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Proposed local interstellar spectra for cosmic ray electrons

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Abstract. Galactic propagation models for cosmic ray electrons give a synchrotron spectral index which is larger than the recently determined radio index between 22 - 408 MHz in the direction of the galactic disk (Roger et al., 1999), and smaller than the radio index between 0.5 - 2000 MHz in the direction of the galactic poles (Peterson et al., 1999). Diffuse gamma-ray data appear to be 'contaminated' by Crab-like point sources, so that it is difficult to derive a consistent local interstellar spectrum (IS) for electrons in the 1 to 30 MeV range. Using a phenomenological approach, we introduce two adjusted IS, such that the model radio spectral index agrees with observations of the galactic disk- and polar approaches above and below 20 MHz. By adding the constraints expected from the heliospheric modulation of galactic electrons, we find that the IS obtained by the 'galactic disk approach' is marginally above the lower limit for a local IS set by Pioneer 10 electron data at ~4 MeV and ~16 MeV observed in the outer heliosphere. The 'polar approach' gives an IS which can be considered a reasonable local IS for cosmic ray electrons.

1. Introduction

The local interstellar spectrum (IS) for electrons is crucially important for the proper study of the heliospheric modulation of cosmic ray electrons. Below ~10 GeV solar modulation effects become increasingly important, making it impossible to determine a realistic local IS for electrons from observed modulated electron spectra at Earth because the heliospheric diffusion coefficients are simply not known well enough (e.g., Potgieter, 1996; Ferreira et al., 2000). Fortunately, electron measurements had been made by the Pioneer 10 spacecraft up to ~70 AU (Lopate, 1991; 2001; private communication, 2000). These electron observations are at ~4 and ~16 MeV, making them useful to determine what the lowest value of a local IS for cosmic ray electrons may be at these energies.

Recently, Strong et al. (2000) produced several new calculations for electron interstellar spectra using a sophisticated galactic propagation model in combination with γ-ray and radio synchrotron data. They argued that their steeper electron spectrum (Strong et al., 1994), which is similar to what had been used in cosmic ray modulation models for many years (e.g., Potgieter, 1996; Ferreira et al., 2000), was significantly too high at electron energies < ~200 MeV.

The observation of synchrotron intensities and spectral indices provide essential and stringent constraints on the IS for electrons. New analysis of radio data make it possible to more accurately determine the polar radio spectrum from ~10 MHz where free-free absorption is negligible up to ~2 GHz where the 2.7 K cosmic background radiation dominates the spectrum (Peterson et al., 1999). Below ~10 MHz, where absorption becomes important, new information on the interstellar thermal free electron density and spatial distribution that is responsible for free-free absorption, allow these effects to be determined more accurately and the electron spectrum to be deduced down to ~0.1 GeV (e.g., Peterson et al., 1999).

Galactic propagation models for cosmic ray electrons which assumed injection spectra, and fits to γ-ray data, seem to have difficulties to fit the new synchrotron spectral index data. It is shown that the results of an alternative method, used in this work, agree well with the results produced by full galactic propagation models in the frequency range of interest. A qualitative study of the shape of the local IS for cosmic ray electrons was done, using the results obtained by the alternative method based on the new synchrotron spectral index data. Using this phenomenological method, an alternative local IS was derived for cosmic ray electrons. For a more elaborate discussion see Langner (2001) and Langner et al. (2001).

The synchrotron spectral index data of Peterson et al. (1999) were obtained by using the radio spectrum in the direction of the galactic poles at a frequency range of 0.5 MHz to ~2 GHz, while the 22 - 408 MHz synchrotron spectral index data of Roger et al. (1999) were obtained by

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using the radio spectrum in the direction of the galactic disk, between equatorial declinations -28° to +80°. Important for this study is that the spectral index *b* of this radio emission is related to the spectral index of the electron spectrum *d* by $b = (d - 1)/2$.

2. Alternative method

The phenomenological method, used for this work, to derive a local IS assumes that the observed electron spectrum at energies $E > 10$ GeV is correct and can be considered the local IS, since the direct measurement of electrons is not significantly influenced by modulation effects at these energies.

Two further constraints were employed: (1) The computed IS must exceed the Pioneer 10 intensities observed at ~70 AU at ~4 MeV and ~16 MeV, because the Pioneer 10 intensities must already been modulated to some degree; (2) The effective power law index of at low energies (where we have no synchrotron data to constrain) is similar to the Strong et al. (2000) index, since this index manifests to some degree the physics of propagation effects.

The synchrotron emissivity *e (n)* for an isotropic population of electrons with spectrum *J(E)* in an interstellar magnetic field strength of B = 3μG and 5μG is calculated. Note that the absolute synchrotron intensity is not of importance, since we assume that the emissivity scales as $\varepsilon(n) \propto n^{-b}$, with b a slowly varying function of the frequency *n*. Thus, by fitting the function $b = -\, dlne / dlnn$ to the observed indices, we obtain further constraints on the model parameters. Full details are given by Langner (2001).

In Fig. 1 the observed synchrotron spectral indices and those computed with the alternative method are shown for interstellar magnetic fields of 5μG and 3μG respectively. In Fig. 2 the corresponding IS for cosmic ray electrons are shown.

From Fig. 1 it follows that the galactic disk data of Roger et al. (1999) and others, constrain the IS *J(E)* only above 22 MHz, whereas the polar data of Peterson et al. (1999) constrain *J(E)* above 0.5 MHz. The IS derived from the polar data is therefore better constrained. We also see a systematic effect: The observed *b* in the direction of the galactic disk is decreasing towards lower frequencies, and the lack of galactic data below 22 MHz causes the IS derived from the galactic data to flatten more rapidly towards low energies, compared to our derivation of *J(E)* from the polar data. The result is that the IS derived from the galactic data drops below the IS derived from the polar data at low energies, which is physically unrealistic and a numerical artifact, since propagation effects into the galactic halo into the polar direction should have forced *J(E)* for the polar data to drop below *J(E)* in the direction of the galactic disk at low energies. Furthermore, for the 'local' IS derived from the galactic data we have normalized to the directly observed spectrum above 10 GeV, but *b* observed in the direction of the galactic disk is contaminated with line of sight effects, and is therefore not strictly representative of the 'local' IS. Although we will address this issue in the next section, by isolating the effect of propagation effects along the line of sight, the 'local' IS derived from the polar data is assumed more representative of a local IS.

The polar 'approach' LIS in terms of differential intensity as a function of rigidity is given by the following equations:

$$J_{LIS} = \frac{1.7(a + c\ln P)}{1 + b\ln P + d(\ln P)^2}$$

with a = 126.07, b = 0.26, c = 1.95 and d = 0.02 if $P \le$ 0.0026 GV,

$$J_{LIS} = 1.7\left(\frac{a + cP}{1 + bP}\right)^2$$

with a = 52.55, b = 148.62 and c = 23.01 if 0.0026 GV < P < 0.1 GV,

$$J_{LIS} = \frac{1.7(a + cP + eP^2 + gP^3)}{1 + bP + dP^2 + fP^3 + hP^4}$$

with a = 915.23, b = –11.22, c = 10.21, d = 7532.93, e = –0.002, f = 2405.01, g = 3.02x10^{-7} and h = 103.87 if 0.1 GV ≤ P ≤10.0 GV and

$$J_{LIS} = 1.7\exp(a + b\ln P)$$

with a = –0.89 and b = –3.22 if 10.0 GV < P < 50.0 GV.

3. Results

Five different interstellar spectra for electrons are shown in Fig. 2. The spectrum used in many modulation studies of cosmic ray electrons as a local interstellar spectrum (e.g., Potgieter, 1996; Ferreira et al., 2000) is similar to the one computed by Strong et al. (1994). This spectrum is indicated by Strong94 (19-004606 in their model). Recently, Strong et al. (2000) improved their previous model and made subsequent calculations to produce alternative electron spectra of which only two are shown, indicated by Strong98a (19-004526) and 98c (19-004508). All these spectra were calculated with their full galactic propagation model. The different assumptions, numerical method and corresponding computer code used for the calculation of galactic cosmic ray propagation are described in detail by Strong and Moskalenko (1999) and Strong et al. (2000). The two data points in Fig. 2 are electron intensities at ~4 and ~16 MeV measured with the Pioneer 10 at ~70 AU (Lopate, 1991; 2001; private communication, 2000).

Our approach based on the galactic disk synchrotron data gives an IS that is even lower than Strong98c at low energies, but our approach based on the polar synchrotron data gives a spectrum which lies between Strong94 and Strong 98a. Peterson et al. (1999) used the measurements of the polar radio intensities between 10 MHz and 2 GHz with the 2.7 K cosmic background radiation and a 20% extra-galactic component subtracted, thus representing only the galactic component of the polar radio spectrum. They derived three IS in the 0.1 - 6 GeV range (see also Higbie et al., 1999) for a 5μG interstellar magnetic field, using

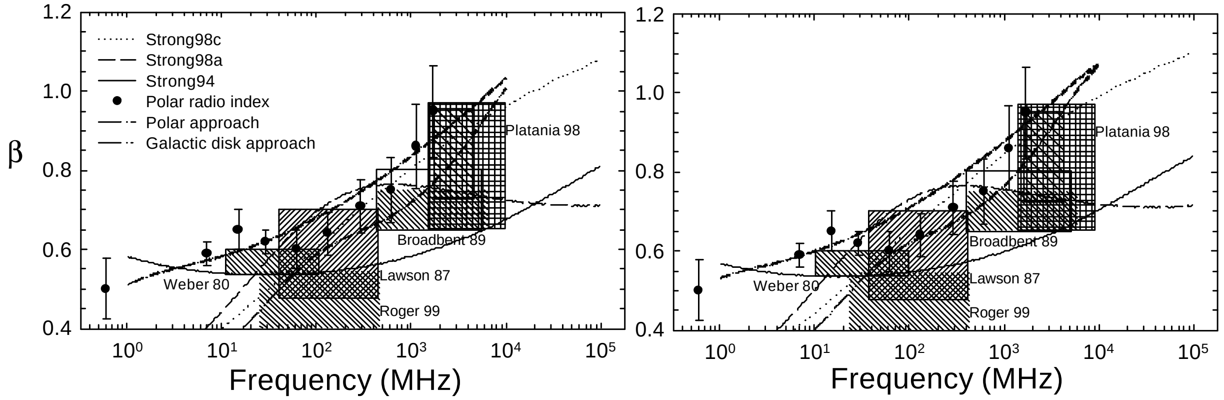

Fig. 1. The synchrotron spectral indices computed with the alternative method for an interstellar magnetic field of 5 μG (left panel) and 3 μG (right panel) respectively. This is also done for the interstellar spectra computed by Strong et al. (2000), and for the polar and galactic disk 'approaches' described in the text. Measurements taken from Strong et al. (2000) are shown as boxes: Webber et al. (1980), Lawson et al. (1987), Broadbent et al. (1989), Platania et al. (1998) and Roger et al. (1999). The data of Peterson et al. (1999), represented by solid circles, are in addition to what were shown by Strong et al. (2000).

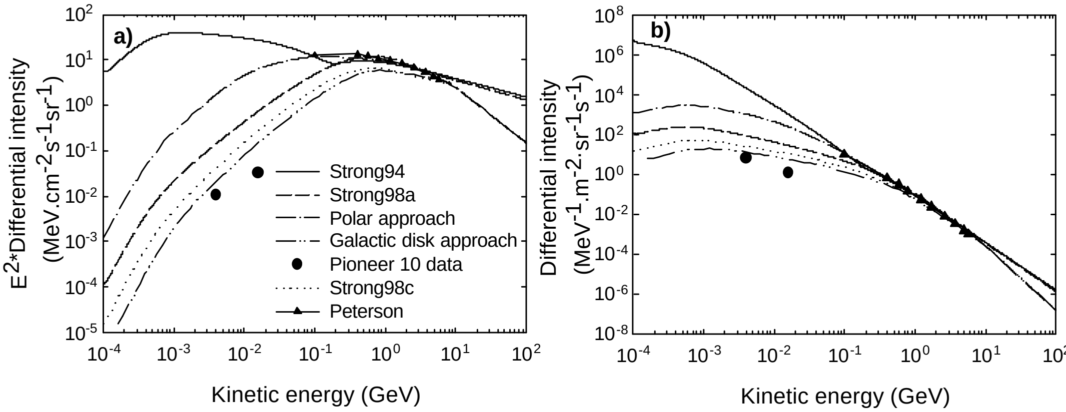

Fig. 2. The different electron interstellar spectra (IS) produced by Strong et al. (2000), denoted here as Strong94 (Strong et al., 1994), Strong98a and 98c (Strong et al., 2000) and Peterson (Peterson et al., 1999). IS computed for the polar and galactic disk 'approaches' were calculated using the alternative method described in this work. The Pioneer 10 data at ~70 AU are shown as solid circles (Lopate, 1991; 2001; private communication, 2000).

source spectra with exponents of -2.2, -2.3 and -2.4. From Fig. 2 it is also clear that our IS derived from the polar data is consistent with the corresponding IS derived by Peterson et al. (1999) above 100 MeV. Our IS derived for the galactic- and polar approaches were used to recalculate b as a function of n. Fig. 1 shows that our alternative method spectral indices are consistent with the observations for both cases, but the fast drop in b for n < 20 MHz for the galactic approach results in its corresponding IS to flatten significantly towards low energies, such that the predicted IS drops unacceptably close to the lower limits derived from the Pioneer 10 data. The differences between the synchrotron spectral indices calculated with the alternative method and with the full propagation model of Strong et al. (2000) are < 0.15 (Langner et al., 2001), which are comparable with the sizes of the error boxes shown in Fig. 1. The alternative method evidently therefore gives synchrotron spectral indices comparable to the more sophisticated models. (Of course, we do not claim here that the alternative method does a better job). Note that our IS derived for the galactic disk approach represents an averaged effect along the line-of-sight into the galactic plane, and is therefore less representative of the local IS, compared to the IS derived for the polar approach.

4. Discussion

The two recent Strong et al. (2000) spectra (Strong98a and 98c) shown in Fig. 2 are not significantly different from each other but their intensities at low energies are considerably less than the Strong94 case. These authors argue that the Strong94 spectrum (their steeper spectrum model) is no longer an option because it gives too high intensities below 100 MeV, which makes it inadequate for γ-ray observations. Based on modulation studies of cosmic ray electrons in the heliosphere the same conclusion cannot be made because the diffusion coefficients applicable to modulation are not known well enough to constrain the local IS - see Potgieter (1996). But, with cosmic ray electron data available at ~70 AU, the lower limit of any local IS can be set using modulation studies. It is reasonable to assume that some modulation occurs between 70 AU and the outer heliospheric boundary conservatively considered to be located between ~100 AU and ~120 AU. The Strong98c spectrum and the spectrum for the galactic disk approach are marginally above the observed electron intensities at ~70 AU. The implication of this is that the recent IS of Strong et al. (2000), at least Strong98c, and the one based on the galactic disk 'approach', may be too low at low energies. When these two spectra are used in a modulation model, very little modulation is required between 120 AU and the Pioneer 10 data (Ferreira et al., 2001; Ferreira et al., this volume). If the radial gradients for these low energy electrons are indeed tiny, and consequently produce almost no modulation in the outer heliosphere, it can still be concluded that the spectrum for the galactic disk approach is the absolute lower limit of the available local IS for galactic cosmic rays. If the galactic synchrotron data extended to frequencies lower than 22 MHz, the significant flattening in our model b below 20 MHz would most likely have been avoided, and the difference between the predicted IS and the Pioneer 10 data would have been comfortably larger. By adding the Peterson et al. (1999) polar radio index to the collection of data shown by Strong et al. (2000), as was done in Fig. 1, it also becomes evident that the galactic disk 'approach' and the Strong98a and -98c spectra cannot represent the Peterson data below ~50 MHz. These data show that b remains almost constant around 10 MHz to decrease slowly below this value. Our IS derived from the polar synchrotron data should and does reproduce the IS of Peterson et al. (1999), but with the difference that we extended this calculation to much lower energies as required for heliospheric modulation studies. The inclusion of the low energy electron spectral index constraint results in a further flattening below 10 MeV.

Our IS derived from galactic disk synchrotron data cannot be considered as a realistic measure of the local IS, mainly due to three reasons: (1) The observed synchrotron spectral data in the disk represents a line-of-sight averaged value, which includes a contribution from distant electrons. (2) The lack of synchrotron data below 20 MHz allows the IS to be weakly constrained at low energies, and (3), the result of (1) and (2) is that the predicted electron intensities at 4 and 16 MeV lie too close to the observed Pioneer 10 intensities, resulting in unrealistic heliospheric modulation parameters.

Our IS based on the synchrotron data derived from polar synchrotron data should be closer to the real local IS. This is because we have isolated the effect of galactic propagation, and all the unknown contributions from discrete sources in the plane. The data are also better, since the synchrotron observations extend to much lower frequencies compared to the galactic disk observations. However, there is still the effect of diffusion from the local interstellar region into the galactic halo, and the polar observations sampled the local region as well as the halo. A simple diffusion model for electrons into the galactic halo, which includes a disk scale height dependency for the galactic magnetic field B, but fitted to the same synchrotron data of Peterson et al. (1999), should produce an even more accurate spectrum for the real local IS at the lowest electron energies. We therefore predict significant advances in the knowledge of the local IS from future research.

5. Conclusions

The IS which fits the synchrotron spectral index data in the 0.5 MHz - 2 GHz range, shown as the polar 'approach' spectrum in Fig. 2, is also compatible to the high energy electron observations at Earth, and the Pioneer 10 electron observations in the outer heliosphere. We considered this IS, which is consistent with the IS calculated by Peterson et al. (1999), as a reasonable local interstellar spectrum for cosmic ray electrons as seen from a modulation point of view. For heliospheric modulation applications of the LIS derived here, together with LIS's for other species, see Potgieter et al., Langner and Potgieter, and Ferreira et al., (SH3.1, this volume).

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