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Implications of Cosmic Ray Electron Observations on the Modeling of Electron Modulation in the Heliosphere

M. S. Potgieter[1,2] and S. E. S Ferreira[1]

[1]*Space Res. Unit, School of Physics, Potchefstroom University for CHE, 2520 Potchefstroom. South Africa*

[2]*International Space Science Institute, Hallerstrasse 6, CH-3012 Bern, Switzerland*

Abstract

Electron spectra from the Ulysses spacecraft only have been compared to numerical models developed by the Modulation Group in South Africa. Mainly because of the lack of published data, no attention has been given to electron modulation at larger radial distances. However, recently upper limits from Voyager 1 measurements of low energy cosmic ray electrons have become available and have presented new incentives to model electron modulation. Surprisingly, the observed electron intensities indicate a very small radial dependence between 1-5 AU and ~70 AU. This challenge to modeling is discussed and it is shown what seems required for the diffusion tensor to make the model compatible to electron observations. The model results contain information about how close Voyager 1 may be to the heliospheric boundary.

1 Introduction

Spectra observed by the KET instrument onboard Ulysses have been published regularly for galactic electrons in the inner heliosphere; e.g. Rastoin et al. (1996), Ferrando, (1997) and Heber et al. (1997). Comparative studies have also been done between observations and numerical modulation models (e.g., Potgieter et al. 1997, 1999). These studies have obviously been limited to Earth or inner heliospheric measurements because electron measurements are difficult to do, to say the least, and spacecraft experiments are handicapped in several ways in producing reliable electron data especially at energies below 100-300 MeV (Heber et al., SH3.2.28, this volume). It has been pointed out in several publications (e.g. Potgieter et al. 1999) how useful electron data at these energies are to modeling and our understanding of modulation especially concerning the rigidity dependence of the diffusion tensor. Drift effects become negligible for electrons at these low energies, while energy losses are also small, so that electrons respond directly to what is assumed for parallel and perpendicular diffusion. Modulated electron spectra give therefore explicit information about the rigidity dependence of these diffusion coefficients. Using this approach the importance of perpendicular diffusion to modulation has been argued by us in several papers (e.g. Potgieter, 1996; see also Burger et al. SH3.3.02; Ferreira & Potgieter, SH3.1.07; Potgieter, Ferreira & Heber, SH 3.1.15).

Recently, electron data from Voyager 1 for 1997 have been presented by McDonald et al. (1998) in the energy range from ~ 10 MeV to ~ 100 MeV, but only as upper limits for intensities at ~ 70 AU. The upper limit at ~ 10 MeV was 0.5 particles m^{-2} sr^{-1} s^{-1} MeV^{-1} and at ~ 100 MeV it was 0.07 particles m^{-2} sr^{-1} s^{-1} MeV^{-1}. Because the values at ~ 10 MeV are comparable to the Ulysses-KET data for 1997 (Heber et al., SH3.2.28, this volume), the implication is that almost no radial dependence existed for cosmic ray electron intensities between 1-5 AU and ~70 AU at these low energies. This is a very interesting observation, although still preliminary, and provides an interesting challenge to modeling especially what has to be assumed for the diffusion tensor in present drift models.

2. The Modulation Model

The numerical model is based on Parker's transport equation and is given in Ferreira et al. (SH3.1.14). The symmetric part of the diffusion tensor in the this equation consists of a parallel diffusion coefficient ($K_{\|}$) and a perpendicular diffusion coefficient ($K_{\perp}$) whereas the anti-symmetric element K_A describes gradient and curvature drifts in the large scale heliospheric magnetic field (HMF). The pitch angle averaged guiding centre drift velocity for a near isotropic cosmic ray distribution is given by $\langle v_D \rangle = \nabla \times K_A e_B$, with $\boldsymbol{e}_B = \boldsymbol{B}/B$, where B is the magnitude of the background HMF. The transport equation was solved in a spherical coordinate system assuming azimuthal symmetry and $\partial f/\partial t = 0$, that is a steady-state for solar minimum modulation, with the neutral sheet "tilt angle" $\alpha = 13°$ during so-called A > 0 epochs (~1990 to present). A two-dimensional numerical model, called the WCS-model, was used (Burger & Hattingh, 1995). The HMF was modified in the off equatorial regions of the heliosphere according to Jokipii & Kota (1989). The solar wind speed V was assumed to change from 450 km.s^{-1} in the equatorial plane ($\theta = 90^{\circ}$) to a maximum of 850 km. s^{-1} when $\theta \leq 60^{\circ}$. The outer boundary of the simulated heliosphere was assumed at 100 AU. The galactic electron spectrum based on COMPTEL results (Strong et al., 1994) was assumed as the local interstellar spectrum (LIS); see also Potgieter (1996).

The perpendicular diffusion coefficients and the "drift" coefficient were assumed respectively as given by the following general forms:

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

The assumption for $K_{||}$ will be discussed in detail in the next section. The ratio of the speed of the charged particles to the speed of light is given by β; $a = 0.01$ is a constant determining the value of $K_{\perp r}$ which contributes to perpendicular diffusion in the radial direction, and $b = 0.15$ a constant determining the value of $K_{\perp\theta}$ which contributes to perpendicular diffusion in the polar direction; $b \neq a$ means that diffusion perpendicular to the HMF was enhanced in the polar direction (Kota & Jokipii, 1995; Potgieter, 1996). We assumed $(K_A)_0 = 0.5$, which means we reduced drifts by 50%; B_m is the magnitude of the modified HMF. 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. Note that $K_{||}$ dominates K_{rr} in the inner and polar regions and $K_{\perp r}$ dominates in the middle to outer equatorial regions of the heliosphere.

3. Results and Discussion

The indication that essentially no radial dependence seems to exist for modulated cosmic ray electron intensities between 1-5 AU and ~70 AU in the energy range ~5 MeV to ~20 MeV for the present A > 0 epoch has the complication that a different $K_{||}$ had to be used in our model compared with what Potgieter et al. (1999) used to fit Ulysses electron spectra. Potgieter & Ferreira (1999) showed that $K_{\perp}$ dominates electron modulation at low energies so that $K_{\perp}$ had to be changed as well. At the same time we wanted to maintain the sophistication in choosing a diffusion tensor presented in Ferreira (1999) and Ferreira et al. (SH3.1.20, this volume). The newly assumed values for $K_{||}$ are depicted schematically in Figure 1, showing that at 1 AU the P^2 dependence of $K_{||}$ (and by assumption also $K_{\perp}$) changes to a P^{-2} and then to a steady value with decreasing rigidity, which happens at rigidities significantly higher than used before. This was necessary in order to fit reasonably electron spectra at high (~300 MeV to ~9 GeV) and low rigidity (~5 MeV to ~20 MeV) from Ulysses, and to comply to the upper limits from Voyager 1 for 1997, as will be shown in the next figure. No explicit polar angle dependence was required for $K_{||}$ or $K_{\perp}$.

The corresponding computed electron spectra are shown in Figure 2 at 1AU, 70AU, 80AU, 90AU, 95AU, 97AU and 100AU in the equatorial plane. The HMF magnetic cycle was chosen to be the A > 0 polarity situation (~1990 to present). The filled circles represent the Ulysses/KET electron data at ~5 AU and the triangles the Voyager 1 upper limits at ~70 AU, for the same period. The computed spectra show the characteristic features of drift models for this epoch: A maximum intensity and a change of slope at ~0.5 GeV; a second change of slope at ~0.08 GeV and then an increase in intensities with decreasing energy at almost a steady slope except in the far outer heliosphere. The energies where these slope changes occur dependent on what the rigidity dependencies are for $K_{||}$ and $K_{\perp}$, and on how large drift effects are, and may therefore change. Evidently, what we assumed here fit the electron data between 1- 5 AU most reasonably while the computed spectra up to ~80 AU stay below the Voyager upper limits for this period.

The computation was repeated for a polar angle θ = 55° which is approximately the value Voyager 1 will reach at the end of 1999, and again for a polar angle of θ = 15°. These computed spectra are shown in Figures 3 and 4 respectively. Note that although no latitude dependence was assumed for $K_{||}$ or $K_{\perp}$, the computed spectra show latitude effects because of drifts. It follows from both figures that the distribution of cosmic ray electrons as a function of radial distance is different at these latitudes than in the equatorial plane (Figure 2) but still very small. Because of the enhancement of $K_{\perp\theta}$ in the polar direction, the latitudinal dependence of the intensities is also small corresponding to what Ulysses observed; of course, we do not

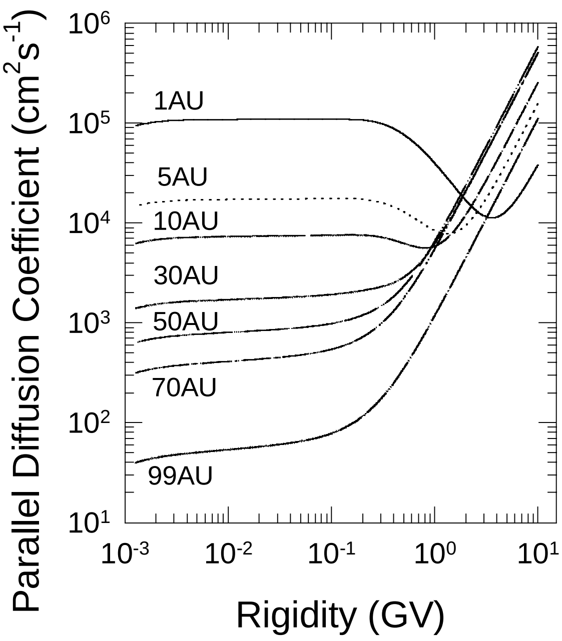

Figure 1: Parallel diffusion coefficient $K_{||}$ in units of 6.0 x 10^{20} for cosmic ray electrons as a function of rigidity at 1AU, 70AU, 80AU, 90AU, 95AU, 97AU and 100AU in the equatorial plane. Note the changes in slope and radial dependence. No latitude dependence was assumed.

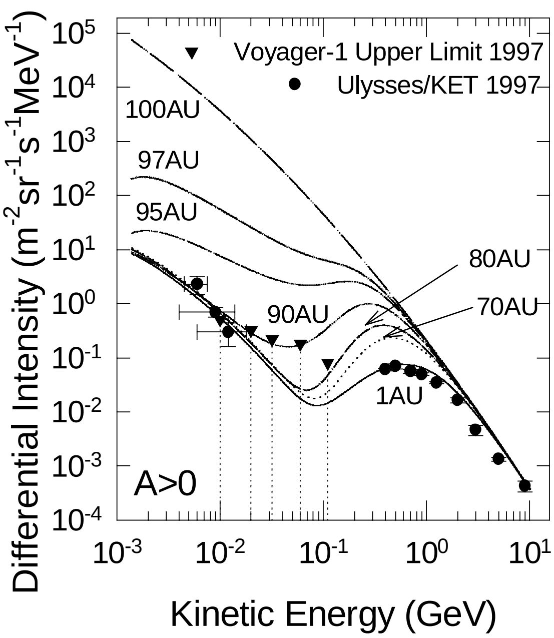

Figure 2: Computed electron spectra in the equatorial plane, based on $K_{||}$ shown in Figure 1 and with $K_{\perp} \propto K_{||}$, compared with Ulysses/KET electron data at ~5 AU and Voyager 1 upper limits at ~70 AU, for 1997. The LIS is assumed at 100AU.

know what the situation is at large radial distances and for small polar angles.

Concerning the position of the Voyager spacecraft with respect to the heliospheric boundary the results presented her give some interesting insights. If the boundary were assumed in the vicinity of 100 AU, and if the LIS from Strong et al. (1994) were assumed correct, the implication is that galactic electrons measured by Voyager 1 will increase by a factor of up to 10^3 within the next few years. If the boundary was further out, the sharp increase in low energy electrons would be delayed accordingly. It should also be kept in mind that measured low energy electrons in the inner heliosphere might contain a Jovian contribution If so, it will make the increase in galactic electrons even larger. Qualitatively, all these uncertainties will not change the essence of what is presented here.

4 Conclusions

The recently obtained upper limits from Voyager 1 at ~70 AU for cosmic ray electron intensities in the energy range ~5 MeV to ~20 MeV for the present A > 0 epoch indicate that essentially no radial dependence

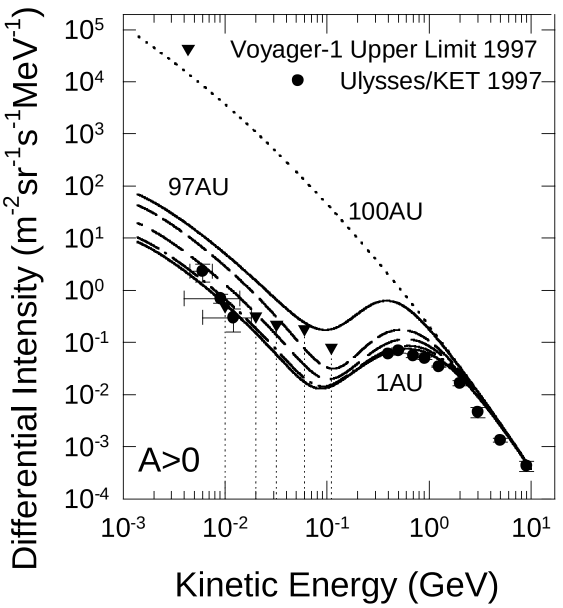

Figure 3: As Fig. 2 but for a polar angle of θ = 55°.

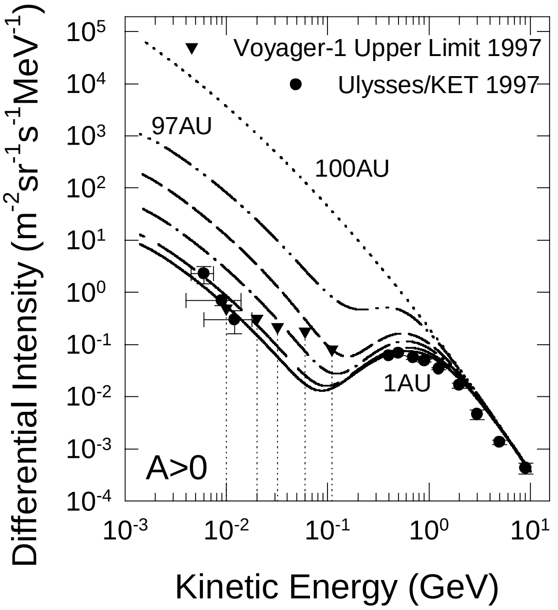

Figure 4: As Fig. 2 but for a polar angle of θ = 15°.

existed between Ulysses and Voyager 1 in 1997. This is a unexpected, but very interesting observation. To obtain compatibility between these two set of data and drift models, a $K_{||}$ as shown in Figure 1, and a $K_{\perp}$ according to Eq. (1) had to be assumed, but still based on the more sophisticated approach used for these diffusion coefficients as presented in SH3.1.15 & SH3.1.20. The corresponding computed electron spectra in Figures 2 to 4 show that very large modulation occurs at these low energies over the first 5 – 10 AU of the simulated heliosphere. At higher energies (> 300 MeV) the computations show relatively small positive radial gradients. The latitude gradient e.g. at 70 AU changes from negative at high energies to positive at low energies. If the boundary were assumed in the vicinity of 100 AU and if the LIS were assumed correct, the implication is that galactic electrons measured by Voyager 1 will increase by a factor of $\sim 10^3$ within the next few years. It also shows that electron data, especially at low energies, are of crucial importance to fully understand what happens in heliospheric modulation.

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