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Ulysses observations of Jovian relativistic electrons in the interplanetary space near Jupiter: Determination of perpendicular particle transport coefficients and their energy dependence

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Abstract

Intensities of ~1–10 MeV relativistic electrons in several energy channels of the high-energy telescope (HET) on Ulysses increase dramatically during its flybys of Jupiter in 1992 and 2004. Perpendicular diffusion coefficients of these particles are derived by fitting the spatial profile of Jovian electron intensity to a diffusion-convection model of particle transport. It is found that the latitudinal diffusion coefficient during the 2004 Jupiter flyby has to be enhanced from its value during the 1992 Jupiter flyby and it is also enhanced relative to the radial perpendicular diffusion. Such an enhancement of latitudinal particle transport was implied previously through the observations of Jovian electrons, cosmic rays and solar energetic particles at high heliographic latitudes, and now this requirement extends further to low latitude region of the heliosphere. Energy dependence of the perpendicular diffusion coefficient is obtained quite precisely through the variation in the slope of energy spectrum of Jovian electrons. The perpendicular diffusion coefficient increases with energy, which can put a tight constraint on models of the particle transport coefficient. The newest nonlinear guiding center (NLGC) theory of perpendicular diffusion is consistent with this observation, but only when it is combined with a parallel diffusion coefficient from the quasilinear theory in a slab magnetic turbulence without dynamic damping.

Keywords: Jupiter; Relativistic electrons diffusion; Interplanetary medium

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1. Introduction

In 1973, as *Pioneer*-10 was approaching Jupiter for the first time, the intensity of relativistic electrons of a few MeV energies increased dramatically (Simpson et al., 1974; Chenette et al., 1974; Teegarden et al., 1974). Since then, Jupiter has been known to be a steady source of relativistic electrons that dominate the inner heliosphere from Mercury's orbit (Eraker and Simpson, 1979), to Earth (Trainor et al., 1974; Chenette, 1980) and to beyond ~25–30 AU (Eraker, 1982). On the large scale of the heliosphere the Jovian magnetosphere appears to be a point source of relativistic electrons at a known location, thus providing a tool for investigating charged particle propagation in turbulent heliospheric magnetic fields and for probing the magnetic field and solar wind structures. For example, it is known that Jovian electrons are periodically interrupted when corotating interaction regions (CIRs) pass between the observer and Jupiter (Conlon and Simpson, 1977; Conlon, 1978). The spatial profile of Jovian electron intensity can permit the determination of particle diffusion coefficient in the heliospheric magnetic field. Using a simple convection-diffusion model, Conlon (1978), Hamilton and Simpson (1979) and Chenette (1980) were able to derive the diffusion coefficients both parallel and perpendicular to the average Parker magnetic fields. Some of the previous values of

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Table 1
Jovian electron (~1–10 MeV) diffusion coefficients in the interplanetary space

Reference	Diffusion coefficient	Value (cm^2/s)
Chenette et al. (1974)	$\kappa_{\parallel}$	5×10^{22}
	$\kappa_{\perp r}$	1×10^{20}
Conlon (1978)	$\kappa_{\parallel}$	5×10^{22}
	$\kappa_{\perp r}$	5×10^{20}
Hamilton and Simpson (1979)	$\kappa_{\perp\theta}$	2×10^{20}
Ferrando et al. (1993)	$\kappa_{\parallel}$	5×10^{22} [a]
	$\kappa_{\perp r}$	8×10^{20}
	$\kappa_{\perp\theta}$	2×10^{20} to 8×10^{20}
Simpson et al. (1993)	$\kappa_{\perp\theta}$	8×10^{20} to 3×10^{20}
Ferreira et al. (2001)[b]	$\kappa_{\parallel}$	1×10^{23}
	$\kappa_{\perp r}$	$0.005\kappa_{\parallel}=5\times10^{20}$
	$\kappa_{\perp\theta}$ (equator)	$0.005\kappa_{\parallel}=5\times10^{20}$
	$\kappa_{\perp\theta}$ (pole)	$13\kappa_{\perp\theta}$ (equator) $=65\times10^{20}$

[a] Ulysses observation does not have sensitivity to $\kappa_{\parallel}$. Data taken from Conlon (1978).

[b] Diffusion coefficients are calculated from the formula in Ferreira et al. (2001) for 4 MeV electrons at 4 AU.

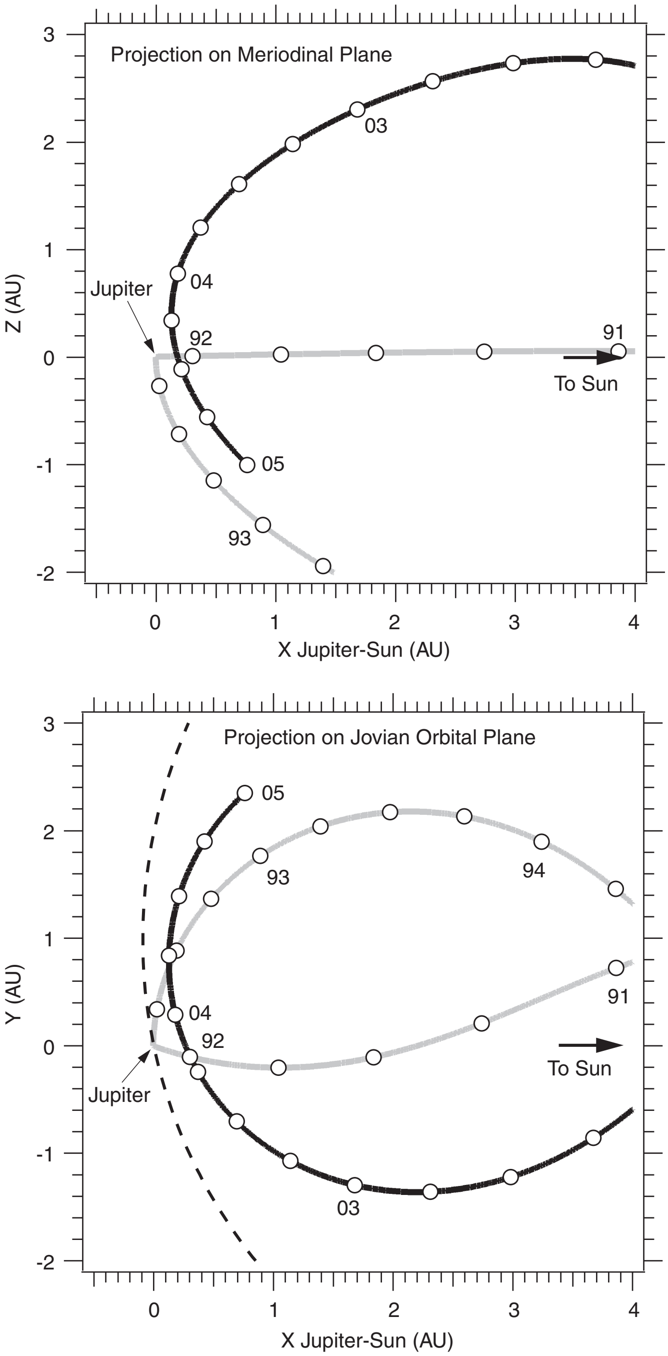

Fig. 1. Trajectory of Ulysses projected on the meriodinal plane and orbital plane of Jupiter during the two flybys. Ticks on the trajectory are in 3-month intervals. The dashed line is a Parker magnetic field connecting to Jupiter.

diffusion coefficients determined using the observations of Jovian electrons are listed in Table 1.

Ulysses was the fifth spacecraft that encountered Jupiter. It has had two flybys of Jupiter separated by 12 years, one with the closest approach of 6 Jovian radii (R_J) in February 1992 and the other at the closest distance of 1684 R_J in February 2004. Fig. 1 shows the Ulysses trajectory near the two Jupiter flybys in a Jupiter-centered sun-fixed coordinate system. A model Parker magnetic field line that connects to Jupiter is also shown in the ecliptic projection. On the inbound part of its trajectory in the first Jupiter flyby Ulysses was moving essentially in the ecliptic plane (approximately Jupiter's orbital plane), which is similar to the trajectories of *Pioneers* and *Voyagers* before Ulysses. For this part, the intensity of Jovian electrons is sensitive to perpendicular particle diffusion in the radial direction. *Ulysses* received a gravitation slingshot from Jupiter to the south in order to reach high heliographic latitudes. After the Jupiter encounter in 1992, Ulysses mainly traveled in the latitudinal direction with little movement in radial distance. On this part of the trajectory, the intensity of Jovian electrons is sensitive to perpendicular particle diffusion in the latitudinal direction. 12 years later, Ulysses returned to Jupiter's orbit, although the closest approach was a little further. The characteristics of Ulysses motion relative to Jupiter are very similar to the 1992 post-Jupiter encounter trajectory, although this time the spacecraft experienced both northern and southern hemispheres. Therefore, the spatial variation of Jovian electron intensity along the trajectory is also sensitive to perpendicular particle diffusion in the latitudinal direction. It should be pointed out that the Ulysses motion along the average magnetic field does not affect Jovian electron intensity because the parallel particle mean free path is typically larger than the parallel distance during the time intervals adjacent to the Jupiter flybys.

In both flybys, the intensity of Jovian electrons increased significantly toward Jupiter. Ferrando et al. (1993) applied the simple diffusion-convection model derived by Conlon (1978) to the Ulysses observations of Jovian electrons in the first Jupiter flyby. He was able to find the perpendicular diffusion coefficient out of the ecliptic for the 3–10 MeV electrons. By looking at the phase shift of the 10 hr variation of Jovian electron spectra, Simpson et al. (1993) were able to derive a latitudinal diffusion coefficient that was roughly consistent with the values derived by Ferrando et al. (1993). The simple diffusion-convection model by Conlon (1978) is a homogeneous model that should be limited to regions close to the source. Ferreira et al. (2001) developed a three dimensional model by numerically solving the full particle transport equation (Parker, 1965) including the particle gradient curvature drift so that they can fit the Ulysses measurements over the entire range of latitudes and radial distances. Their diffusion coefficients were chosen to be functions of location and particle rigidity. Fits limited to the region adjacent to the first Ulysses flyby in 1992 yielded the latitudinal diffusion coefficient that is basically consistent with that derived using the simple homogeneous diffusion-convection model (see Table 1).

The recent Jupiter flyby has given us another opportunity to study the properties of particle transport coefficients. It is the main purpose of this paper to use the spatial profile of the Jovian electron intensity to derive the particle diffusion coefficient. Comparison with previous investigations is made to show the solar cycle dependence of the diffusion coefficients. Energy dependence of the diffusion coefficients is also determined using Jovian electron observations in different energy channels. The result is compared with newest theories of particle transport coefficient to put constraints on the particle transport theory and the magnetic turbulence model.

2. Instrumentation and data handling

We use relativistic electron measurements from the high-energy telescope (HET) instrument in COSPIN (Cosmic and Solar Particle Investigations) consortium on Ulysses. A detailed description of the HET can be found in Simpson et al. (1993). Although the detection system is optimized for determining the isotopic composition of nuclei, there are several channels that measure electrons in the energy range from ~1 to ~10 MeV with low efficiencies of just a few percent. The characteristics of the HET electron channels are listed in Table 2.

Ulysses carries a radioactive thermo-electric generator (RTG) as its source of electric power. Gamma rays emitted from the RTG may be converted by material on the spacecraft to pairs of electron and positron, both of which are counted as electrons by the HET electron channels. As a result, during interplanetary quiet time, the H6 channel responds primarily to RTG-induced events with a rate of ~10 c/s. Even when Ulysses is very close to Jupiter, the RTG-induced counting rate in the H6 channel still takes up more than 50% (most time over 90%) of the total H6 counting rate. We cannot reliably use the H6 measurement to figure out the true intensity of Jovian electrons with this large RTG background. Thus we only use the H7 and H8 electron channels that have a maximum of ~0.007 and ~0.02 c/s from the RTG background, respectively, as we can deduce from minimum counting rates of these channels (Fig. 2). The RTG background is steady over long time periods and we found that it does not change much over the entire Ulysses mission. So in our data analysis, a constant RTG background is subtracted out from the raw counting rate measurements. Only when the counting rates of real Jovian electrons fall close to the RTG background is this background subtraction important.

Another contamination to the HET electron channels is high-energy cosmic ray protons (Fig. 2). The detector logic of the electron channel has been designed to minimize such contamination. However, due to the detector dead time and high counting rate in the anticoincidence shield (S) from the RTG, a small percentage of high-energy minimum ionizing cosmic ray protons can be registered as electrons. Fortunately, the counting rate of this contamination is proportional to the high-energy cosmic ray

Table 2
High energy telescope data channels for electron measurements

Channel name	Detector logic	Energy range (MeV)	Geometric factor cm^2 sr
H6	$D_1D_2\overline{D_{1M}D_3D_4AS}$	~1–3	87
H7	$D_1D_2D_4D_6K_1\overline{D_{1M}D_{2M}K_4AS}$	~5–10	8.2–5.5
H8	$D_1D_2D_4\overline{D_{1M}D_{2M}D_6AS}$	~3–5	16.2–14.9

Table data are from Simpson et al. (1992).

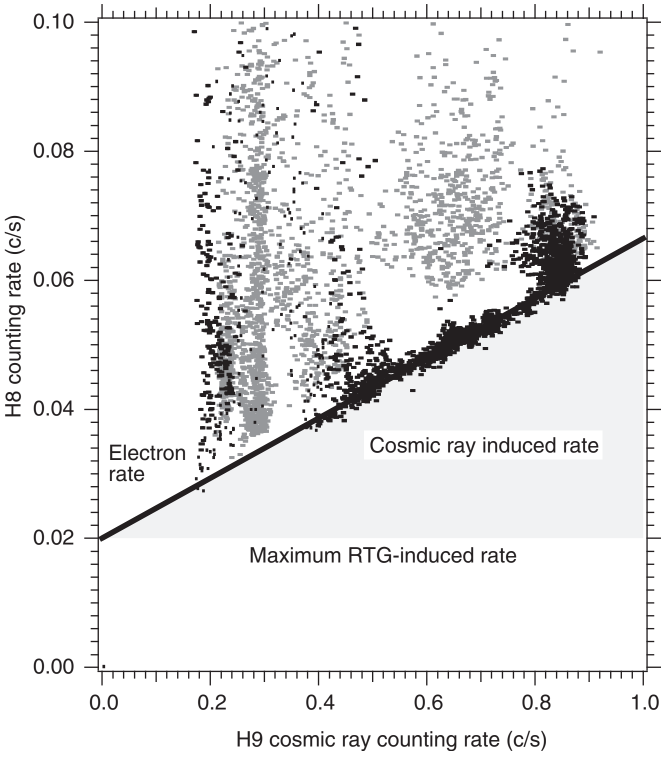

Fig. 2. A correlation between the raw H8 and H9 counting rates, showing the contributions from cosmic rays, RTG and real electrons to the H8 counting rate. The black dots are data before 1998 and gray dots are the rest of the Ulysses HET data.

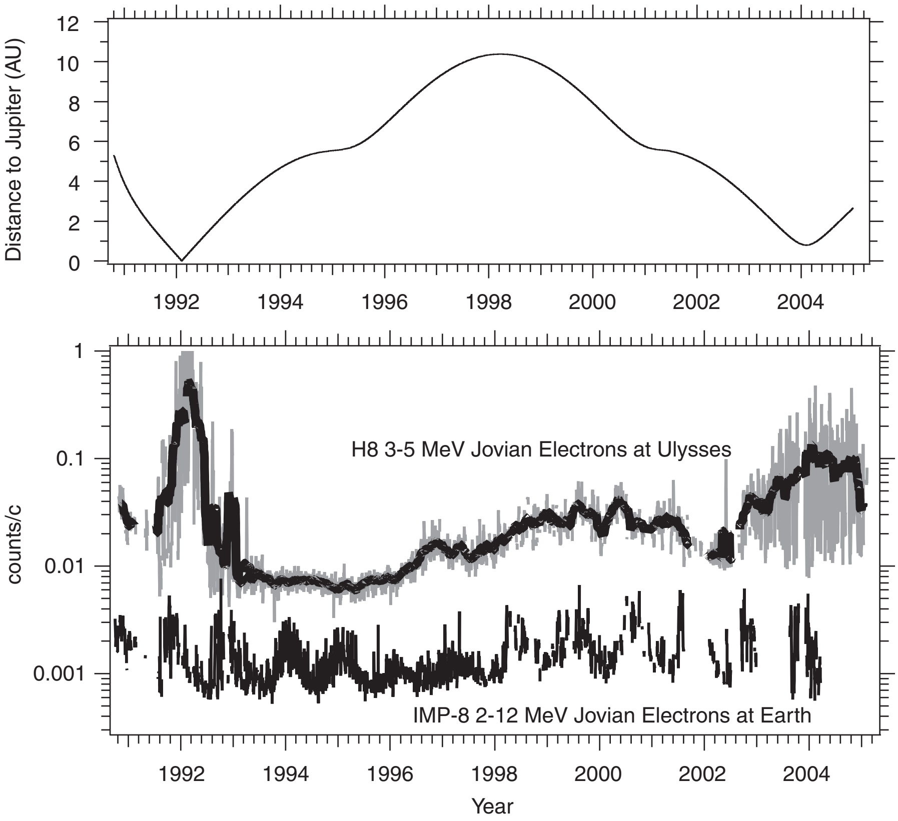

Fig. 3. Radial distance of Ulysses to Jupiter and intensity of Jovian electrons observed by Ulysses and IMP-8 at 1 AU. The thin lines are daily averages and thick line is 53-day running averages.

intensity (Fig. 2), which is measured by the H9 E > 92 MeV channel of the same instrument. The percentage of high-energy cosmic ray protons registered as electrons has been found from the correlation between the minimum quiet time counting rate in the electron channels and the H9 counting rate. We then subtract out the contribution of high-energy cosmic ray protons from the counting rate in the electron channels with a fixed constant times the H9 counting rate. It is found that cosmic rays may contribute up to 0.04 c/s in the H8 channel and 0.03 c/s in the H7 channel during the solar minimum of 1997 when cosmic ray intensity is the highest. The contamination during the two Jupiter flybys is only about a third of the above number due to lower cosmic ray intensity. The uncertainty of this background contamination is much smaller <0.001 c/s (1σ). Therefore, uncertainty of Jovian electron intensity due to the cosmic ray proton contamination is small, particularly when the electron-counting rate is much higher than the maximum contribution from cosmic rays.

Energetic solar events or strong interplanetary shocks can occasionally accelerate electrons to multiple MeV. These events have much higher electrons intensity than Jovian electrons. Because energetic electrons produced by solar events or interplanetary shocks have very different characteristics, i.e., their spectral slope is much steeper than Jovian electrons and they are always accompanied by enhancements of energetic protons above 10 MeV, we can easily eliminate the time intervals when our measurements are dominated by electrons from these events.

After the above background eliminations, the counting rate of the H8 channel from the 3 to 5 MeV Jovian electrons is plotted in Fig. 3. The HET Jovian electron intensity exactly matches the Kiel electron telescope (KET) electron measurements in a similar energy range on the same spacecraft (Heber et al., 2005). The KET uses a more complicate analysis involving pulse height information to eliminate the RTG and cosmic ray backgrounds.

We also use 2–12 MeV electron measurement obtained by the CPD instrument on IMP-8 to monitor the level of Jovian electrons intensity at 1 AU. Since we will not do in depth analysis of Jovian electrons at 1 AU, we omit the detail of that instrument and data analysis. Interested readers may see Garcia-Munoz et al. (1975) for more information.

3. Results

Fig. 3 provides an overview of Jovian electron observations obtained by Ulysses for the entire mission so far. Counting rate of electrons in a similar energy channel on IMP-8 spacecraft at 1 AU is shown as a reference. There is a 13-month periodicity in the Jovian electron intensity observed at 1 AU because the two planets come into direct connection by the interplanetary magnetic fields every ~13 months as they revolve around the sun. The Jovian electron intensity is modulated by the passage of CIRs (Conlon, 1978). The maximum of the Jovian electron intensity at 1 AU does not vary much since 1972 (less than a factor of 3 in a solar cycle). So it is reasonable to assume that the Jovian electron source is roughly constant in a short time of ~1 year. In fact, the Jovian electron intensity at 1 AU in 2002–2004 is almost the same as that in 1992–1993. This fact may allow us to extend our assumption of constant Jovian electron source for a little longer time.

The distance of Ulysses to Jupiter is plotted in the top panel of Fig. 3. The two minima of the distance indicate the time of the two closest approaches of Jupiter, one in 1992 and the other 2004. An overview of Ulysses observations of Jovian electrons for the entire mission can be found in a companion paper (Heber et al., this issue, 2005) and a detailed description of impulsive Jovian electron jets can be found in McKibben et al. (this issue, 2005). In the paper, we concentrate our analysis on the regions near Jupiter flybys, roughly within 3 AU distance. We choose only the flyby intervals for three reasons. (1) Uncertainties in the RTG and cosmic ray background does not affect the result of our analysis due to high intensity of Jovian electrons. (2) The Jovian electron intensity is much higher than the galactic cosmic ray electron intensity, which, due to the higher solar modulation during the two Jovian encounters, should be lower than the minimum measured electron intensity in 1994–1995. (3) We can use Conlon's (1978) simple homogeneous diffusion-convection model without sacrificing too much accuracy.

The interplanetary propagation of Jovian electrons should obey the Parker particle transport equation for the particle distribution function f (Parker, 1965):

$$\frac{\partial f}{\partial t} = \nabla \cdot (\kappa \cdot \nabla f) - (\mathbf{V} + \mathbf{V}_{\mathrm{d}}) \cdot \nabla f + \frac{1}{3}(\nabla \cdot \mathbf{V}) p \frac{\partial f}{\partial p} + S\delta(x), \tag{1}$$

where κ is the diffusion tensor, which in the magnetic field coordinates may be written as

$$\kappa = \begin{pmatrix} \kappa_{\|} & 0 & 0 \\ 0 & \kappa_{\perp r} & 0 \\ 0 & 0 & \kappa_{\perp\theta} \end{pmatrix}, \tag{2}$$

where $\kappa_{\|}$ is the parallel diffusion coefficient, $\kappa_{\perp\theta}$ the perpendicular diffusion coefficient in the latitudinal direction and $\kappa_{\perp r}$ the other perpendicular diffusion coefficient in the plane containing the radial direction. $\mathbf{V}$ the solar wind speed, $\mathbf{V}_{\mathrm{d}}$ is the particle gradient/curvature drift speed, and S the source particle injection rate located at Jupiter. Normally, because the parameters in Eq. (1) are not a simple function of position and particle momentum, only numerical solution is possible (e.g. Ferreira et al., 2001). For electrons of a few MeV, gradient curvature drift is negligible compared to the other terms. If we only consider the region very close the Jovian source at ~5 AU, both the magnetic field and solar wind velocity (vector) can be treated as uniform so that the magnetic field coordinate system is approximately a Cartesian coordinate system and the solar wind velocity is roughly constant. Furthermore, because the propagation time from the source to an observer is short, the adiabatic cooling term can be neglected. We assume that the diffusion coefficients are constant, representing the average properties of particle transport near Jupiter. Conlon (1978) obtained an analytical steady-state three-dimenional solution to Eq. (1) for the above-simplified case, which, if expressed in a Cartesian coordinates of the local magnetic field at Jupiter, can be written as

$$f = S\left[8\pi D\sqrt{\kappa_{\|}\kappa_{\perp r}\kappa_{\perp\theta}}\right]^{-1} \exp(2\mathbf{F} \cdot \mathbf{D} - 2FD), \tag{3}$$

where $\mathbf{D}$ and $\mathbf{F}$ are vectors whose three components in the magnetic coordinates $(\perp r, \perp\theta, \|)$ can be written in terms of the diffusion coefficients, location vector $\mathbf{x}$ and solar wind vector $\mathbf{V}$ as $D_i = x_i/2\sqrt{\kappa_i}$ and $F_i = V_i/2\sqrt{\kappa_i}$ ($i = 1, 2, 3$), and D and F are the magnitude of the $\mathbf{D}$ and $\mathbf{F}$ vectors, respectively.

Eq. (3) has been proven quite satisfactory to fit the data near Jupiter (Conlon, 1978; Ferrando et al., 1993). Even at somewhat greater distances from Jupiter, the homogeneous Cartesian model performs reasonably well, because the effects of deviation of the assumed diffusion coefficient and coordinates system from those in the real Parker spiral field cancel each other. The reason is that the diffusion coefficient usually gets smaller in stronger magnetic fields but in the mean time field lines are getting closer so that the time of particle transport relative to the magnetic field lines remains roughly constant over a larger range. Therefore, the homogeneous Cartesian model can be stretched a little further for the perpendicular transport. Conlon (1978) even applied the model to observations at 1 AU and his results were quite satisfactory.

The usage of Conlon's diffusion-convection model has its limitations because of the above assumptions made. The reader should be aware that any diffusion coefficient derived from an observation is model dependent. The previous numbers derived using Conlon's (1978) model or Ferreira et al. (2001) model have been quite close (Table 1), so we may at least use Conlon's model to get the overall behavior of the particle transport coefficient near Jupiter. Furthermore, conclusions based on the change of derived coefficient using the same model can be drawn more confidently.

Fig. 4 shows fits of Eq. (3) to Ulysses observations for the 1992 Jupiter flyby. Normally, according to Conlon (1978), one has to fit the maxima of Jovian electron intensity in order to get the diffusion coefficient in the average interplanetary magnetic field because Jovian electrons are periodically interrupted by the passage of CIRs. However, we found the behavior of the Jovian electron intensity maxima is roughly the same as long-term averages of the intensity, which can be represented by

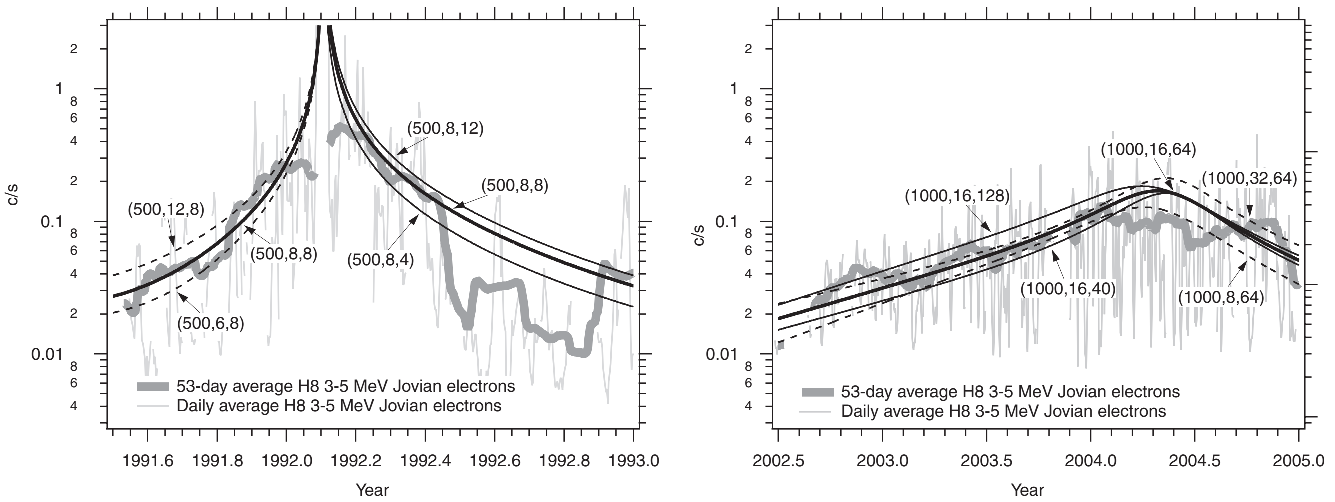

Fig. 4. Intensity of 3–5 MeV Jovian electrons and its fits to a diffusion-convection model of particle transport (Conlon, 1978) for the two Jupiter flybys. The thin gray line is the daily average of the Ulysses measurement and thick gray line is its 53-day running average. The dark lines are model fits with different sets of three diffusion coefficients ($\kappa_{\|}, \kappa_{\perp r}, \kappa_{\perp\theta}$), all in the unit of 10^{20} cm^2/s.

53-day (about two solar rotations) running averages. So we fit the 53-day averages with Eq. (3) to obtain particle diffusion coefficients.

The fits to the inbound part of the 1992 Jupiter flyby are only sensitive to $\kappa_{\perp r}$. This is because there is no motion of the spacecraft in the latitudinal direction and the parallel distance is too short for the parallel diffusion to modify the intensity significantly given that two diffusion coefficients, $\kappa_{\|}$ and $\kappa_{\perp\theta}$ are within the order of magnitude that agrees with the previous publications or our usual understanding. Fits yield that $\kappa_{\perp r} = 8(^{+4}_{-2}) \times 10^{20}\,\mathrm{cm}^2/\mathrm{s}$, where the numbers in the parentheses are the upper and lower error bars.

The fits to the outbound observation of the 1992 flyby are mostly sensitive to $\kappa_{\perp\theta}$ because the spacecraft mainly moves in the latitudinal direction. The fits yield $\kappa_{\perp\theta} = 8(\pm 4) \times 10^{20}\,\mathrm{cm}^2/\mathrm{s}$. There are regions in late 1992 where the observed Jovian electron intensity falls much below the model, probably because of the passage of strong solar wind stream interaction regions. But even so, the slope of the intensity profile still roughly agrees with the model fits. It should be pointed out in the fits we should weigh more heavily the data closer to Jupiter. The 53-day average of Jovian electrons immediately before and after the passage of Jupiter's magnetosphere is below the model fits, which is probably due to the data gap inside the magnetosphere in combination with chance temporary lows of Jovian electron intensity upon the exit from the magnetosphere. In the fits, due to the short parallel distance, the parallel diffusion coefficient $\kappa_{\|}$ can be arbitrary within the order of magnitude that matches the previous determinations, but $\kappa_{\perp r}$ has some effect on the fits because the spacecraft has some slight motion in the radial direction. However, the effect of $\kappa_{\perp r}$ is much smaller than that of $\kappa_{\perp\theta}$. Given the constraints from the analysis of the inbound part, we could conclude that $\kappa_{\perp r}$ and $\kappa_{\perp\theta}$ are approximately the same in the interplanetary space near Jupiter, a constraint also used in the global simulation by Ferreira et al. (2001). Of course, this assumes that $\kappa_{\perp r}$ does not change much before and after the closest approach of Jupiter.

To fit the observations of the 2004 Jupiter flyby, we have to change the diffusion coefficient significantly. The requirement was also concluded by Heber et al. (2005) using the more accurate model of Ferreira et al. (2001). The model fits are still sensitive to $\kappa_{\perp\theta}$ as the spacecraft was mainly moving in latitude. In order to fit the slope of particle intensity increase towards Jupiter, we have to increase $\kappa_{\perp\theta}$ by several times the value obtained from the first Jupiter flyby. A $\kappa_{\perp\theta}$ in the range of 40×10^{20} to $128 \times 10^{20}\,\mathrm{cm}^2/\mathrm{s}$ can produce reasonable fits to most part of the observations. Some bad fits near the closest approach (2004.3) are probably due to a data gap eliminated due to the presence of a solar event. The model fits have some sensitivity to $\kappa_{\perp r}$, but change of $\kappa_{\perp r}$ does not change the slope of the curves as much as $\kappa_{\perp\theta}$ simply because there is less motion in the radial direction. The same $\kappa_{\perp r}$ as the first flyby does not fit the data this time very well. We have to slightly increase it to within the range of 8×10^{20} to $32 \times 10^{20}\,\mathrm{cm}^2/\mathrm{s}$. However, due to the larger radial separation between Jupiter and Ulysses in the second flyby, the absolute intensity is sensitive to $\kappa_{\perp r}$, which is particularly true in the post closest approach part. Again the fits are not sensitive to $\kappa_{\|}$ because the parallel mean free path is much larger than the parallel separation. In order to fit the observations with increased $\kappa_{\perp\theta}$ and $\kappa_{\perp r}$ to accommodate the slope of the Jovian electron intensity variation, the source injection strength has to be reduced by a factor of ~3 from the epoch of 1992 flyby in order to match the absolute intensity level. A slight increase in $\kappa_{\|}$ is necessary in order to maintain the level of Jovian electrons observed at 1 AU. However, the Ulysses data do not have any sensitivity as to how large $\kappa_{\|}$ should be.

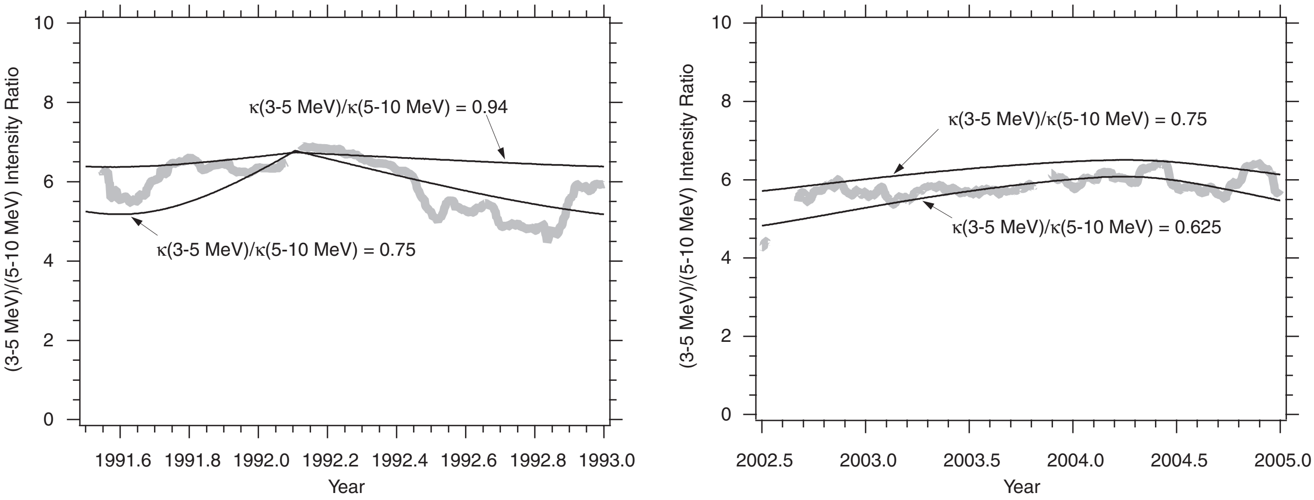

Fig. 5. Ratio of 3–5 to 5–10 MeV Jovian electron intensity and its fits to a diffusion-convection model of particle transport (Conlon, 1978), yielding the ratio of particle diffusion coefficients for the two energies.

The second HET electron channel (H7 5–10 MeV) behaves very similarly to the H8 3–5 MeV electron channel. The same analysis can be applied to yield the diffusion coefficient. However, due to large fluctuating nature of the Jovian electron intensity we cannot pin down the values of the diffusion coefficient within a factor 2 as can be seen from the above analysis of the H8 electron channel. In order to investigate the energy dependence of the diffusion coefficient more precisely, we calculate the ratio of the H8 to H7 Jovian electron intensities. Fig. 5 shows the time profile of 53-day averages of this ratio for the two Jupiter flybys. The variation of the ratio is much smaller than that of their intensity, simply because interplanetary disturbances have similar effects on the intensities in the both energy range. The maximum variation of the ratio is only 30%.

The logarithm of the ratio is approximately proportional to the index of energy spectrum assuming a power law spectrum. However, we are not able to calculate the exact value of the spectral index due mainly to the uncertainties of the detection efficiency and the energy range of each channel.

The H8 to H7 Jovian electron intensity ratio increases towards Jupiter. Since the H8 electrons have energies definitely lower than the H7 electrons because the H7 electrons have to through more Si material in the instrument, we can conclude that diffusion coefficients of electrons increase with energy, regardless of some uncertainty in the energy range determination. This is a very robust result. It is independent of detection efficiency. Because the intensity of Jovian electrons near Jupiter is so high, a small uncertainty in the background subtraction will not change this behavior.

Fits to the H8 to H7 Jovian electron ratio using the diffusion-convection model (Conlon, 1978) yield a ratio of the diffusion coefficient of the electrons in the two energy channels. It ranges from 0.75 to 0.94 for the first Jupiter flyby and 0.63 to 0.75 for the second Jupiter flyby. There is a region in the first post encounter part in which the ratio falls below the model calculation. This is due to the passage of solar wind stream interaction region. But even so, the slope of intensity ratio variation is still consistent with the model fits. The determination of the diffusion coefficient ratio is every accurate, although the absolute values of each of the diffusion coefficients in the two energy channels have larger error bars from the fits to the intensity only.

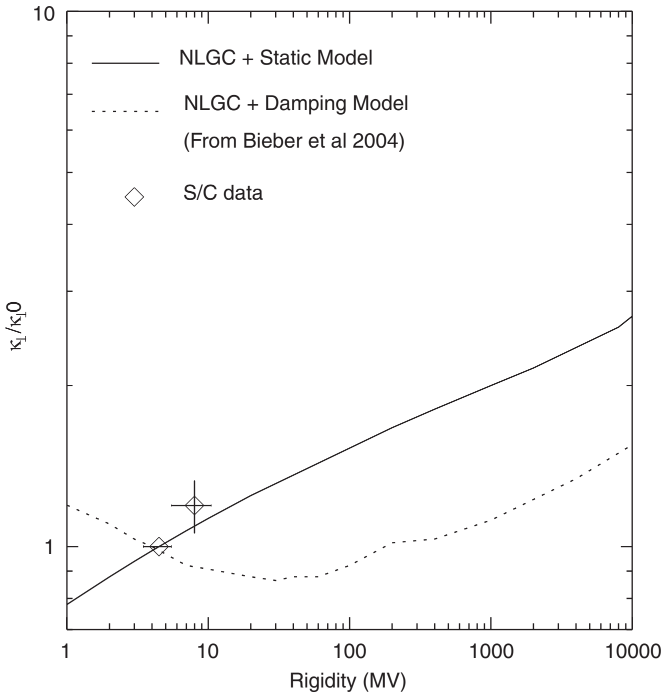

Fig. 6. Rigidity (approximately energy) dependence of the perpendicular diffusion coefficient for relativistic electrons and model calculations with the NLGC theory. The diffusion coefficient is normalized to its value for electrons in the H8 3–5 MeV channel.

Fig. 6 shows the diffusion coefficient as a function of particle energy along with model predictions using the newest nonlinear guiding center (NLGC) theory of particle transport (Matthaeus et al., 2003). The diffusion coefficients in Fig. 6 are normalized to the diffusion coefficient in one of the channels (the H8 3–5 MeV channel) so that we can highlight the trend of their energy dependence more precisely. The data are for the first Jupiter flyby since they are more certain than the second flyby because of the higher Jovian electron intensity so that the background subtraction is less important.

4. Discussion

Our analyses have shown that latitudinal diffusion coefficient $\kappa_{\perp\theta}$ in the interplanetary space near Jupiter has changed significantly from 1992 to 2004 by 5–16 times, but $\kappa_{\perp r}$ is only slighted increased. Enhancement of $\kappa_{\perp\theta}$ over the $\kappa_{\perp r}$ of up to 13 times is needed to fit Ulysses observations of Jovian electrons at middle to high latitudes (Ferreira et al., 2001), but it is only necessary in the high latitude region of the heliosphere. This time in the 2004 epoch, the enhancement of $\kappa_{\perp\theta}$ over $\kappa_{\perp r}$ is even required at low latitudes near Jupiter. This result is consistent with an independent study of Jovian electrons by Ferreira et al. (2003), in which they claimed that the latitudinal perpendicular diffusion must increase with solar activity.

The result suggests that latitudinal transport of energetic particles is relatively easy. The physical reason, which must come from the properties of interplanetary magnetic field, is not clear, but this conclusion is consistent with observations of nearly uniform intensity of solar energetic particles throughout in the inner heliosphere that can be established quickly after a solar event (McKibben et al., 2003). The latitudinal gradient of cosmic rays should be small. In fact, an almost zero latitudinal gradient of galactic and anomalous cosmic rays during the Ulysses fast latitude scan in 2000–2001 was reported (McKibben et al., 2003). The enhanced latitudinal transport near Jupiter in 2004 predicts that the latitudinal gradient of cosmic rays should continue to be small.

We have obtained a quite precise energy dependence of diffusion coefficient for relativistic electrons in the few MeV energy range. The diffusion coefficient increases with energy, although the energy or momentum dependence is weak, ranging from $p^{0.1}$ to $p^{0.7}$, where p is particle rigidity. A model of particle transport theory that predicts a flat or decreasing energy dependence is inconsistent with these Jovian electron observations. In Fig. 6 we compare with two predictions using the NLGC theory of particle transport. One (the dashed line) is taken from Bieber et al. (2004), who calculated particle perpendicular diffusion coefficient using the NLGC theory (Matthaeus et al. 2003) with a rigidity dependence of $\kappa_{\parallel}$ corresponding to the damping model of dynamical slab turbulence (Bieber et al. 1994). Clearly, the calculation of Bieber et al. (2004) predicts a trend of the energy dependence inconsistent with our analysis. We have made another calculation with the NLGC theory using the rigidity dependence of $\kappa_{\parallel}$ corresponding to the quasilinear model in a static magnetic turbulence (Jokipii, 1966; Bieber et al., 1995) instead of the damping model. The parameters we use to do the above calculation are very similar to those used in Bieber et al. (2004). Only small adjustments are made in order to make the absolute value of $\kappa_{\perp}$ consistent with the experiment value we derive in this paper. However, the adjusted parameters used in the model calculation are still typical of those observed in the solar wind (see more details in Bieber et al., 2004).

5. Summary

Ulysses observations of Jovian electrons during the recent Jupiter flyby have given us another opportunity to estimate the diffusion coefficient of relativistic electrons of a few MeV energies in the interplanetary space near Jupiter. Although not required by the observations in the previous Jupiter flyby, we find that latitudinal transport has to be enhanced relative to the radial transport, which is consistent with Ulysses observations of Jovian electrons, cosmic rays and solar energetic particles at high heliographic latitudes. This requirement now extends to the low latitude region of the heliosphere. The latitudinal transport is also more effective in 2004 than in 1992.

Another important finding of this paper is the energy dependence of relativistic electrons. The perpendicular diffusion coefficient increases with energy. It puts a tight constraint on models of particle transport coefficients. The newest nonlinear guiding center (NLGC) theory of perpendicular diffusion is consistent with this observation, but only when it is combined with a parallel diffusion coefficient from the quasilinear theory in a slab magnetic turbulence without dynamic damping.

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