Effects of Anisotropic Perpendicular Diffusion on the Energy and Spatial Dependence of Galatic Electron Intensities in the Heliosphere

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Abstract

Perpendicular diffusion enhanced in the polar directions of the heliosphere seems required in numerical models based on Parker's transport equation for cosmic rays, especially in explaining the small latitudinal gradients observed for protons by the Ulysses spacecraft during its fast latitude scan. This modulation topic is further studied using electron modulation. The enhancement generally produced an increase in modulation for both the A > 0 (e.g. ~1990 to ~2000) and A < 0 (e.g. ~1980 to ~1990) solar magnetic polarity cycles. With increasing perpendicular diffusion, the radial dependence of the computed electron spectra at distances with a large radial dependence was decreased but increased at distances with small radial dependence. Important is that a reduction in the latitudinal dependence of the differential intensities followed at all radial distances, with the largest effects in the inner heliosphere and at low energies.

1 Introduction

An enhanced perpendicular diffusion coefficient in the polar directions of the heliosphere ($K_{\perp\theta}$) plays an important role in cosmic ray modulation. It was first argued by Kóta & Jokipii (1995) that perpendicular diffusion is not isotropic but seems enlarged in the polar directions. The effects of this enhancement have been studied intensively by Potgieter (1997, 1998). In this regard, Potgieter et al. (1997) illustrated that an enhanced $K_{\perp\theta}$ produced latitude effects for both protons and electrons as a function of rigidity that were compatible to observations made by Ulysses during the fast latitude scan (Heber et al. 1997). For this work the effects of enhancing $K_{\perp\theta}$ on modulated electron intensities and spectra were studied as a function of radial distance and polar angle in a simulated heliosphere. This effect as a function of heliospheric "tilt angle" is described with more detail in Ferreira, Potgieter & Burger (SH3.1.14).

2 The modulation model

A two-dimensional (2D) drift model which emulates the effects of the heliospheric wavy current sheet (HCS) as developed by Hattingh & Burger (1995a) was used for this study. The details of the model are given in Ferreira, Potgieter & Burger (SH3.1.14). Using a 2D model is well justified and for a comparison of this 2D model and a 3D wavy HCS model developed by Hattingh & Burger (1995b), the reader is referred to Ferreira, Potgieter & Burger (SH3.1.20). For details on the numerical approaches used for the two models, see Burger & Hattingh (1995, 1998).

For the parallel and perpendicular diffusion coefficients, and the "drift" coefficient, the following general forms were assumed respectively:

$$K_{||} = K_0 \beta \; f_1(R) f_2(\theta, r); K_{\perp r} = aK_{||}; K_{\perp\theta} = bK_{||}; K_A = (K_A)_0 \frac{\beta R}{3B_m}. \quad (1)$$

Here β is the ratio of the speed of the particles to the speed of light; $f_1(R)$ gives the rigidity dependence in GV; K_0 is a constant in units of 6.0 x 10^{20} cm^2 s^{-1}; a = 0.05 is a constant determining the value of $K_{\perp r}$, and b is a constant determining the value of $K_{\perp\theta}$. Diffusion perpendicular to the heliospheric magnetic field (HMF) was enhanced in the polar direction by increasing b = 0.05 to b = 0.25. The effective radial diffusion coefficient is given by $K_{rr} = K_{||} \cos^2\psi + K_{\perp r} \sin^2\psi$, with ψ the angle between the radial direction and the averaged HMF direction. The differential intensity is calculated in units of particles $m^{-2}\ sr^{-1}\ s^{-1}\ MeV^{-1}$. The model parameters were: $f_2(\theta,r) = (1+r/r_0)$, with r radial distance and r_0 = 1 AU; K_0 = 30.0; $(K_A)_O$ = 1.0 and the "tilt angle" $\alpha = 10°$. The rigidity dependence is given by $f_1(R) = \beta\ R/R_0$ with R > 0.4 GV, and $f_1(R) = \beta\ (0.4\text{GV})/R_0$, with $R \leq 0.4$ GV and R_0 = 1 GV. This simple rigidity dependence has proven to be most useful (Potgieter 1996). The outer boundary of the simulated heliosphere was assumed at 100 AU, and the galactic electron spectrum published from the COMPTEL results (Strong et al., 1994) used as the local interstellar spectrum.

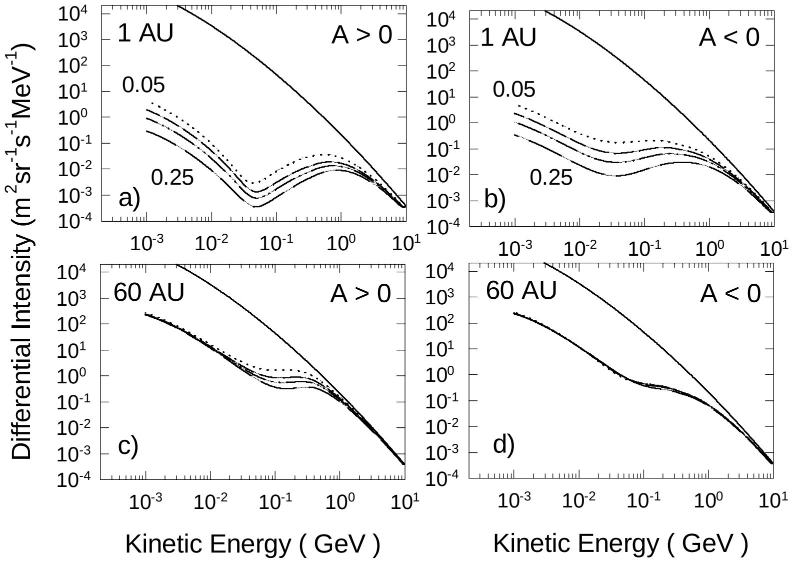

Figure 1: Computed electron spectra for the A > 0 and A < 0 polarity cycles shown at 1 AU in (a) and (b), and at 60 AU in (c) and (d) respectively. Here $K_{\perp\theta}$ was increased from 5% to 25% of the value of $K_{||}$ and corresponding solutions are shown from top (5%) to bottom (25%) in the equatorial plane ($\theta = 90°$).

3 Results and discussion

The consequences on electron spectra of increasing $K_{\perp\theta}$ from 5% to 25% of $K_{||}$ are shown in Figure 1(a) and 1(b) for 1 AU in the equatorial plane ($\theta = 90°$) for the A > 0 and A < 0 polarity cycles respectively. Figure 1(c) and 1(d) show the corresponding spectra at 60 AU, with b = 0.05, 0.10, 0.15 and 0.25, from top to bottom respectively. In Figure 1(a), a significant change in the energy gradient (a sharp turn-up in the shape of the spectra) occurs; for b = 0.05 this happens at ~30 MeV. This is due to the assumed constant rigidity dependence of $K_{\perp}$ and $K_{||}$ at rigidities between ~1 MV and 0.4 GV. As $K_{\perp\theta}$ was increased a shift in the upturn from ~30 MeV for b = 0.05 to ~40 MeV for b = 0.25 followed.

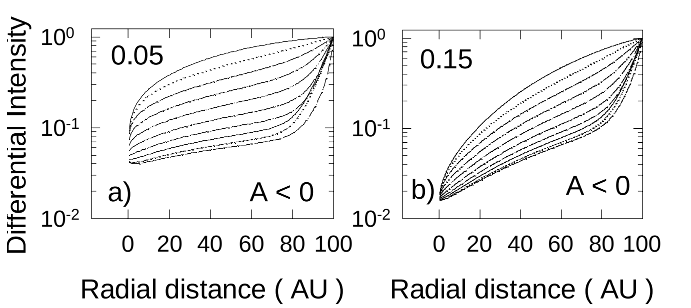

Figure 2: Electron differential intensities for 0.30 GeV as a function of radial distance for the A < 0 polarity cycle. Here $K_{\perp\theta}$ was increased from 5% to 15% of $K_{||}$ respectively in panels (a) and (b); from $\theta = 90°$ (bottom line) to $\theta = 5°$ (top line) in steps of 10°, in units of particles $m^{-2}\ sr^{-1}\ s^{-1}\ MeV^{-1}$.

The increase of $K_{\perp\theta}$ resulted generally in an increase in electron modulation where the spectra for b = 0.25 are lower than the spectra for b = 0.05. In Figure 1(b), the increase in $K_{\perp\theta}$ has similar effects as for the A > 0 cycle. For the A > 0 cycle at 60 AU in Figure 1(c) , the increase in $K_{\perp\theta}$ only effected energies between ~30 MeV and ~1 GeV while for the A < 0 cycle at 60 AU, shown in Figure 1(d) , the increase has little effect on the modulation spectra at all energies. The enhancement of $K_{\perp\theta}$ is clearly less significant in the outer heliospheric regions.

The consequences of increasing $K_{\perp\theta}$ on the

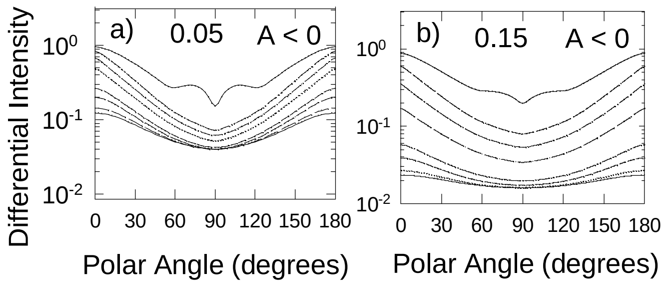

Figure 3: Electron differential intensities for 0.30 GeV as a function of polar angle for the A < 0 polarity cycle. Here $K_{\perp\theta}$ was increased from 5% to 15% of $K_{||}$ respectively in panels (a) and (b); from r = 1 AU (bottom line) to r = 90 AU (top line), for 1→30 AU and for 60→90 AU in steps of 10 AU in units of particles $m^{-2}\,sr^{-1}\,s^{-1}\,MeV^{-1}$.

radial dependence of electron differential intensities are shown for the A < 0 cycle in Figure 2(a) with *b* = 0.05 and in Figure 2(b) for *b* = 0.15. The *b* = 0.25 case in Figure 1 which is considered as rather large, is not shown here. Intensities are shown for 0.30 GeV electrons from θ = 90° (bottom line) to θ = 5° (top line) in steps of 10°. Figure 2(a) shows a small radial dependence for intensity at θ = 90° (bottom line) at r < ~80 AU; for larger distances the radial dependence increased significantly. This is a characteristic feature of drift models for this cycle and may be of value in establishing when a spacecraft approaches the heliospheric boundary. At θ = 5° (top line), a large radial dependence in the inner heliosphere at r < ~10 AU was computed with a relative smaller dependence beyond this value. By increasing $K_{\perp\theta}$, shown in Figure 2(b), the latitude dependence was decreased, especially significantly in the inner heliosphere. The radial dependence was increased, in general, except in the innermost heliosphere.

The effects of enhancing $K_{\perp\theta}$ on the electron differential intensities as a function of polar angle are shown in Figure 3(a) for *b* = 0.05 and in Figure 3(b) for *b* = 0.15. Intensities are shown for the A < 0 cycle for 0.30 GeV electrons from r = 1 AU (bottom line) to r = 90 AU (top line) for 1→30 AU and again for 60→90 AU in steps of 10 AU. From Figure 3(a) follows that there is a relative strong global positive latitudinal dependence which increasing with radial distance. The latitude dependence must be zero at θ = 90° due to the boundary conditions in the model. This will change when a north-south asymmetry is assumed for the HMF (see e.g. Hattingh et al., 1997). By increasing $K_{\perp\theta}$, shown in Figure 3(b), an overall reduction in the latitudinal dependence of the intensities occurred in the inner heliosphere. The latitudinal dependence

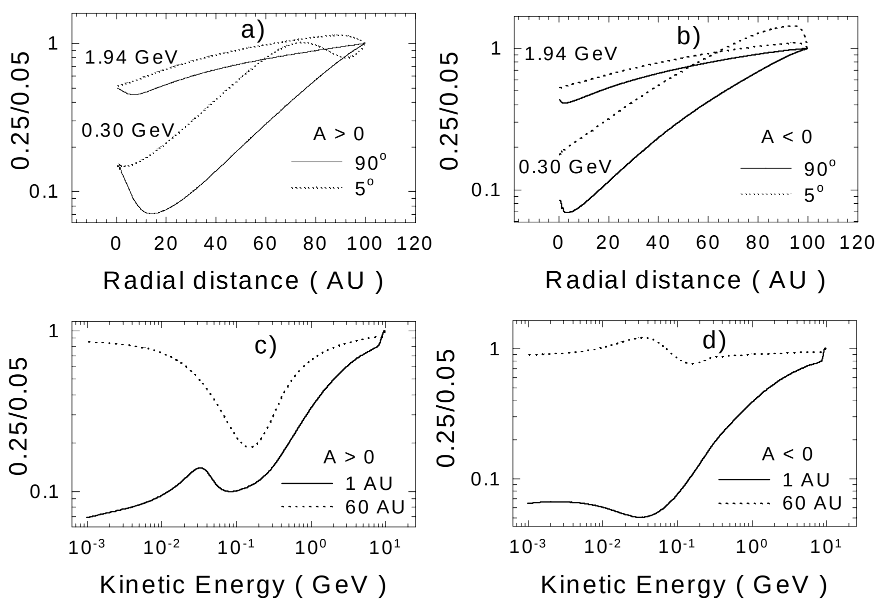

Figure 4: Electron differential intensities for 1.94 GeV and 0.30 GeV obtained for *b* = 0.05 and *b* = 0. 0.25 in Eq.(1); the ratio (0.25/0.05) of the intensities is depicted here as a function of radial distance and kinetic energy: In panels (a) and (b) for the equatorial plane (θ = 90°) as the solid line and for the polar regions (θ = 5°) as the dotted line; in panels (c) and (d) the solid line represents 1 AU and the dotted line 60 AU.

however stayed positive throughout the heliosphere, although quite small in the inner heliosphere.

The effects and importance of the enhancement of $K_{\perp\theta}$ are summarized in Figure 4 by depicting the ratio of b = 0.25 to b = 0.05. This is done in Figure 4(a) for the A > 0 cycle as a function of radial distance for 1.94 GeV and 0.30 GeV electrons respectively. In Figure 4(b) the corresponding situation is shown for the A < 0 cycle. The solid lines represent the equatorial plane ($\theta = 90^o$) and the dotted lines the polar regions ($\theta = 5^o$). Figures 4(c) and 4(d) show the ratio as a function of kinetic energy for the A > 0 and A < 0 cycles respectively with the solid line for 1 AU, and the dotted line for 60 AU.

From Figure 4(a) and 4(b) follows that the ratio converges to unity at the larger radial distances for both $\theta = 90^o$ and $\theta = 5^o$. This emphasizes that the effect of the increase in $K_{\perp\theta}$ are more important in the inner and middle heliosphere where the ratio deviates significantly from unity. In the A > 0 cycle, shown in Figure 4a, the ratio converges to the same value in the innermost heliosphere irrespective of the latitude but this does not occur for the A < 0 cycle. Qualitatively, the effects of increasing $K_{\perp\theta}$ are similar for both cycles.

In Figures 4(c) and 4(d) the ratio is shown as a function of kinetic energy for the two polarity cycles respectively. For the A > 0 cycle, shown in Figure 4(c), follows that at 1 AU the ratio is significantly smaller than unity for the lower energies. For higher energies this ratio converges to unity, illustrating that the increase in $K_{\perp\theta}$ has a lesser effect at the higher energies. For 60 AU, the effect becomes negligible at the lower and higher energies but not at the intermediate energies even at large distances, illustrating that the increase in $K_{\perp\theta}$ is important at these intermediate energies when electrons drift into the heliosphere predominantly through the equatorial plane. However, this is not the case for the A < 0 when electrons drift into the heliosphere predominantly through the polar regions as is shown in Figure 4(d) and as was also illustrated in Figure 1.

4 Conclusions

Assuming that perpendicular diffusion is anisotropic, $K_{\perp\theta}$ was increased from 5% to 25% of the value of $K_{||}$. This resulted generally in an increase in modulation for both polarity cycles at almost all energies as was shown for the electron spectra in Figure 1. The radial dependence also increased in general, except in the innermost heliosphere as shown in Figure 2. Figure 3 illustrated that an overall reduction in the latitudinal dependence of the intensities occur in the inner heliosphere as is required by Ulysses measurements. The latitudinal dependence however stays positive. From Figure 4 we conclude that the effect of the enhancement of $K_{\perp\theta}$ on model solutions is the largest at low energies in the inner heliosphere. This work illustrates that the enhancement of $K_{\perp\theta}$ in the polar directions of the heliosphere, which makes perpendicular diffusion anisotropic, has profound effects on the modulation of galactic cosmic ray electrons during both magnetic polarity cycles of the Sun.

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