = \sqrt{R^2 + E_r^2}$. Because $E_r$ is sufficiently small for electrons, $R \approx E$ for most energies interesting to electron modulation, and for all results shown in this work. For $E < \sim 20$ GeV, $\gamma \neq 2.6$ due to heliospheric modulation effects which is discussed below.

Apart from galactic electrons, other dominant sources of electrons, especially in the energy range of 0.2–25.0 MeV and for radial distances, <10 AU, are solar flares and the jovian magnetosphere (Eraker, 1982, and references therein). While solar flares have long been recognized as a source of energetic interplanetary electrons, it remained until the Pioneer 10 spacecraft was within 1 AU of Jupiter before the jovian magnetosphere was discovered to emit energetic electrons with energies up to at least $\sim 30$ MeV (Simpson et al., 1974; Teegarden et al., 1974; Chenette et al., 1974). Measurements of electrons on the Pioneer 10 and 11 spacecraft have shown that Jupiter’s magnetosphere is a continual emitter of relativistic electrons which propagate along and across the HMF directions in interplanetary space and are observed inward to Earth and outward to $\sim 10$ AU (e.g., Eraker and Simpson, 1979, and references therein). Moses (1987) found that the jovian electron intensity demonstrates little or no solar cycle variation and the energy spectrum between 5 and 30 MeV is fitted by a simple power law $j \propto E^{-\gamma}$, where $\gamma$ increases from $\gamma = 1.5$ at low energies to $\gamma = 6$ at high energies.

3. Electron transport models

To describe electron propagation in the outer heliosphere, axisymmetric (two-dimensional) shock acceleration models were developed (Jokipii and Kóta, 1991; Moraal et al., 1991; Haasbroek et al., 1997; Potgieter and Ferreira, 2002). As these models showed jovian electrons can be convected outward to the termination shock (TS), where they undergo diffusive shock acceleration. Together with galactic cosmic ray electrons, these particles can be transported and modulated to contribute to electron intensities in the heliosphere, especially
at Earth. However, these models are not suitable for a study of the propagation of jovian electrons for regions inside Jupiter’s orbit. There, the transport is truly three-dimensional because of the proximity of the jovian source which cannot be treated as a ring source. With the recent measurements of jovian electrons made by the Ulysses spacecraft in the inner heliospheric region (Heber et al., 2001) the need for a fully three-dimensional treatment of jovian electron propagation has again been emphasized.

Several valued attempts have been made to calculate the three-dimensional distribution of the jovian contribution to the total electron intensity in the inner-heliospheric regions. The first model was developed by Conlon (1978) and later modified by Rastoin (1995) which included adiabatic deceleration. Due to the analytical approach made possible by assuming Cartesian geometry, this model is limited to regions close to the source and is not suited to simulate the global modulation of galactic cosmic ray electrons. A three-dimensional steady state model was developed by Fichtner et al. (2000) and a more recent time dependent version by Fichtner et al. (2001). The latter model was adopted by Kissmann et al. (2004) to study the effects of corotating interaction regions on the transport of jovian electrons. These models are based on the Parker (1965) transport equation and are most suitable to simulate the modulation of galactic cosmic ray and jovian electrons. These studies was complemented by Ferreira et al. (2001a,b) who developed a similar model but used a different numerical scheme. Fig. 2 shows an example (from Ferreira et al., 2001a) of the computed three-dimensional distribution of jovian electrons in the equatorial plane in the inner heliospheric regions. Shown here is that within 10 AU the jovian is mainly transported along the HMF toward and away from the Sun resulting in an unique distribution.

4. Cosmic ray transport

When cosmic rays enter our heliosphere they are convected with the solar wind outward away from the Sun resulting in adiabatic cooling (deceleration). However they can also be accelerated in compression regions or at shocks via first order Fermi acceleration. Due to irregularities in the HMF these particles are also scattered so that they effectively undergo a diffusive random

Fig. 2. The computed three-dimensional distribution of jovian electrons in the equatorial plane and in the inner heliospheric regions using a modulation model as discussed in text (from Ferreira et al., 2001a).
walk along and across the HMF lines. Cosmic rays may also experience drift motions due to gradients and curvature of the HMF or any abrupt changes in the field direction, such as the heliospheric current sheet (HCS). These processes described above were combined by Parker (1965) into a transport equation

$$\frac{\partial f}{\partial t} = - (\mathbf{V} + \langle \mathbf{v}_i \rangle) \cdot \nabla f + \nabla \cdot (\mathbf{K} \cdot \nabla f) + \frac{1}{3} (\nabla \cdot \mathbf{V}) \times \frac{\partial f}{\partial \ln R} + Q$$

(1)

with \( f(\mathbf{r}, R, t) \) is the omni-directional cosmic ray distribution function; \( \mathbf{r} \) is position, \( \mathbf{V} \) is the solar wind velocity and \( t \) is time. Terms on the right-hand side represent convection, gradient, and curvature drifts, diffusion, adiabatic energy changes, and a source function, respectively. This equation contains all the relevant physics to describe cosmic ray transport and acceleration in the heliosphere (see Potgieter, 1998, for a detailed discussion).

In Eq. (1) the heliospheric diffusion process are described by the symmetric tensor elements \( \mathbf{K} \), and the diagonal elements give the diffusion coefficients of special interest

$$K_{rr} = K_0 \cos^2 \psi + K_{\perp} \sin^2 \psi; \quad K_{\theta \theta} = K_{\perp} \theta,$$

(2)

where \( K_{rr} \) is the effective radial coefficient consisting of a parallel \( K_i \) and a perpendicular diffusion coefficient in the radial/azimuthal direction \( K_{\perp} \), while \( K_{\theta \theta} \) is the perpendicular diffusion coefficient in the polar direction to the mean HMF. The pitch angle averaged guiding center drift velocity for a near isotropic cosmic ray distribution is given by \( \langle \mathbf{v}_i \rangle = \nabla \times (\mathbf{K} \mathbf{e}_B) \), with \( \mathbf{e}_B = \mathbf{B}/B_m \) and \( B_m \) the magnitude of the modified background HMF, with \( \mathbf{K} \) the off-diagonal element of the full diffusion tensor. The spiral angle \( \psi \) is defined as the angle between the radial direction and the average HMF. As pointed out by Ferreira et al. (2000) \( K_{\perp} \) is more important in the outer heliosphere, especially for the lower energies, than \( K_i \).

This aspect is illustrated in Fig. 3 (from Ferreira, 2002) which shows \( \cos^2 \psi \) (dotted line) and \( \sin^2 \psi \) (solid line) as a function of radial distance for both the equatorial regions (\( \theta = 90^\circ \)) and the polar regions (\( \theta = 10^\circ \)).

5. Parallel diffusion

To determine the exact form of the diffusion coefficients two different but complementing approaches can be used: the turbulence approach. For this approach, the coefficients are determined from plasma and magnetic field observations using either turbulence theory (e.g., Bieber et al., 1994) or the theory of particle wave interaction (e.g., Lerche and Schlickeiser, 2001). For these approaches \( K_i \) are described by weak turbulence quasi-linear theory (QLT) (Jokipii, 1966). However, a long standing problem is that these parallel mean free paths, \( \lambda_i = 3K_i/v \), with \( v \) the speed of the particles, is smaller than those from solar particle observations (Palmer, 1982; Droge, 2003). This follows from the calculation of these parameters, where a power spectrum of the magnetic field fluctuations is needed. This power spectrum can be divided in three ranges: the energy range where the power spectrum variation is independent of the wavenumber; the inertial; the dissipation range. In the original derivation of the parallel mean free path the dissipation range was neglected resulting in a mean free path that is too small at low rigidities, and has the wrong rigidity dependence (Bieber et al., 1994). However, this \( \lambda_i \) is applicable to proton modulation in the heliosphere because cosmic ray protons experience large adiabatic energy changes below 300 MeV. At these energies the proton modulation seems unaffected by changes in the \( \lambda_i \) (e.g., Potgieter, 1984). For electron modulation,
the knowledge of the parallel mean free path is vital because the electrons respond directly to changes in $\lambda_{\parallel}$ for rigidities $<100$ MV. Including the dissipation range, the original QLT predicts a $\lambda_{\parallel}$ which is infinite. A higher order theory is therefore needed. Several mechanisms have been proposed to overcome this problem. An example is the effects of dynamical turbulence (Bieber et al., 1994) with two models, namely the damping model and the random sweeping model. This leads to a finite $\lambda_{\parallel}$ at the lower energies. However, for medium to low energies dynamical effects in the solar wind, such as propagation and thermal damping of waves, and time-dependent decorrelation of magnetic fluctuations, have a strong influence on the scattering mean free path. A model was presented by Dröge (2003) that addresses the above effects and was able to explain the observed rigidity dependence of solar particle mean free paths ranging from keV electrons to GeV protons.

Most theoretical studies using standard QLT, with the inclusion of dynamical turbulence models, concentrates on a $\lambda_{\parallel}$ in the inner heliospheric regions, while most of the cosmic ray modulation occurs in the outer heliosphere, where the knowledge of $\lambda_{\perp}$ is vital. Therefore, although valuable efforts are in progress, no complete modulation theory exists as yet, one in which the diffusion coefficients are determined on the basis of turbulence theory and the theory of charged particle scattering (e.g., Parhi et al., 2001; Minnie, 2002; Minnie et al., 2003). To overcome these problems the phenomenological approach is commonly used. Fortunately, anomalous cosmic rays (ACR) observations – see Fichtner (2000) for a overview – and GCR observations are done onboard the Pioneer, Voyager and Ulysses spacecraft and with the assistance of modulation models valuable information can be deduced from these observations (e.g., Moraal et al., 1999; Potgieter, 2000; Ferreira et al., 2001a,b; Fuji and McDonald, 2001; Ferreira and Potgieter, 2004). Discussed below are some examples of what can be learned by comparing model results with cosmic ray electron observations.

6. Perpendicular diffusion

Because of its complexity, theoretical work on $K_{\perp}$ had mostly been neglected (see e.g., le Roux et al., 1999). However, simulations by e.g., Giacalone and Jokipii (1999) suggest that $K_{\perp} \approx K_{\parallel}$ with $K_{\perp}/K_{\parallel}$ in the range of 0.02–0.04 for rigidities between $\sim$0.04 and $\sim$1.7 GV, while Ferrando (1997) found $K_{\perp}/K_{\parallel} = 0.005$ for $\sim$7 MeV electrons (see also Ferreira et al., 2001a,b). Recently, Bieber et al. (2004) suggested a new nonlinear guiding center theory (NLGC) for diffusion perpendicular to the mean magnetic field. Results from this theory are shown in Fig. 4, and show a perpendicular mean free path almost independent of rigidity and the ratio of $\lambda_{\perp}/\lambda_{\parallel}$ in the range of 0.01–0.04. These results support at least qualitatively the standard practice of assuming in modulation models that $K_{\perp} \approx K_{\parallel}$ (e.g., Jokipii and Kóta, 1995; Potgieter, 1996; Ferreira et al., 2000; Burger et al., 2000). Furthermore, prior to the Ulysses mission it was believed that positively charged cosmic rays preferentially enter the heliosphere easily from above the Sun’s poles in $A > 0$ HMF polarity cycles (e.g., $\sim$1990–2000). However, observations showed that the latitude dependence of cosmic ray protons is significantly less than predicted (Potgieter and Haasbroek, 1993; Heber et al., 1996). This rather surprising result led Kóta and Jokipii (1995) to revive the concept that $K_{\parallel}$ must be anisotropic, therefore $K_{\perp,\parallel} > K_{\perp,\perp}$ in off equatorial regions. This may arise naturally from the radial development of irregularities imposed by supergranulation at the surface of the Sun. Assuming this in modulation models (e.g., Kóta and Jokipii, 1995; Potgieter, 1996; Burger et al., 2000; Ferreira et al., 2000; Ferreira et al., 2001a) resulted in more realistic computed cosmic ray latitudinal gradients, comparable to observations (Potgieter, 2000), and in explaining the observed corotating interaction regions related effects at high heliospheric latitudes (e.g., Kóta and Jokipii, 1998).
7. Enhanced latitudinal perpendicular transport

Apart from anisotropic perpendicular diffusion, described above, Burger et al. (2000) illustrated that to produce the correct magnitude and rigidity dependence of the observed latitudinal cosmic ray proton gradient by Ulysses, enhanced latitudinal transport was also required (see also Potgieter et al., 1997). This is accomplished by increasing $K_h^t$ toward the poles by a factor $d$ with respect to its value in the equatorial plane. This aspect, and the effect on cosmic ray electron transport was studied in detail by Ferreira et al. (2001a) by comparing results to Ulysses observations. The relative contribution of the jovian and galactic electron intensities to the total intensity along the Ulysses trajectory was computed and it was shown that for this period the model could reproduce the Ulysses/KET electron measurements convincingly. This is shown in Fig. 5 (from Ferreira et al., 2001a) which shows computed 7 MeV jovian only, galactic only and combined intensity along the Ulysses trajectory. In comparison the 3–10 MeV electron count rate of the KET instrument onboard Ulysses is shown as a 4-day average count rate (top shaded line) with the selection of “1 electron” events (Ferrando et al., 1996), and the count rate corrected (bottom shaded line) for the estimated $\gamma$-ray background as upper and lower limits, respectively, (Heber et al., 2001).

As shown in Fig. 5 a parameter study was done of the effects of different $d$ scenarios with four different model computations shown corresponding to different $d$, where $d = 13$ is shown as the dashed–dotted line, $d = 6$ as the dotted line, $d = 3$ as the solid line and $d = 1$ as the dashed line. Shown here is that increasing the enhancement of $K_{l,0}$ toward the poles from $d = 1$ to $d = 13$ resulted in an increase in the computed jovian and in a decrease in the computed galactic electrons at high heliographic latitudes. By comparing these scenarios to the observations it was found that, and shown in Fig. 6 (from Ferreira et al., 2001a), that there is a linear dependence between $d$ and $K_h^t/K_i$. Therefore, to produce solutions compatible with observations measured by Ulysses, it was found that $K_{l,0}/K_i$ could be as high as 0.020 and as low as 0.005 in the equatorial regions as long as the factor $d$ has the correct magnitude. An upper limit to the ratio of $K_{l,0}/K_i$ in the polar regions was propose as 0.050–0.065 when computing solutions compatible with data. These results indicate that valuable information on $K_i$ can be deduced by comparing model results with spacecraft observations.

8. Perpendicular radial transport

By comparing model computations (Ferreira et al., 2004a) to ~6 MeV electron data from Voyager 1, which show that these low-energy electrons have almost no radial gradient up to ~82 AU, an upper limit of 0.003 was
found for $K_{\perp}/K_i$. This is illustrated in Fig. 7 (from Ferreira et al., 2004a) which shows the measured \( \sim 6 \text{ MeV} \) Voyager 1 intensities together with three model scenarios based on different assumptions of $K_{\perp}/K_i$. The scenario with $K_{\perp}/K_i = 0.005$ results in a too high intensities for $r > \sim 70 \text{ AU}$, whereas $K_{\perp}/K_i = 0.001$ seems to give too strong modulation. Optimal compatibility with the data is found with $K_{\perp}/K_i = 0.003$. However, for these simulations the radial dependence of the diffusion coefficients was assumed to increase moderately toward the TS. Therefore, the ratio of $K_{\perp}/K_i$ may increase at these energies if a different radial dependence, e.g., decreasing toward the solar wind TS, is assumed in the model. These effects are currently under investigation.

In Fig. 7 the effects of different $K_{\perp}$ are especially evident as the shock is approached, and in the upstream region. For $K_{\perp}/K_i = 0.005$ the model shows a moderate effect at the TS with a gradual increase in intensities toward the boundary. For $K_{\perp}/K_i = 0.003$ and $K_{\perp}/K_i = 0.001$ the shock effect is enhanced and a sharper intensity increase occurs closer to the inside of the TS, even as close as $\sim 10 \text{ AU}$. Beyond the TS the upturn to the required LIS value is significantly postponed the smaller $K_{\perp}$ is made. Clearly, in all cases the model indicates a large modulation “barrier” for low energy electrons inside the heliospheric boundary and even inside the TS depending on the ratio $K_{\perp}/K_i$ and of course the energy considered.

It is important to note that these studies predict a $K_{\perp}/K_i$ which is energy dependent. As shown in Fig. 8 (from Ferreira et al., 2004a) it must be increased to compute compatibility with observed electron intensities at higher energies in the inner heliosphere. Shown here are four computed scenarios corresponding to different $K_{\perp}/K_i$. Shown as triangles are observations at Earth from balloon experiments (Evenson et al., 1983) and observations from Ulysses with error bars when it was positioned at $r = 5 \text{ AU}$ and $\theta = 80^\circ$ (Heber private communication, 1998; Potgieter et al., 1999) (from Ferreira et al., 2004a).

\[ K_{\perp}/K_i \leq 0.003 \text{ produced model computations compatible with the observed Voyager 1 data, for } 100 < E < 500 \text{ MeV, } K_{\perp}/K_i = 0.010 \text{ results in compatibility with the observations, while for } E > 500 \text{ MeV, } K_{\perp}/K_i \text{ could be 0.030 and still results in compat-} \]
ibility with the observations in the inner heliosphere. These values at higher rigidities are in qualitative agreement with simulations done by Giacalone and Jokipii (1999) who found that the value of $K_i/K_\parallel$ is in the range 0.02–0.04 for 0.04–1.7 GV and to theoretical studies from Bieber et al. (2004).

9. Solar cycle related changes in the transport parameters

Although, the studies of Ferreira et al. (2001a,b) and Ferreira et al. (2004a), of which some of the results are shown above, provided new insights into model parameters, especially on the radial and latitudinal transport coefficients, they mainly concentrated on solar minimum conditions. As shown, for these periods no solar cycle related changes in the transport parameters were necessary to compute realistic modulation. However, with increased solar activity up to the recent solar maximum (~1998 onwards), the computed intensities from these models are found considerably lower than observed onboard Ulysses (Heber et al., 2002). These observed intensities has stayed at surprisingly high values and remained almost unchanged in contrast to what has been observed at higher energies, where drifts become more pronounced. As argued by Heber et al. (2002) these observations could neither be explained by solar particle events nor by locally accelerated electrons and must be of galactic and/or jovian origin.

To improve the compatibility of the model computations with Ulysses electron observations after ~1998, the effects of different solar wind speed $V$ scenarios, corresponding to different solar activity conditions, on the modulation of these electrons along the Ulysses trajectory were modelled by Ferreira et al. (2003) and results shown in Fig. 9 (from Ferreira et al., 2003; see also Moeketsi, 2004). Four computed jovian electron contour distributions at 7 MeV in the equatorial plane, which correspond to the scenarios assumed for $V$ in the modulation models, are shown. The dotted lines are the corresponding Parker HMF spiral. The scenarios characteristic to solar minimum conditions are shown in Fig. 9(a) and (c), and labelled ‘Min A’ and ‘Min B’ with $V$ highly latitude dependent, changing e.g., from a slow solar wind speed in the equatorial regions to a fast speed of 800 km s$^{-1}$ in the polar regions. Comparing these two figures illustrates that when $V$ is decreased from 400 km s$^{-1}$ (Min A) to 300 km s$^{-1}$ (Min B) in the equatorial regions (while keeping $V$ = 800 km s$^{-1}$ at the poles), the HMF spiral becomes more tightly wound as expected and the computed three-dimensional electron distribution follows suite. However, for solar maximum conditions, no well-defined high speed solar wind is observed (e.g., Richardson et al., 2001). The ‘Max A’

![Fig. 9. Four computed jovian electron contour distributions at 7 MeV in the equatorial plane, which correspond to the scenarios assumed for $V$, is shown (from Ferreira et al., 2003; see also Moeketsi, 2004).]
and ‘Max B’ scenarios are more representative of solar maximum conditions and are shown in Fig. 9(b) and (d), with $V = 400$ and 500 km s$^{-1}$ for all latitudes, respectively. Comparing these shows similar features as mentioned above. Figs. 9(a) and (b) are quite similar inside 5 AU because $V = 400$ km s$^{-1}$ in the equatorial regions for both although, it differs significantly in the polar regions. This indicates that although, the two scenarios are applicable to different solar activity conditions the computed low energy electrons seem less sensitive to the changes in the solar wind dependence in the polar regions. Figs. 9(c) and (d) are less similar because the corresponding $K_{irr}$, (where the spiral angle is depending on $V$) now also differs in the equatorial plane. This is especially evident outside of 5 AU (away from the Sun) because the effect of the less wound HMF is more pronounced the further away one moves outward. This indicates that the computed three-dimensional distribution of low energy electrons can indeed be changed during a solar activity cycle by assuming $V$ (which influences $K_{irr}$) as the only time dependent parameter.

However, it was concluded by Ferreira et al. (2003) that realistic solar cycle related changes in the solar wind speed alone, could still not explain the general trend in the Ulysses observations after $\sim 1998$. For these maximum activity periods the computed intensities were still significantly lower than observed. It was shown by Ferreira et al. (2004b) that in addition to solar cycle related changes in the solar wind speed a reduction in the enhancement of perpendicular transport toward the heliospheric poles, from its solar minimum value, seems necessary to compute realistic modulation. The decrease in this enhancement of perpendicular latitudinal transport results in higher computed galactic electron intensities, and can be correlated to the disappearance of the fast solar wind and/or the vanishing of a meridional component of the heliospheric magnetic field at solar maximum. However, this is under the assumption that there must be a significant jovian component present at high heliographic latitudes (Heber et al., 2003), and may change if a large solar component is present (see also Mocketsi, 2004).

10. Summary

An overview was given on what we know about the cosmic ray diffusion process from the modelling of low-energy (MeV) galactic and jovian electron transport inside the heliosphere. Electron modulation is unique because for energies below $\sim 300$ MeV, they give a direct indication of the diffusion process. This is because they do not experience large adiabatic energy changes and their modulation is largely unaffected by global gradient and curvature drifts. Furthermore, within 10 AU in the equatorial regions, the jovian electron intensity shows a three-dimensional distribution where these particles are transported along the HMF toward and away from the Sun and are sensitive to changes in the magnetic field geometry. Because of this a fully three-dimensional treatment of jovian electron propagation is needed in modulation models when low-energy electron transport is considered.

By comparing model results with Ulysses electron observations (e.g., Heber et al., 2001), it was shown by Ferreira et al., (2001a) that valuable information on the perpendicular diffusion coefficient in the polar direction $K_{\perp,0}$, can be learned. E.g., it was shown that enhanced latitudinal transport was required (see also Potgieter et al., 1997) by increasing, $K_{\perp,0}$ toward the poles by a factor $d$. Furthermore, there is a linear dependence between $d$ and $K_{\perp,0}/K_{\|}$ indicating that $K_{\perp,0}/K_{\|}$ could be as high as 0.020 and as low as 0.005 in the equatorial regions as long as the factor $d$ has the correct magnitude. An upper limit to the ratio of $K_{\perp,0}/K_{\|}$ in the polar regions was proposed as 0.050–0.065 when computing solutions compatible with data. (Here, the magnitude of $K_{\perp,0}$ is given in terms of the parallel diffusion coefficient $K_{\|}$)

By comparing model computations (Ferreira et al., 2004a) to $\sim 6$ MeV electron data from Voyager 1, which show almost no radial gradient up to $\sim 82$ AU, an upper limit of 0.003 was found for $K_{\perp,0}/K_{\|}$ with $K_{\perp,0}$ the perpendicular diffusion coefficient in the radial direction. However, for these simulations the radial dependence of the diffusion coefficients was assumed to increase moderately toward the TS. Therefore, the ratio of $K_{\perp,0}/K_{\|}$ may increase at these energies if a different radial dependence, e.g., decreasing toward the TS, is assumed in the model. Furthermore, (Ferreira et al., 2004a) found that $K_{\perp,0}/K_{\|}$ is energy dependent and must be increased to compute compatibility with observed electron intensities at higher energies. E.g. for $E > 500$ MeV, $K_{\perp,0}/K_{\|}$ could be 0.030 (see also Giacalone and Jokipii, 1999; Bieber et al., 2004) and still results in compatibility with the observations in the inner heliosphere.

Concerning solar cycle related changes, from $\sim 1998$ onwards computed intensities from current three-dimensional steady-state models were found considerably lower than observed onboard Ulysses (Heber et al., 2002). These stayed at high values and remained almost unchanged in contrast to models which predict a decrease toward solar maximum. To improve the compatibility, the effects of different solar wind speed scenarios, on the modulation of these electrons were modelled by Ferreira et al. (2003). They showed that the corresponding three-dimensional distribution of the electron intensities can be changed during a solar activity cycle by assuming the solar wind as a time dependent parameter. However, this could still not explain the general trend in the Ulysses observations after...
~1998. It was shown later by Ferreira et al. (2004b) that in addition, a reduction in the enhancement of perpendicular transport toward the heliospheric poles, from its solar minimum value, seems necessary. This decrease in the enhancement can be correlated to the disappearance of the fast solar wind and/or the vanishing of a meridional component of the heliospheric magnetic field at solar maximum. However, this is under the assumption that there must be a significant jovian component present at high heliographic latitudes (Heber et al., 2003), and may change if a large solar component is present. However, these issues may be better explained in future with a fully three-dimensional time dependent approach (e.g., Kissmann et al., 2004).

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