



# Electron acceleration at Jupiter: input from cyclotron-resonant interaction with whistler-mode chorus waves

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**Abstract.** Jupiter has the most intense radiation belts of all the outer planets. It is not yet known how electrons can be accelerated to energies of 10 MeV or more. It has been suggested that cyclotron-resonant wave-particle interactions by chorus waves could accelerate electrons to a few MeV near the orbit of Io. Here we use the chorus wave intensities observed by the Galileo spacecraft to calculate the changes in electron flux as a result of pitch angle and energy diffusion. We show that, when the bandwidth of the waves and its variation with  $L$  are taken into account, pitch angle and energy diffusion due to chorus waves is a factor of 8 larger at  $L$ -shells greater than 10 than previously shown. We have used the latitudinal wave intensity profile from Galileo data to model the time evolution of the electron flux using the British Antarctic Survey Radiation Belt (BAS) model. This profile confines intense chorus waves near the magnetic equator with a peak intensity at  $\sim 5^\circ$  latitude. Electron fluxes in the BAS model increase by an order of magnitude for energies around 3 MeV. Extending our results to  $L = 14$  shows that cyclotron-resonant interactions with chorus waves are equally important for electron acceleration beyond  $L = 10$ . These results suggest that there is significant electron acceleration by cyclotron-resonant interactions at Jupiter contributing to the creation of Jupiter's radiation belts and also increasing the range of  $L$ -shells over which this mechanism should be considered.

**Keywords.** Magnetospheric physics (energetic particles, trapped; planetary magnetospheres) – Space plasma physics (wave-particle interactions)

## 1 Introduction

Jupiter has the most intense radiation belts of all the magnetized planets, with electron energies in excess of 50 MeV at  $L = 1.4$  (Bolton et al., 2002; de Pater and Dunn, 2003). These belts are believed to be formed by inward radial transport of electrons from a source beyond the orbit of the moon Io ( $L = 6.6$ ) on the assumption that the first adiabatic invariant remains conserved (Santos-Costa and Bourdarie, 2001; Sicard and Bourdarie, 2004). However, this idea requires a source of electrons in excess of 1 MeV for  $L > 6.6$  (Woch et al., 2004); the first such indications of a source were given in Horne et al. (2008).

Strong whistler-mode waves have been observed outside the orbit of Io (Gurnett et al., 1996; Menietti et al., 2008) in association with magnetic flux interchange instabilities (Kivelson et al., 1997; Thorne et al., 1997; Xiao et al., 2003). These waves are thought to be generated by the inflow of relatively warm electrons at energies of typically a few keV resulting from the interchange instability (Hill et al., 1981; Kivelson et al., 1997). The interchange instability moves overdense flux tubes, created by ionization of material ejected from Io, outwards to be replaced with an inflow of hotter but less dense plasma originating further away from the planet. The potential energy released during this process both drives the instability and adiabatically heats the incoming plasma (Thorne et al., 1997). At Earth chorus waves are very effective in accelerating electrons to MeV (Summers et al., 1998; Horne et al., 2005; Chen et al., 2007), and thus, by analogy, it has been suggested that electron acceleration

by whistler-mode chorus waves could provide the source of MeV electrons for Jupiter's radiation belts (Horne et al., 2008). Recent work shows that Jupiter is the most favorable planet for this type of acceleration (Shprits et al., 2012).

Wave acceleration is most effective when the ratio of plasma frequency to gyrofrequency ( $f_{pe}/f_{ce}$ ) is low, typically  $< 4$  (Horne et al., 2005). At Jupiter wave observations have only been made for latitudes  $\lesssim 10^\circ$  in the region outside Io; previous work to calculate the electron acceleration due to chorus waves assumed the waves only extended to  $10^\circ$  (Horne et al., 2008). However, observations at Earth and Saturn show that waves are observed up to latitudes of  $45^\circ$  (Meredith et al., 2001, 2012; Bunch et al., 2012; Menietti et al., 2012). Since the plasma density drops significantly with increasing latitude (Bagenal, 1994), the conditions for acceleration may be more favorable at higher latitudes. Shprits et al. (2012) showed that changing the theoretical latitudinal extent of the chorus waves plays a major role in the effectiveness of wave-particle interactions at Jupiter and Saturn. In this study we use data from the Galileo spacecraft to investigate in more detail the acceleration of electrons by wave-particle interactions at Jupiter in the region outside Io.

## 2 Calculating diffusion coefficients

When whistler-mode chorus waves are examined with high time resolution they are usually characterized by short-duration bursts of radiation below the local electron gyrofrequency,  $f_{ce}$ , which rise or fall rapidly in frequency. This type of frequency time structure is observed at Jupiter (Gurnett and Scarf, 1983) as well as the Earth (e.g., Burtis and Helliwell, 1969; Tsurutani and Smith, 1974; Santolík et al., 2003) and Saturn (Hospodarsky et al., 2008). Individual chorus bursts may only last a few milliseconds, but they often overlap in time and occur repeatedly for periods of hours and longer. For example, chorus waves were observed for several hours by Galileo each time the spacecraft orbited inside  $12 R_J$ , and this occurred on several orbits (e.g., Fig. 4 of Menietti et al., 2008). The frequency-time characteristics and discrete bursty nature of the signals suggests that the waves are generated by nonlinear wave-particle interactions (Trakhtengerts, 1999; Nunn et al., 1997; Omura et al., 2009). The general concept is that an electron temperature anisotropy causes linear wave growth and some of the resonant electrons become trapped and phase bunched by the waves via nonlinear effects. The trapped particles then act as a resonant current and re-radiate at a higher frequency with a nonlinear growth rate (for rising tones). These nonlinear wave-particle interactions and the formation of rising frequency elements have been shown in simulations (Omura et al., 2009; Katoh and Omura, 2007, 2011) which require large amounts of computing resources.

While nonlinear effects are very important for the generation of chorus waves, it is not yet possible to calculate the

effects of chorus on the electron distribution over a period of several hours or days due to computer limitations. It is therefore necessary to use an approximation. One of the most widely used approximations is quasi-linear theory, which has been used extensively in radiation belt models at the Earth (e.g., Varotsou et al., 2005, 2008; Albert et al., 2009; Shprits et al., 2009a, b; Fok et al., 2008; Su et al., 2010). Quasi-linear theory does not include phase trapping or phase bunching of electrons but assumes a broad band of waves and uses the time-averaged wave power. Quasi-linear theory treats the interaction as a diffusion process where the electrons are diffused in pitch angle  $\alpha$  and energy  $E$  by the waves (e.g., Glauert and Horne, 2005). Test particle simulations (Tao et al., 2012) and comparisons between particle scattering in the fully nonlinear and diffusive regimes (Albert, 2010) provide a remarkable level of agreement for small-amplitude waves, and also when quasi-linear diffusion rates are averaged over wave frequency and direction of propagation in a non-homogeneous plasma (Albert, 2010).

Changes in electron distribution due to wave-particle interactions can be calculated from a diffusion equation given by Schulz and Lanzerotti (1974); Subbotin and Shprits (2009),

$$\frac{\partial f}{\partial t} = \frac{1}{g(\alpha)} \frac{\partial}{\partial \alpha} \left| \left( g(\alpha) D_{\alpha\alpha} \frac{\partial f}{\partial \alpha} \right) \right|_E + \frac{1}{A(E)} \frac{\partial}{\partial E} \left| \left( A(E) D_{EE} \frac{\partial f}{\partial E} \right) \right|_\alpha - \frac{f}{\tau} \quad (1)$$

$$g(\alpha) = \sin 2\alpha \left( 1.3802 - 0.3198(\sin \alpha + (\sin \alpha)^{\frac{1}{2}}) \right) \quad (2)$$

$$A(E) = (E + E_0) (E(E + 2E_0))^{\frac{1}{2}}, \quad (3)$$

where  $f$  is the phase space density,  $\alpha$  is the equatorial pitch angle,  $D_{\alpha\alpha}$  and  $D_{EE}$  are the pitch angle and energy diffusion coefficients respectively,  $E_0$  is the electron rest energy and  $\tau$  is the loss timescale which is only non-zero inside the loss cone. The first term represents diffusion in pitch angle, the second diffusion in energy and the third represents losses to the atmosphere. The diffusion coefficients are calculated separately before solving Eq. (1) by using a code such as the PADIE code (Pitch Angle and energy Diffusion of Ions and Electrons; Glauert and Horne, 2005) to generate a value of  $D_{\alpha\alpha}$  and  $D_{EE}$  for each electron energy and  $L$ -shell. We then assume that the underlying cold plasma conditions on which the diffusion coefficient calculations are based do not change while solving Eq. (1) so the calculated values of  $D_{\alpha\alpha}$  and  $D_{EE}$  also do not change with time. Radial diffusion has been omitted as the focus of this paper is to examine the role of wave-particle interactions. The cross diffusion terms, which tend to be important at pitch angles near  $10^\circ$ – $45^\circ$  (Tao et al., 2009), have also been omitted, but their importance is described in relation to the results below.

The energy diffusion coefficients in Horne et al. (2008) were calculated using the PADIE code at  $L = 10$ . We use the same wave parameters here to allow a direct comparison

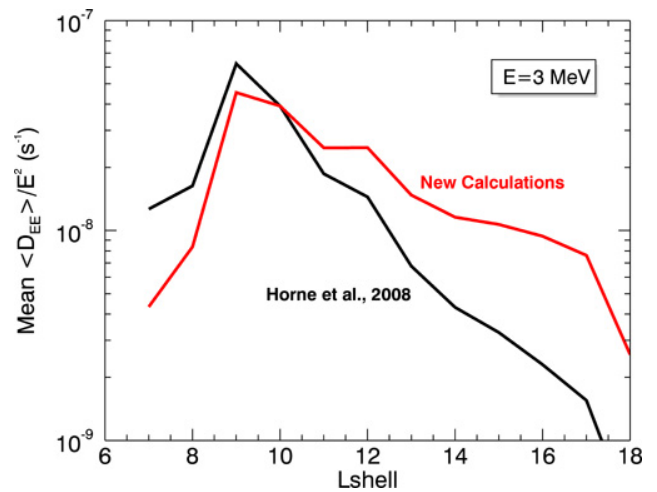
to Horne et al. (2008). A Gaussian power spectrum for the chorus waves is assumed with a frequency of the peak or maximum given by  $f_{\max} = 0.15f_{ce}$  and a half width at half maximum of  $0.05f_{ce}$ . We have assumed that the chorus wave power is dominated by lower-band chorus since upper-band chorus has rarely been seen at Jupiter (Menietti et al., 2012). The direction of propagation (wave normal angle,  $\psi$ ) is assumed to be described by a Gaussian distribution of  $X = \tan(\psi)$ , field aligned with a width of  $X_w = \tan(30^\circ)$  in common with studies of chorus at the Earth (Horne et al., 2003). When wave propagation at an angle to the magnetic field,  $\mathbf{B}$ , is considered, electron diffusion by both Landau ( $n = 0$ ) and higher-order cyclotron harmonic resonances are important. We use  $n = 0$  and  $n = \pm 1, \pm 2, \pm 3, \pm 4, \pm 5$  resonances in calculating the diffusion coefficients. We start by assuming that the resonant interactions occur within  $\pm 10^\circ$  of the magnetic equator following Horne et al. (2008). The diffusion coefficients from the PADIE code are bounce averaged; i.e., the bouncing of the electrons along the magnetic field line and the corresponding changes in resonances, plasma density, magnetic field, and wave power are included in the final diffusion coefficients. We use the plasma density model from Bagenal (1994) and a dipole magnetic field (with equatorial field strength  $409.113 \mu\text{T}$ ).

An important input to the PADIE code is the amplitude of the chorus wave magnetic field  $B_w$ . In previous work (Horne et al., 2008) the bounce-averaged diffusion rates were calculated using PADIE for  $L = 10$  and then scaled by the wave electric field  $E_w^2$  to obtain the diffusion rates over the range  $6 \leq L \leq 18$  so that

$$B_w^2(L) = B_w^2(L = 10) \frac{E_w^2(L)}{E_w^2(L = 10)}, \quad (4)$$

where  $B_w^2(L)$  and  $E_w^2(L)$  are the magnetic and electric wave intensities measured by Galileo at different  $L$ . This scaling was used since only wave electric field measurements were available. However, the chorus wave bandwidth was not scaled by  $f_{ce}$  in the calculations of Horne et al. (2008) (they assumed a bandwidth of  $0.05f_{ce}$ , but the factor of  $f_{ce}$  was missing in the calculations). We have therefore re-computed the bounce-averaged diffusion rates at each  $L$  taking into account the variation in bandwidth and show the results in Fig. 1. Here the diffusion rates have been averaged over all pitch angles at a given  $L$ . The correct scaling increases the diffusion rates by up to a factor of 8 for  $L > 10$  and decreases them for  $L < 10$ , and suggests that cyclotron-resonant interactions should be more effective over a wider range of  $L$ .

The survey of chorus wave activity as seen by the Galileo spacecraft (Menietti et al., 2008) shows that intense whistler-mode chorus is observed at a wide range of  $L$  from the orbit of Io out to beyond  $L = 15$ . The orbit of Galileo was such that it covered regions close to the magnetic equator, but the quantity of wave data falls off dramatically at latitudes  $\lambda \gtrsim 10^\circ$ . Evidence from both the Earth and Saturn, where



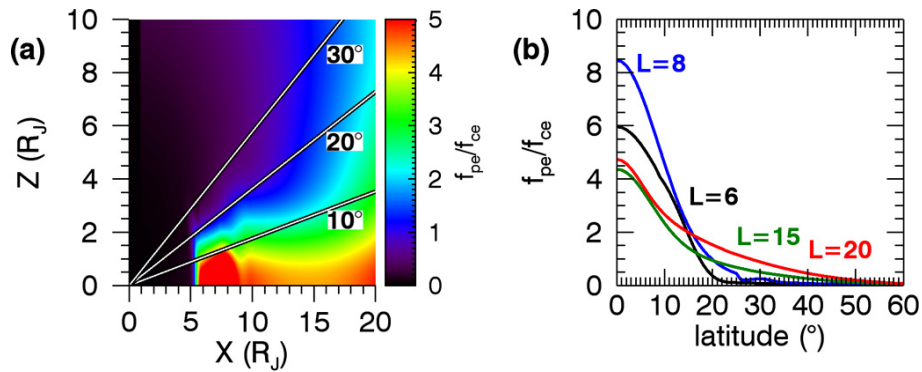
**Fig. 1.** Mean energy diffusion coefficients (averaged over all pitch angles) for our new results and those of Horne et al. (2008).

chorus is observed up to  $45^\circ$  (Meredith et al., 2012; Bunch et al., 2012; Menietti et al., 2012), suggest that chorus may be present at Jupiter far from the equator.

Recalling that acceleration due to chorus waves is dependent on the ratio  $f_{pe}/f_{ce}$ , and is most efficient when this ratio is  $\leq 4$  (Horne et al., 2003, 2005), it is important to consider  $f_{pe}/f_{ce}$  over the whole range of  $L$  and latitudes for which the waves are present. The strength of the background magnetic field is also important; when the background field is large, scattering is inefficient since the ratio of the wave magnetic field to the background field,  $B_w/B$ , becomes smaller (Lyons, 1974). We use the plasma density model of Bagenal (1994) and a dipole magnetic field to calculate the variation of  $f_{pe}/f_{ce}$  shown in Fig. 2a. This shows the region close to Jupiter where  $X$  is the distance from the planet in the magnetic equatorial plane in Jovian radii,  $R_J$ , and  $Z$  is the distance above the same plane. Overlaid as dashed lines on Fig. 2a are selected lines of constant latitude. Figure 2b shows how  $f_{pe}/f_{ce}$  varies along the field lines. The ability of chorus to accelerate electrons should be suppressed by the Io plasma torus between  $X \sim 6$  and  $10 R_J$  and for  $Z \lesssim 2 R_J$  where  $f_{pe}/f_{ce} > 4$ . Jupiter's plasma sheet is thinned by the rapid rotation of the planet, and this influences the values of  $f_{pe}/f_{ce}$  close to the equator until  $X \approx 15 R_J$  where the decreased magnetic field dominates the frequency ratio. Beyond  $L \sim 10$  and for  $\lambda \gtrsim 5^\circ$  there is a region where  $f_{pe}/f_{ce}$  is small, which suggests that chorus waves could be important for electron acceleration and loss to the atmosphere.

### 3 Latitude distribution of chorus

Following the work of Horne et al. (2008), we first assume that the power of the chorus waves remains constant with latitude and then calculate the bounce-averaged pitch angle,



**Fig. 2.** Plots of  $f_{pe}/f_{ce}$ : (a) in the magnetic  $xz$  plane, with white on black lines showing 3 latitudes; (b) along selected magnetic  $L$ -shells.

**Table 1.** BAS model boundary conditions.

Boundary	Condition
$\alpha = 0^\circ$	$\frac{\partial f}{\partial \alpha} = 0$
$\alpha = 90^\circ$	$\frac{\partial f}{\partial \alpha} = 0$
$E_{\min} = 20 \text{ keV}$	$f = \text{constant}$
$E_{\max} = 85 \text{ MeV}$	$f = \text{constant}$

$\langle D_{\alpha\alpha} \rangle$ , and energy,  $\langle D_{EE} \rangle$ , diffusion rates using the PADIE code for chorus waves extending to different latitudes  $\lambda_w$ . For example, if  $\lambda_w = 10^\circ$  then the waves are present only from  $-10^\circ$  to  $+10^\circ$  magnetic latitude. Figure 3a shows that as the latitude distribution of the waves is extended from  $\lambda_w = 10^\circ$  to  $30^\circ$ , pitch angle diffusion at 3 MeV increases at smaller pitch angles and into the loss cone near  $\sim 2^\circ$ . In both panels (a) and (b) it is apparent that increasing the latitudinal range of the waves increases the diffusion rates at small pitch angles as there is a larger range of latitudes where electrons can resonate with the chorus waves and  $f_{pe}/f_{ce}$  is smaller at higher latitudes. The increase in pitch angle diffusion with increasing  $\lambda_w$  (Fig. 3a) should result in electrons of all pitch angles being scattered towards the loss cone if intense chorus waves extend up to  $30^\circ$ . The energy diffusion rate in Fig. 3b peaks near  $40^\circ$  and is over an order of magnitude larger than the diffusion rate at  $70^\circ$  to  $90^\circ$  pitch angle.

The variation of the diffusion rates with electron energy is shown in panels (c) to (f) of Fig. 3. The effect of increasing the latitude distribution of chorus is to increase  $\langle D_{\alpha\alpha} \rangle/p^2$  for electrons of a few MeV and to increase  $\langle D_{EE} \rangle/E^2$  at pitch angles between  $20^\circ$  and  $60^\circ$ . The combination of these increases implies that although much more energy diffusion will occur, the electrons will also be scattered rapidly towards the loss cone and depending on the gradient of the distribution function may be lost before they can be accelerated.

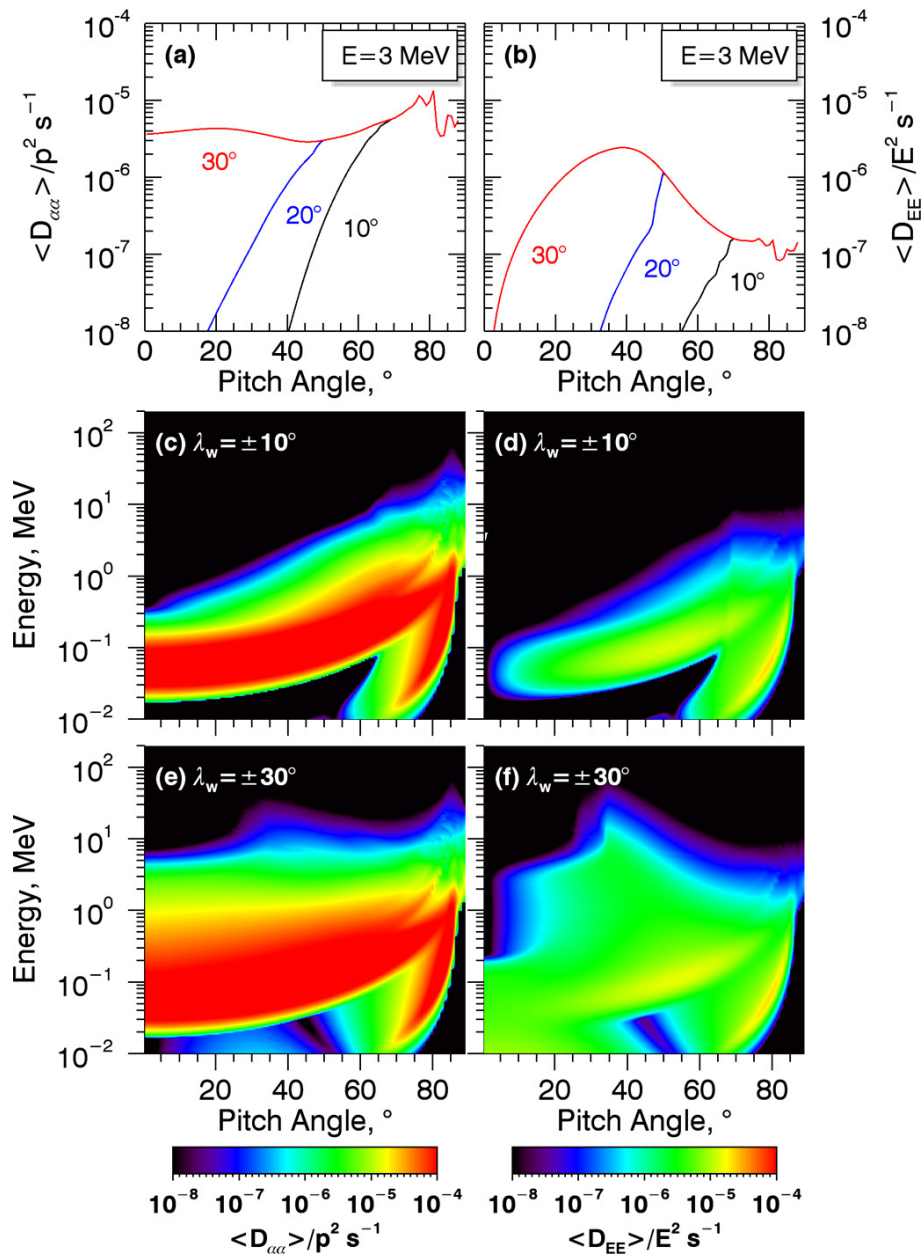
#### 4 Evolution of electron flux

In order to assess the effect of the combined pitch angle and energy diffusion on the electron flux we have used the British Antarctic Survey Radiation Belt (BAS) model which has been adapted for Jupiter. We have switched off the radial diffusion term and only included pitch angle and energy diffusion so as to focus on the effects of chorus waves. The BAS model uses an unconditionally stable fully implicit numerical scheme to solve the modified Fokker–Planck equation, which in the absence of radial diffusion is given by Eq. (1).

We have used a fixed loss cone angle of  $2^\circ$  and included a loss term for particles inside the loss cone where the loss timescale  $\tau$  is a quarter of the bounce time and is calculated using the method from Schulz and Lanzerotti (1974). The boundary conditions used in the model are listed in Table 1. The initial pitch angle distribution of phase space density is set to

$$f(\alpha) = f(\alpha = 90^\circ) \sin \alpha \quad (5)$$

to provide a value of  $f$  that decreases towards the loss cone (Subbotin and Shprits, 2009). The constant values for the boundaries and initial values are taken from the Galileo Interim Radiation Environment model (GIRE) for Jupiter (Garrett et al., 2003), which is based on averaged measurements from Galileo combined with the earlier Divine model (Divine and Garrett, 1983). The minimum energy boundary we use ( $E_{\min} = 20 \text{ keV}$ ) is much lower than that used previously (300 keV) (Horne et al., 2008) so that we can investigate a wider energy range. We use the GIRE model to set  $f$  at the  $E_{\min}$  boundary. The values of  $f$  are kept constant on the assumption that there is a balance of sources and losses at this low energy. The GIRE model based on measurements from Galileo shows that at 85 MeV there is a very small flux of electrons, so we have set  $f$  at the maximum energy  $E_{\max}$  to be constant. In reality the initial conditions may already include acceleration and loss due to cyclotron-resonant interactions with chorus and other waves, but at present this contribution cannot be separated out of the observations. A



**Fig. 3.** Pitch angle and energy diffusion coefficients at  $L = 10$  produced with chorus waves of constant intensity as a function of latitude and for different latitude ranges; left column: (a) shows  $\langle D_{\alpha\alpha} \rangle / p^2$  at 3 MeV, (c) variation of  $\langle D_{\alpha\alpha} \rangle / p^2$  with energy for  $\lambda_w = \pm 10^\circ$  and (e) same for  $\lambda_w = \pm 30^\circ$ . Right column (b, d and f): same but for  $\langle D_{EE} \rangle / E^2$ .

useful discussion of this effect can be found in Shprits et al. (2012).

A dipole magnetic field was used in the model, which is a reasonable assumption for distances up to approximately  $14 R_J$  along the equator. The change from dipole magnetic field to current-sheet-dominated magnetic field occurs between approximately  $12$  and  $20 R_J$  (Tomás et al., 2004). Figure 4 shows the results of the BAS model at  $L = 10$  where  $\lambda_w$  takes values of  $10^\circ$ ,  $20^\circ$  and  $30^\circ$ . The intensity of the chorus waves is assumed to be constant with latitude in this case.

Figure 4a shows the electron spectrum at  $\alpha = 84^\circ$  at 0 days (dashed line) and then at 30 days (solid line); Fig. 4b shows the corresponding pitch angle distributions.

The flux evolution is similar to that of Horne et al. (2008), where for  $\lambda_w = 10^\circ$  the flux at energies of a few MeV increases by an order of magnitude over a timescale of 30 days (comparable to the timescale for transport near the Io torus for thermal plasma (Delamere and Bagenal, 2003)). However, as the latitude range is increased to  $20^\circ$  (blue) and  $30^\circ$  (red) there is a significant loss of flux at lower energies and

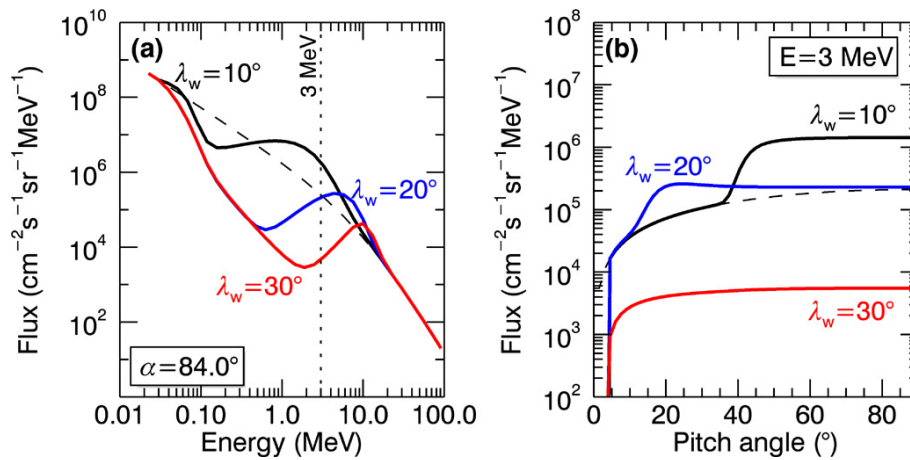


Fig. 4. Electron fluxes after 30 days for constant wave intensity extending to  $\pm\lambda_w$ . Dashed line shows initial condition.

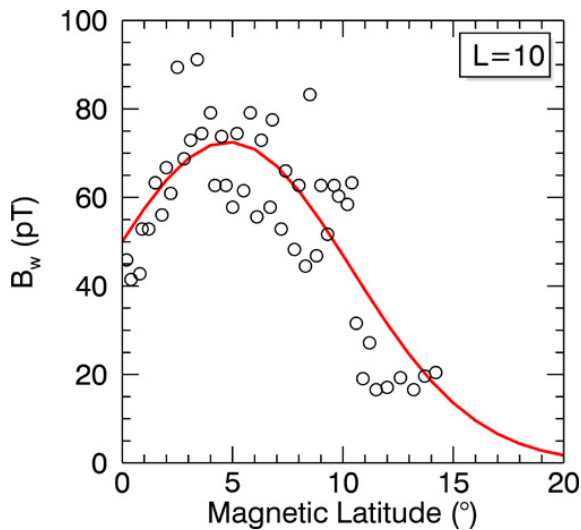


Fig. 5. Magnetic wave amplitude derived from electric field energy density from the Galileo spacecraft from Menietti et al. (2008) and an equatorial value of  $B_w$  as shown at  $L = 10$ . In red, a Gaussian fit to that data.

the energy where enhanced flux is seen has increased towards 10 MeV. The pitch angle distributions have a flat top between  $45^\circ$  and  $90^\circ$  which becomes broader for waves which extend to higher latitudes. The distribution also becomes anisotropic as the electron distribution at large pitch angles is much higher than that at small pitch angles. The shape of the pitch angle distribution is highly dependent on the value of  $\lambda_w$ . Although cross diffusion terms are not included in our calculations, simulations show that they are important at pitch angles in the region  $10^\circ$ – $40^\circ$  (Tao et al., 2009) and would lead to more rapid diffusion in this region, which would tend to make the anisotropy more apparent.

### 5 Wave intensity with latitude

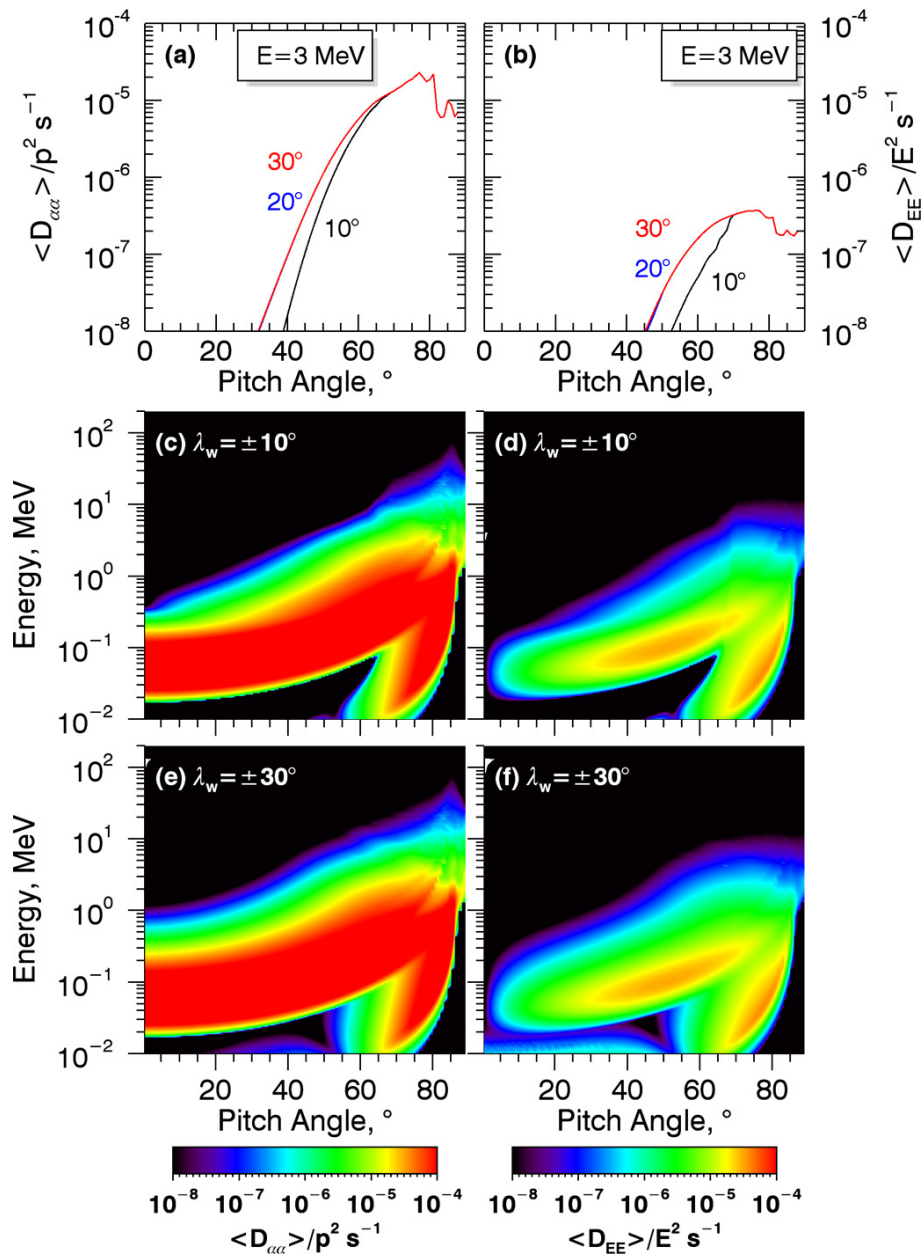
Although the path of Galileo was restricted close to the equator there is some suggestion in the data that the wave intensity decreases with latitude  $\lambda$  (Menietti et al., 2008). Therefore we have used the data in Fig. 6 of Menietti et al. (2008) to produce a Gaussian power profile of  $B_w$  with latitude (Fig. 5). Based on the symmetry of the data in Fig. 6 of Menietti et al. (2008) we assume the wave intensity is symmetrical about the magnetic equator, and we use all the data from both sides of the equator to produce a Gaussian model of the variation of wave intensity with latitude

$$B_w = \frac{B_{w0} e^{-z^2/2}}{0.48} \tag{6}$$

$$z = \frac{\theta - 4.80}{3.94}, \tag{7}$$

where  $B_{w0}$  is the magnetic wave amplitude at the equator and  $\theta$  is the magnetic latitude in degrees. We note that the wave intensity is highest about  $5^\circ$  off the equator; a similar effect has also been observed at Saturn which may be linked to weak or linear wave growth close to the equator (Menietti et al., 2013). We assume the same intensity profile model for all  $L$ -shells. Figure 5 shows that the waves become very weak by  $\lambda \sim 20^\circ$ . Although chorus waves at Jupiter may extend beyond this latitude as they do at the Earth and Saturn, there are no measurements at high latitudes at Jupiter. Extrapolation of the data using our model indicates that wave power is likely to be low at high latitudes (Fig. 5).

Using the model of the wave intensity distribution shown in Fig. 5, we have calculated new diffusion coefficients (Fig. 6). The large reduction in wave intensity by  $\lambda_w = 20^\circ$  results in almost identical diffusion coefficients for the maximum latitude of the waves  $\lambda_w = 20^\circ$  and  $\lambda_w = 30^\circ$  such that the red lines in Fig. 6a and b overlay the blue  $\lambda_w = 20^\circ$  lines. The diffusion coefficients are increased somewhat at large pitch angles compared to Fig. 3 due to the increase in wave



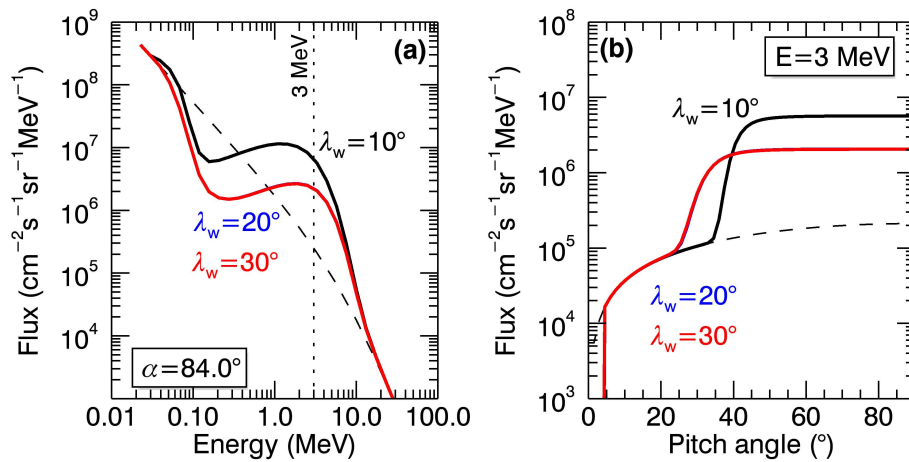
**Fig. 6.** Pitch angle and energy diffusion coefficients at  $L = 10$  produced with chorus waves of varying intensity as a function of latitude and for different latitude ranges; left column: (a) shows  $\langle D_{\alpha\alpha} \rangle / p^2$  at 3 MeV (please note that the red and blue lines are overlapping), (c) variation of  $\langle D_{\alpha\alpha} \rangle / p^2$  with energy for  $\lambda_w = \pm 10^\circ$  and (e) same for  $\lambda_w = \pm 30^\circ$ . Right column (b, d and f): same but for  $\langle D_{EE} \rangle / E^2$ .

intensity from  $0^\circ$  to  $\sim 5^\circ$ , which was not taken into account before. Whereas in Fig. 3 at lower pitch angles with  $\lambda_w = 30^\circ$  the pitch angle diffusion rates promoted pitch angle scattering across all pitch angles, with the modeled wave intensity distribution this no longer occurs, allowing electrons to be more easily trapped and accelerated. The diffusion coefficients calculated using the intensity profile model show increases in pitch angle diffusion across a smaller range of energies ( $\sim 0.4$  to 1 MeV, Fig. 6) than with the constant intensity with latitude model ( $\sim 0.4$  to 6 MeV, Fig. 3). This sug-

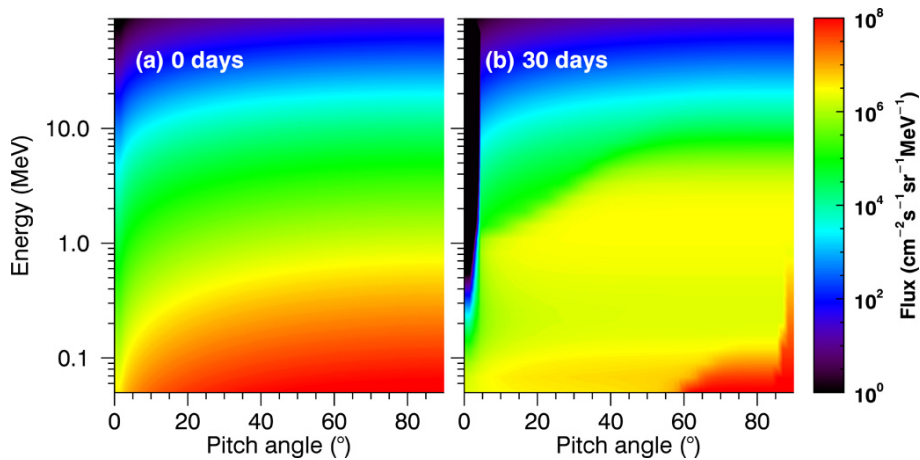
gests that acceleration can extend to a wider range of energies with little loss.

Figure 7 shows the effect the new diffusion coefficients have on the evolution of the electron flux after 30 days. This is very similar to the  $\lambda_w = 10^\circ$  results in Fig. 4 although there are now greater increases of flux for both  $\lambda_w = 10^\circ$  and  $\lambda_w = 30^\circ$  in Fig. 7. For the  $\lambda_w = 30^\circ$  case, the peak flux at 30 days has moved to an energy slightly lower than 3 MeV.

Figure 8 shows how the electron flux evolves over both energy and pitch angle from the initial condition to the flux



**Fig. 7.** Electron fluxes after 30 days using Galileo-based wave intensity extending to  $\pm\lambda_w$ . Please note the red and blue lines are overlapping. Dashed line shows initial condition.



**Fig. 8.** Electron fluxes at 0 days (a) and after 30 days (b) using BAS model calculation based on the varying intensity as a function of latitude profile from Galileo data for  $\lambda_w = 30^\circ$ .

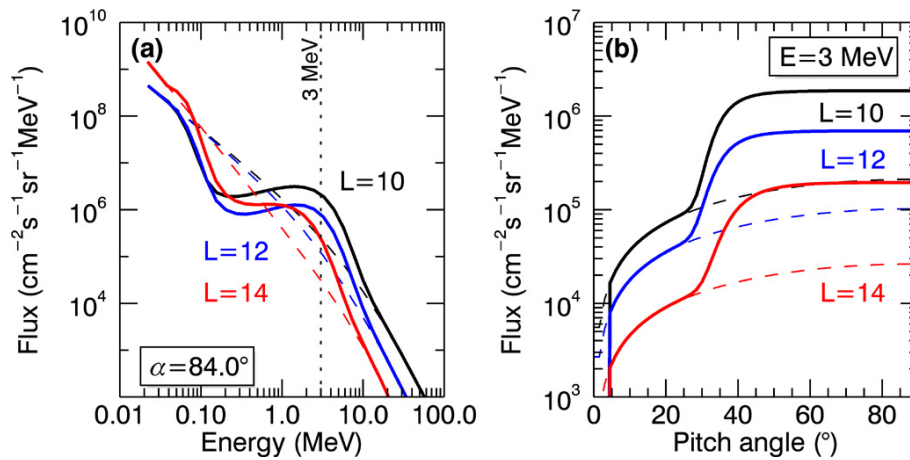
at 30 days using  $\lambda_w = \pm 30^\circ$  and the diffusion coefficients based on Galileo data. Note the electrons very close to  $90^\circ$  pitch angle at energies less than 1 MeV remain trapped because the pitch angle diffusion rate in this limited range of pitch angles is very small when considering chorus waves alone (see Fig. 6). At very low pitch angles electrons are assumed to be lost into the Jovian atmosphere within one quarter of the bounce time; this results in emptying of the loss cone at energies greater than approximately 0.3 MeV (weak diffusion regime), but at lower energies strong diffusion maintains the flux levels at these low pitch angles.

The decreases in flux from the initial condition at energies between approximately 0.1 and 0.6 MeV are seen to be consistent across almost all pitch angles in Fig. 8b. The flux increases observed at energies of a few MeV in Fig. 7a are also observed over a very wide range of pitch angles, with the minimum pitch angle of the elevated flux level increasing with increasing energy.

The increases in energy diffusion at  $L > 10$  shown in Fig. 1 suggests that we should see strong acceleration at  $L > 10$ . We test this hypothesis as far as  $L = 14R_J$ , where a dipole magnetic field model should still provide a reasonable approximation to the magnetic field. The results at both  $L = 12$  (blue line) and  $L = 14$  (red line) in Fig. 9 show that there is still an order of magnitude increase in the flux of electrons at  $\sim 3$  MeV at  $L = 14$ . There is a similarly shaped response in the electron flux at these larger  $L$ -shells to the results at  $L = 10$ , with losses for electrons below  $\sim 1$  MeV and gains above this value.

The pitch angle distributions for all 3  $L$ -shells shown in Fig. 9 are remarkably similar, all showing an increase in the electron flux at pitch angles  $\gtrsim 30^\circ$  by an order of magnitude or more. All the distributions in Fig. 9b show a very pronounced pitch angle anisotropy peaked near  $90^\circ$ , where the distributions at energies of a few MeV have a flat top.





**Fig. 9.** Evolution of electron fluxes at selected  $L$ -shells using diffusion coefficients from varying wave intensity profile with latitude up to  $\lambda_w = 30^\circ$ ; solid lines are flux after 30 days, dashed lines are the starting spectra at each  $L$ -shell, and vertical dotted line in (a) shows energy used for (b).

## 6 Discussion

The results in the previous two sections show the critical difference the location and intensity of whistler-mode chorus makes to the evolution of electron flux through wave–particle interactions. One common feature present in the output of the BAS model throughout our investigations is a plateau in the electron flux as a function of energy. The plateau occurs at varying energies depending on the wave intensity latitude profile. For example in Fig. 9, the flux at 30 days close to 1 MeV remained the same as the initial value for all three  $L$ -shells, whereas at lower energies the flux has deviated below the electron spectrum from the GIRE model and at higher energies it is higher.

Several factors may lead to these deviations from the GIRE model. Firstly, the GIRE model fits a functional form to the accumulated Galileo electron data from many individual orbits, so one might expect a relatively smooth spectrum where some of the variations have been averaged out. Another important factor which could explain why the flux at lower energies is less than the GIRE model is the omission of particle sources in the BAS model (Shprits et al., 2012). For example particle injections are known to occur at Jupiter with a timescale of approximately 3 days (Woch et al., 2004; Mauk et al., 1999; Kronberg et al., 2012). These tend to occur at energies of a few tens of keV to a few hundred keV, whereas we have assumed that the flux is constant at our low energy boundary at 20 keV. It is difficult to say without very detailed modeling of this source whether the injections provide enough electron flux to compensate for the losses at energies of a few hundred keV, and this needs to be investigated in the future. Another possibility is that other waves, such as  $Z$ -mode waves (Glauert and Horne, 2005) and magnetosonic waves (Horne et al., 2007), could contribute to electron acceleration and increase the electron flux.  $Z$ -mode

waves have been observed at Jupiter (Menietti et al., 2012) and are thought to be an important acceleration mechanism at Saturn (Gu et al., 2013).

Although we have included losses within the loss cone there are other potential loss mechanisms that we have neglected in our model runs. For example broadband hiss and electromagnetic ion cyclotron (EMIC) waves are known to cause pitch angle scattering and particle losses; we have also not included any losses due to the orbits of Jupiter’s moons Europa (at  $9.4 R_J$ ) and Ganymede (at  $14.97 R_J$ ). The inclusion of cross terms in the BAS model could also address the excess of electrons at higher energies since these terms tend to reduce local acceleration (Shprits et al., 2012). Tao et al. (2009) have assessed the importance of cross terms on electron acceleration by chorus and concluded that for pitch angles close to  $90^\circ$  the cross terms have a very limited effect on the acceleration, but at high energies ( $\sim$  few MeV) and low pitch angles the flux can be significantly overestimated (by 2 orders of magnitude) if the cross terms are not included. Our results emphasize the importance of electron acceleration at large pitch angles, and so we do not expect the omission of cross terms to affect our results significantly. In fact the results in Tao et al. (2009) suggest that the pitch angle anisotropies in our results may in fact be an underestimate of the level of anisotropy since cross diffusion terms should reduce the acceleration at lower pitch angles.

As a final comment, we have omitted radial diffusion that will transport electrons towards and away from Jupiter with associated acceleration and deceleration of the particles. Radial diffusion would be effective over a range of energies and would tend to smooth the radial profile of the flux. Nevertheless, we point out that anisotropic pitch angle distributions have been observed at Jupiter and have been associated with radial diffusion. Here we show that they could also be

produced by electron acceleration by chorus waves outside the orbit of the moon Io.

## 7 Conclusions

The radiation belts at Jupiter are the most intense in the Solar System. Previous work has suggested that cyclotron-resonant interactions with chorus waves are a significant factor in creating these radiation belts. In this paper we have used Galileo spacecraft data to show the importance of electron acceleration by resonant interaction with chorus waves as a source of high-energy electrons in the region outside of Io at Jupiter.

Three important findings have been reported here:

1. By taking into account the bandwidth of the power spectrum of chorus waves and how it varies with  $L$ -shell, we find that energy diffusion rates due to chorus waves are significantly larger by up to a factor of 8 at  $L$ -shells  $> 10$  and significantly smaller at  $L$ -shells  $< 10$  than previously reported by Horne et al. (2008).
2. Data show that chorus wave intensities peak near  $\lambda \sim 5^\circ$  and fall with increasing magnetic latitude. Modeling of this latitude-dependent intensity profile shows that cyclotron-resonant wave acceleration via chorus waves can increase the electron flux at  $\sim 3$  MeV by a factor of 10 or more over a period of 30 days. Furthermore, this should result in an anisotropic distribution peak between  $\sim 40$  and  $90^\circ$  in pitch angle.
3. Taking into account the observed distribution of chorus wave power with  $L$ -shell, we find that this should result in an increase in the electron flux in the region  $10 < L < 14$ . Acceleration may also extend to larger  $L$ -shells where non-dipole magnetic field effects become important, but this has yet to be confirmed.

We conclude that cyclotron-resonant wave acceleration is an important process for providing a population of few MeV electrons in the radiation belt at 10 to 14  $R_J$ , and which provides the source of particles for transportation to  $\sim 1.5 R_J$  where the most intense radiation belts are located.

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