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Consequences of different local interstellar spectra on 16 MeV electron modulation

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Abstract. The local interstellar spectrum (LIS) for galactic electrons is an important parameter in heliospheric modulation studies, and is still basically unknown at energies of interest to modulation. In this work the effects of different published LIS scenarios on model computations are shown, and in particular compared to the ~16 MeV Pioneer 10 observations. The modulation of galactic and Jovian electrons is studied using a fully three-dimensional, steady-state model based on Parker's transport equation including the Jovian source. Compatibility between the model computations and observations gives an indication as to the magnitude of the diffusion coefficients because electron modulation responds directly to the energy dependence of the diffusion coefficients below ~500 MeV. Comparing the different parallel mean free paths needed to compute compatible solutions with observations an upper and lower limit to the electron LIS are proposed.

1. Introduction

The local interstellar spectrum (LIS) for galactic electrons is important for the study of the heliospheric modulation of cosmic ray electrons. Because of solar modulation it is impossible to determine a realistic LIS from observed modulated electron spectra at Earth because of the lack of knowledge of the transport coefficients (e.g., Potgieter, 1996; Langner et al., 2001). The LIS is therefore still basically unknown at energies of interest (e.g., Langner et al., 2001). Fortunately, ~16 MeV electron measurements had been made by the Pioneer 10 spacecraft up to ~70 AU (Lopate, 1991). The measurements include an encounter with the Jovian magnetosphere which is a relatively strong source of electrons with energies up to at least ~30 MeV (e.g., Simpson et al., 1974; Teegarden et al., 1974).

The modulation of cosmic rays in the heliosphere is generally simulated by numerical models where the LIS is introduced as an initial condition. Ferreira et al. (2001b) compared model calculations with ~7 MeV observations from Ulysses, which covered a wide variety of latitudes in the inner heliosphere. This was followed by Ferreira et al. (2001c) who compared model solutions with ~16 MeV electrons observations from Pioneer 10 that stayed close to the equatorial regions up to ~70 AU. These studies provided new insights of model parameters (especially the transport coefficients) necessary to compute solutions compatible to observations.

Strong et al. (1994) produced a LIS by using a sophisticated galactic propagation model in combination with gamma ray and radio synchrotron data. This spectrum has been used extensively as the LIS in modulation studies (e.g., Potgieter, 1996; Ferreira et al., 2000). Strong et al. (2000) argued that this LIS was too high for energies < ~200 MeV and proposed new, much lower spectra. Recently, Langner et al. (2001) also determined a new electron LIS, using a phenomenological approach.

In this paper, the effects of these proposed LIS on modulation model computations are shown as different scenarios, comparing the computed results with the observed Pioneer 10 intensities.

2. Modulation model and parameters

The model is based on the numerical solution of Parker's [1965] transport equation (TPE) :

$$\frac{\partial f}{\partial t} = -(\boldsymbol{V} + \langle \boldsymbol{v}_{\mathbf{D}} \rangle) \cdot \nabla f + \nabla \cdot (\boldsymbol{K}_s \cdot \nabla f) + \frac{1}{3}(\nabla \cdot \boldsymbol{V}) \frac{\partial f}{\partial \ln R} + Q, \qquad (1)$$

where $f(\boldsymbol{r},P,t)$ is the cosmic ray distribution function; P is rigidity, $\boldsymbol{r}$ is position, and t is time. Terms on the right-hand side represent convection, gradient and curvature drifts, diffusion, adiabatic energy changes and a source function, respectively, with $\boldsymbol{V}$ the solar wind velocity. The symmetric tensor $\boldsymbol{K_s}$ consists of a parallel diffusion coefficient $K_{\|}$ and two perpendicular diffusion coefficients, namely $K_{\perp r}$ the perpendicular diffusion coefficient in the radial/azimuthal direction, and $K_{\perp\theta}$ the perpendicular diffusion coefficient in the polar direction. The parallel mean free path is given by

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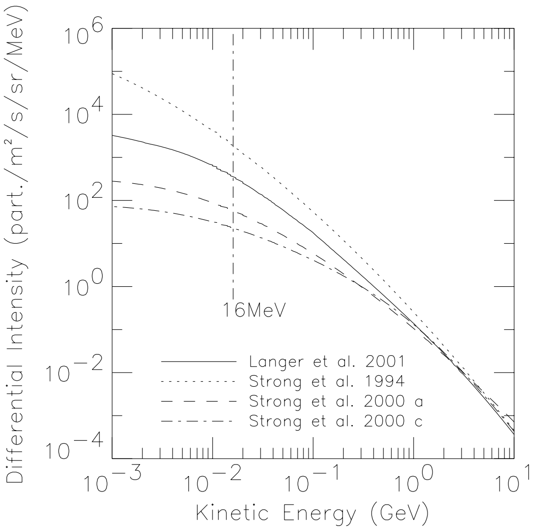

Fig. 1. Four different published LIS scenarios studied in this work. Note: Only two LIS scenarios from Strong et al. (2000) were selected.

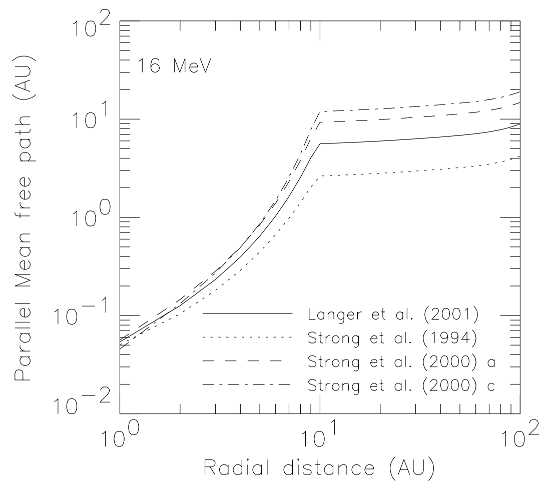

Fig. 2. Computed parallel mean free path $\lambda_{\parallel}$ as a function of radial distance needed to compute compatibility between the model solutions and ~16 MeV Pioneer 10 observations for r > 20 AU.

$\lambda_{\parallel} = 3K_{\parallel}/v$, with v the particle velocity. The anti-symmetric element K_A describes gradient and curvature drifts in the large scale heliospheric magnetic field (HMF), with the averaged drift velocity $\boldsymbol{v}_D$. The source function Q, in this case for electrons produced at Jupiter, is given by Ferreira et al. (2001a). The TPE (1) was solved in a three-dimensional spherical coordinate system and in a steady-state, that is, for solar minimum modulation with the current sheet "tilt angle" $\alpha = 15°$. The HMF was modified according to Jokipii and Kóta (1989) which is qualitatively supported by Ulysses measurements. The solar wind speed V was assumed to change from 400 km.s^{-1} in the equatorial plane ($\theta = 90^o$) to a maximum of 800 km.s^{-1} when $\theta < 60^o$ and $\theta > 120^o$. The outer boundary of the simulated heliosphere was set at 120 AU, where the various LIS were specified respectively. A more detailed discussion of the model and the diffusion coefficients are given by Ferreira et al. (SH3.1.) - see also Fichtner et al. (2000).

3. Results and discussion

Figure 1 shows the different electron LIS scenarios taken from Langner et al., 2001; Strong et al., 1994; and two spectra from Strong et al., 2000. The four scenarios differ considerably at lower energies. At 16 MeV the LIS from Langner et al. (2001) is a factor of ~10 lower than the LIS from Strong et al. (1994), a factor of ~5 higher than the LIS (a) of Strong et al. (2000), and a factor ~14 higher than LIS (c) from Strong et al. (2000), which is the lowest LIS.

The modulation effects of these different LIS scenarios on model computations will be illustrated along the Pioneer 10 trajectory. The Pioneer 10 data serve a unique purpose when compared with model results up to large radial distances in the equatorial regions of the heliosphere. Ferreira et al. (2001c) computed solutions compatible with the observed ~16 MeV Pioneer 10 intensities using the LIS from Langner et al. (2001). They found by studying the radial transport of these low energy electrons that the solutions are very sensitive to the assumed radial dependence of the diffusion coefficients, especially for r < 10 AU. When the LIS of Strong et al. (1994), which is higher than the Langner et al. (2001) scenario, was assumed at the modulation boundary, it became necessary to decrease $\lambda_{\parallel}$ for r > 10 AU in order to fit the Pioneer 10 observations up to ~70 AU, For both the Strong et al. (2000) scenarios, with LIS's lower than the LIS from Langner et al. (2001), $\lambda_{\parallel}$ had to be increased to assure compatibility with the observations. For all four scenarios, $\lambda_{\parallel}$ was set to converge to the same value at Earth

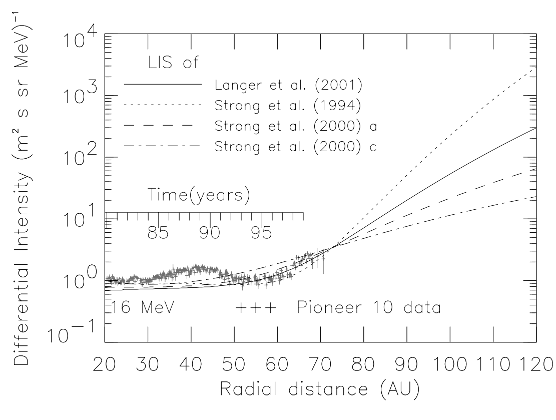

Fig. 3. Computed differential intensities of 16 MeV electrons as a function of radial distance along the Pioneer 10 trajectory for r > 20 AU. In comparison the Pioneer 10 observations (Lopate 2001) are shown for the period ~1980 to ~1990

comparable with the observed values of $\lambda_{\|}$ at solar minimum (Dröge, 2000) and in good agreement with theoretical calculations (e.g., the damping model from Bieber et al., 1994 and fits to measured values given by Ragot, 1999). The four corresponding $\lambda_{\|}$ are shown in Fig. 2 in the equatorial plane. The computed solutions are shown in Fig. 3 as a function of radial distance for r > 20 AU, in comparison with the observed ~16 MeV Pioneer 10 intensities. The factor of ~2 modulation visible in the observations around 40 AU (~1987) and at the end of the data set (~1997) is due to changing solar activity and can only be addressed with a fully time-dependent model. Evidently, all four LIS scenarios give reasonable compatibility to the observations, but the two higher LIS's do better between 50 and 70 AU.

The next step was to compare the model solutions to the observations for r < 15 AU. Figure 4 shows the computed differential intensity in the inner heliosphere along the Pioneer 10 trajectory. This was obtained for the LIS from Strong et al. (1994), shown as Case A, which corresponds to the assumption for $\lambda_{\|}$ as in Fig. 2. Evidently, the computed radial dependence is too large, implying that the assumed radial dependence of $\lambda_{\|}$ for this LIS scenario is too large for r < 10 AU. By decreasing the radial dependence in the inner heliosphere and therefore increasing $\lambda_{\|}$ at Earth, the model solution became compatible with the ~16 MeV observations, as is shown by Case B in Fig. 4. For both the Strong et al. (2000) scenarios the $\lambda_{\|}$ scenarios shown in Figure 2, resulted in too small computed radial dependencies when compared to the Pioneer 10 observations for r < 10 AU (not shown here). Increasing the radial dependence of $\lambda_{\|}$ in the inner heliosphere for these LIS scenarios gave compatibility to the data.

The corresponding modified $\lambda_{\|}$, as required for solutions to be compatible to the observations for the entire Pioneer 10 trajectory, are shown in Fig. 5. Note that for the highest LIS at 16 MeV - Strong et al. (1994) - $\lambda_{\|}$ is less than for the other LIS scenarios for r > 10 AU, but for r < 10 AU the situation reverses, so that $\lambda_{\|}$ becomes larger than for the other two LIS scenarios to assure compatibility with observations during the Jovian encounter. For the lowest LIS scenario - Strong et al. (2000) (c) - $\lambda_{\|}$ is larger than the other LIS scenarios when r > 10 AU, but less for r < 10 AU. This clearly indicates that $\lambda_{\|}$ at Earth has to be changed for different LIS scenarios when solutions compatible with observations are to be computed for the entire Pioneer 10 trajectory.

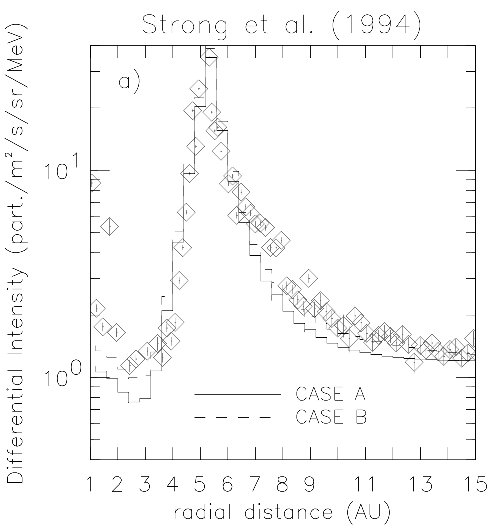

Fig. 4. Computed differential intensities of 16 MeV electrons along the Pioneer 10 trajectory for r < 15AU. In comparison the Pioneer 10 observations (Lopate 1991) are shown. Two solution scenarios are shown for the assumption for the LIS of Strong et al. (1994) at the modulation boundary.

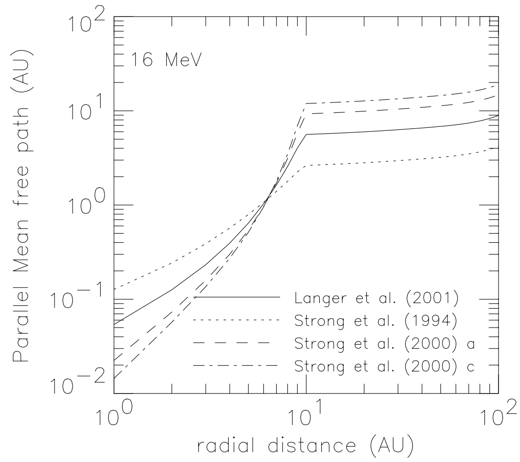

Fig. 5. The computed $\lambda_{\|}$ as a function of radial distance as needed for compatibility between model solutions and the ~16 MeV electron observations over the entire Pioneer 10 trajectory.

When the respective $\lambda_{\|}$ at Earth are plotted as a function of the value of the corresponding LIS at 16 MeV, the results shown in Fig. 6 are obtained, indicating the correlation between the value of $\lambda_{\|}$ at Earth and the assumed LIS value at the modulation boundary. The shaded area represents measurements of $\lambda_{\|}$ at Earth during solar minimum conditions mostly for P < 10 MV. Unfortunately not many measurements exist for 16 MeV at Earth (because these solar flare electrons have fluxes too low to derive meaningful values). However, assuming a constant rigidity dependence for $\lambda_{\|}$ for P < 20 MV, these measurements could be extrapolated to 16 MeV. Also included in the shaded band are three theoretical calculations for 16 MeV electrons at Earth (Bieber et al., 1994; Ragot, 1999). From Fig. 6 follows that for the LIS scenario of Langer et al. (2001), the corresponding $\lambda_{\|}$ at Earth is in good agreement with the shaded band. For the LIS scenario of Strong et al. (1994) the value of $\lambda_{\|}$ is slightly above the shaded area. Strong et al. later argued that this LIS is too high at electron energies < ~200 MeV, and much lower spectra were proposed by Strong et al. (2000). These lower LIS scenarios result in $\lambda_{\|}$ which are lower than the observed and theoretical values at Earth, significantly so for scenario (c). Figure 6 indicates a preferred LIS which is higher than the Strong et al. (2000) scenarios, but less than the Strong et al.

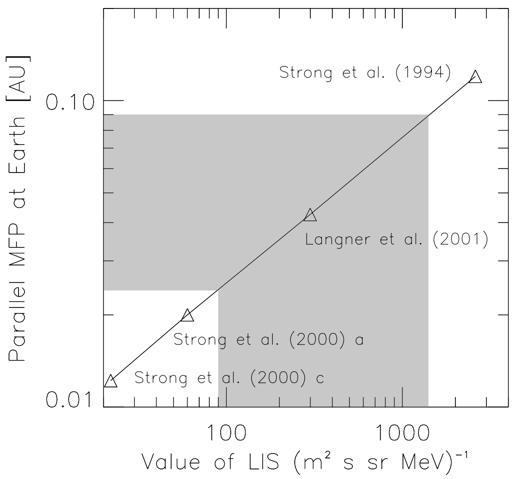

Fig. 6. The parallel mean free path $\lambda_{\parallel}$ required at Earth to compute compatibility between model solutions and Pioneer 10 observations as a function of the value of the LIS at 16 MeV at the modulation boundary of 120 AU. The shaded area represents measurements of $\lambda_{\parallel}$ (Dröge, 2000) during solar minimum conditions and values of three theoretical calculations at Earth (Bieber et al., 1994; Ragot ,1999).

(1994) LIS. The relation in Fig. 6 illustrates that more theoretical work, and better measurements of $\lambda_{\parallel}$ at Earth, could lead to better certainty of the LIS using this approach.

At 4 MeV the LIS scenarios differ even more considerably than at 16 MeV. Figure 7 shows the model solutions at 4 MeV along the Pioneer 10 trajectory together with observations. It follows that the Strong et al. (2000) (c) scenario results in almost no radial dependence of the intensities in the outer heliosphere, indicating that this LIS scenario may be too low and unrealistic from a modulation point of view. The solutions for the other LIS scenarios exhibit moderate to very large radial dependencies for these electrons in the outer heliosphere. Unfortunately, the Pioneer 10 data were only measured up to ~70 AU. Missions to the outer heliosphere, beyond 70 AU, seem required to establish the electron LIS at energies of interest to heliospheric modulation. (Publication of low-energy electron data from the Voyager spacecraft may also help.)

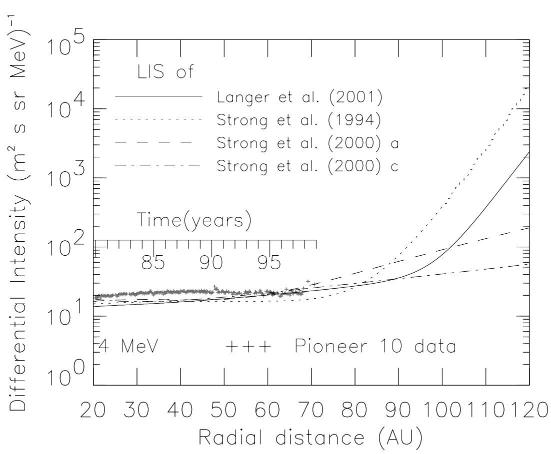

Fig. 7. Same as Fig. 3, but for 4 MeV electrons.

4. Conclusions

We studied four different scenarios for the local interstellar spectrum for cosmic ray electrons. These LIS's were used as input/initial conditions in a fully three-dimensional modulation model, including drifts and a Jovian source for electrons. Solutions of the model were then used to establish a range of parallel mean free paths, $\lambda_{\parallel}$, that produced compatibility between the simulations and electron observations from Pioneer 10 near Jupiter and outwards to ~70 AU. We found that the higher the LIS is taken at 120 AU, the larger the radial dependence of $\lambda_{\parallel}$ must be made for $r < 10$ AU to assure compatibility with the Pioneer observations in the inner and outer heliosphere. By relating the values of $\lambda_{\parallel}$ at Earth to the values of the LIS at 16 MeV, we found the results shown in Fig. 6. Comparing this relation to the observed and theoretical values of $\lambda_{\parallel}$ at Earth, we established that the electron LIS must be between 100 and 1000 particles m^{-2} s^{-1} sr^{-1} MeV^{-1} at 16 MeV. The most reasonable electron LIS appears to be the one given by Langner et al. (2001).

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References

Bieber, J. W., Matthaeus, W. H., Smith, C. W., Wanner, W., Kallenrode, M-B., and Wibberenz, G. *Astrophys. J.*, *420*, 294, 1994.

Dröge, W., *Space Sci. Rev.*, *93*, 121, 2000.

Ferreira, S. E. S., Potgieter, M. S., Burger, R. A., and Heber, B., *J. Geophys. Res.*, *105*, 18305, 2000.

Ferreira, S. E. S., Potgieter, M. S., and Langner, U. W., *Adv. Space Res.*, in press, 2001a.

Ferreira, S. E. S., Potgieter, M. S., Burger, R. A., Heber, B., and Fichtner, H., *J. Geophys. Res.*, in press, 2001b.

Ferreira, S. E. S., Potgieter, M. S., Burger, R. A., Heber, B., Fichtner, H., and Lopate, C., *J. Geophys. Res.*, sub., 2001c.

Fichtner, H., Potgieter, M. S., Ferreira, S. E. S., and Burger, R.A., *Geophys. Res. Lett.*, *27*, 1611, 2000.

Jokipii, J. R. and Kóta, J., *Geophys. Res. Lett.*, *16*, 1, 1989.

Lopate, C., *Proc. 23rd ICRC (Calgary)*, 3, 415, 1991.

Lopate, C., *J. Geophys. Res.*, submitted, 2001

Langner, U. W., de Jager, O. C., and Potgieter, M. S., *Adv. Space. Res.*, in press, 2001.

Parker, E. N., *Planet. Space Sci.*, *13*, 9, 1965.

Potgieter, M. S., *J. Geophys. Res.*, *101*, 24411, 1996.

Ragot, B.R., *Proc. 26th ICRC*, *7*, 83, 1999.

Simpson, J. A., Hamilton, D., Lentz, G., McKibben, R. B.. et al., *Science*, *183*, 306, 1974.

Strong, A. W., Bennett, K., Bloemen, H., Diehl, R., Hermsen, W. et al., *Astron. and Astrophys.*, *292*, 82, 1994.

Strong, A. W., Moskalenko, I. V., and Reimer, O., *Astrophys. J.*, 537, 763, 2000.

Teegarden, B. J., McDonald, F. B., Trainor, J. H., Webber, W. R., and Roelof, E. C., *J. Geophys. Res.*, 79, 3615, 1974.