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Heliospheric modulation of cosmic rays computed with new local interstellar spectra

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Abstract. Data on the synchrotron spectral indices for galactic electrons resulted in a newly proposed local interstellar spectrum (LIS). Proton, anti-proton and positron spectra were also revised recently by other authors. In this study the heliospheric modulation for these new LIS's are shown and discussed. For this we used a comprehensive drift modulation model with newly developed diffusion coefficients. Spectra, positron to electron ratios, and anti-proton to proton ratios are shown for the two polarity dependent modulation cycles and as function of the heliospheric current sheet tilt angles.

1. Introduction

In order to study the transport of cosmic rays (CRs) through the heliosphere and to find the proper diffusion coefficients it is important that the input spectra of these particles are known with adequate precision. Therefore, a crucially important aspect of heliospheric modulation is knowledge of the local interstellar spectra (LIS's) for all the species of particles of galactic origin. Recent new developments, and new data, concerning the modeling of the LIS's for galactic electrons, positrons, protons and anti-protons, as well as other species, have made it necessary to study the effects of these newly proposed spectra on heliospheric CR modulation.

For this paper we have studied the effects and influence of these new LIS's on the corresponding modulated spectra for different heliospheric current sheet (HCS) tilt angles, α. The $e^+/(e^++e^-)$ and the anti-proton to proton ratios at Earth are also shown as a function of α. For the latter we have compared the results of a steady-state model with those of a shock-drift model. The heliospheric boundary was placed at 120 AU and the termination shock at 80 AU. For additional insights into the effects of the termination shock, and various possibilities for the position of the outer boundary, see Ferreira et al. (SH3.1, this volume). (See also Langner, 2001, and references therein). Electron and positron modulation is discussed in greater detail by Potgieter et al. (SH3.1, this volume), and anti-proton and proton modulation by Langner and Potgieter (SH3.1, this volume).

2. Modulation models

To study and test modulation based on various LIS's for galactic electrons, positrons, protons and anti-protons, modulation models of varying complexity were used: (1) a steady-state wavy current sheet (WCS) model based on the work of Hattingh and Burger (1995), and (2) a shock acceleration model based on the work of le Roux et al. (1996), Haasbroek (1997), Haasbroek et al. (1997) and Ferreira et al. (SH3.1, this volume). For a complete description, see Langner (2001). The basic model parameters used for this work are described by Langner and Potgieter (SH3.1, this volume). The diffusion coefficients used for the steady-state WCS model were kept unchanged for the different species and are based on those described in Burger et al. (2000), while those used for the termination shock (TS) model are described in Potgieter et al. (SH3.1) and Potgieter et al. (2001). The diffusion coefficients used here do not give perfect fits to the data at Earth, but they do give reasonable compatibility between model solutions and observations. They are considered adequate for showing the qualitative characteristics of the modulated proton, anti-proton, electron and positron spectra.

In this work the polar approach electron LIS of Langner et al. (2001) - see also Langner et al. (this volume), the positron LIS of Strong et al. (2000), a proton LIS of Webber (private communication, 2000) and the anti-proton LIS of Bieber et al. (1999) were used, respectively. Although other LIS's for the different species were also studied, the modulation produced by them look qualitatively the same as the solutions shown below. The mentioned selection of LIS's is considered representative of what is available at present. For the latest LIS's for protons and anti-protons, and the corresponding modulation, see Moskalenko et al. (this conference).

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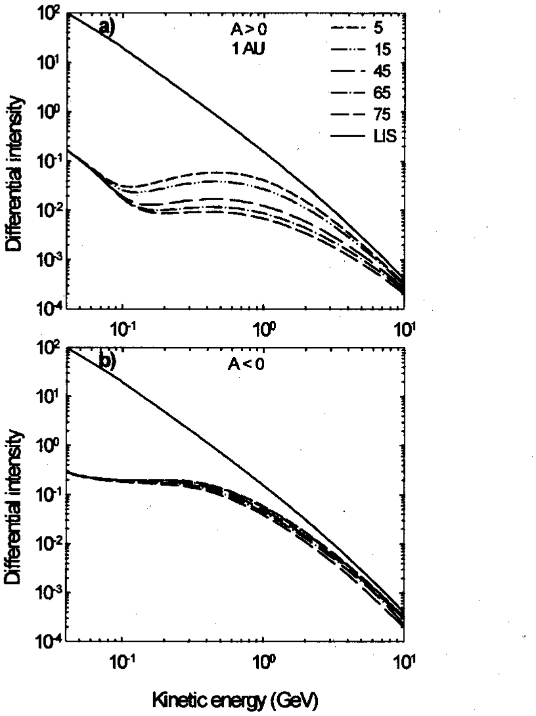

Fig. 1. Modulated electron spectra at Earth produced by the WCS-model using the polar approach electron LIS, shown for tilt angles $\alpha = 5°$, 15°, 45°, 65° and 75°, and for both polarity cycles. LIS is specified at 120 AU. Differential intensities are in units of particles (m^2.s.sr.MeV)$^{-1}$.

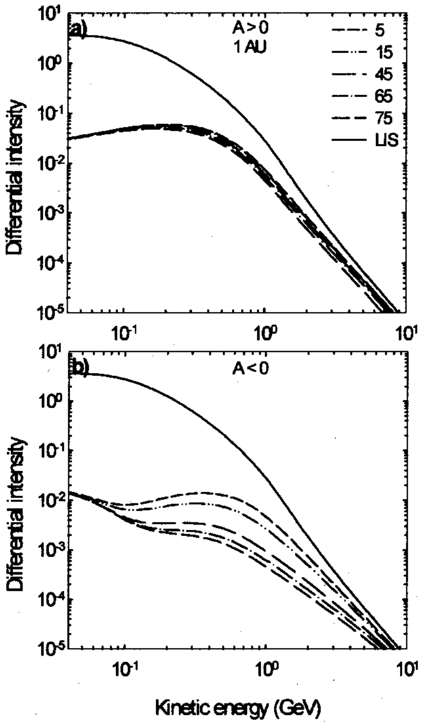

Fig. 2. Same as in Fig. 1, but for positrons.

3. Modulated spectra

In Fig. 1, 2, 3 and 4 the modulated electron, positron, proton and anti-proton spectra are shown, respectively, for different tilt angles at Earth and for the two magnetic field polarity dependent cycles, A > 0 (e.g., 1970's and 1990's) and A < 0 (e.g., 1960's and 1980's). From Fig. 1(a) and (b) it is evident that the modulation for electrons in the A < 0 polarity cycle has a smaller tilt angle dependence than the modulation for electrons in the A > 0 polarity cycle and vice versa for positrons as shown in Fig. 2(a) and (b). This is due to the fact that it becomes increasingly difficult for electrons in the A > 0 polarity cycle to propagate inwards with the increasing waviness of the HCS than when they propagate inwards primarily through the heliospheric poles in the A < 0 cycle. Note that at kinetic energies < 100 MeV the tilt angle dependence dissipates for both electrons and positrons but not for protons and anti-protons as will be shown below. Contrary to expectations, the tilt angle dependence is not identical for electrons and positrons during opposite HMF polarity cycles, (when the particles propagate inwards for both species through the same region of the heliosphere) due to the difference in the spectral indices (shape) of the LIS's.

In Fig. 3(a) and (b) the larger spread between the smallest and largest tilt angles for the A < 0 polarity cycle are clear if compared with the A > 0 cycle. This spread is parameter dependent especially for the A < 0 cycle, which is obviously too large in Fig. 3(b) mainly because too little modulation is given with the minimum tilt angle. This issue illustrates that the same set of diffusion coefficients cannot be used to simultaneously fit observations for A > 0 and A < 0 solar minimum periods (Potgieter, 2000).

Similar qualitative characteristics are evident for the tilt angle dependence of the anti-protons as shown in Fig. 4(a) and (b) as those for the protons, except for the change in drift direction, and the difference in total modulation. The model gives very little modulation for anti-protons, primarily because of the spectral slope at energies below 1 GeV. Except for very low energies, the slope of the anti-proton LIS is almost the same as the characteristic slope of modulated spectra due to adiabatic energy losses. The difference between the two polarity cycles is also not nearly as pronounced as for protons. The latest work of Moskalenko et al. (this conference) shows that the LIS used in Fig. 4 is too low. Increasing the LIS would indeed give better fits to the anti-proton data at Earth, and larger radial gradients, but the qualitative features shown here will not change.

4. The $e^+/(e^++e^-)$ ratios

In Fig. 5(a) the computed $e\ /(e^{'}+e^{-})$ ratios are shown at Earth as a function of tilt angles for kinetic energies of 50.0 MeV, 100.0 MeV and 1.0 GeV, respectively, for both HMF polarity cycles. The distinctive 'V' and 'Λ' shapes of the two

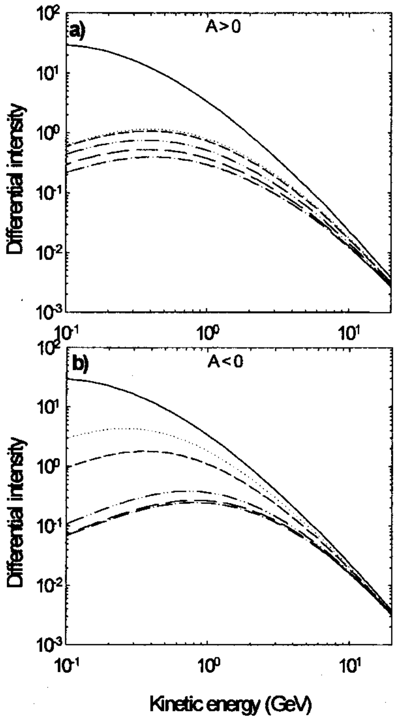

Fig. 3. Same as in Fig. 1, but for protons.

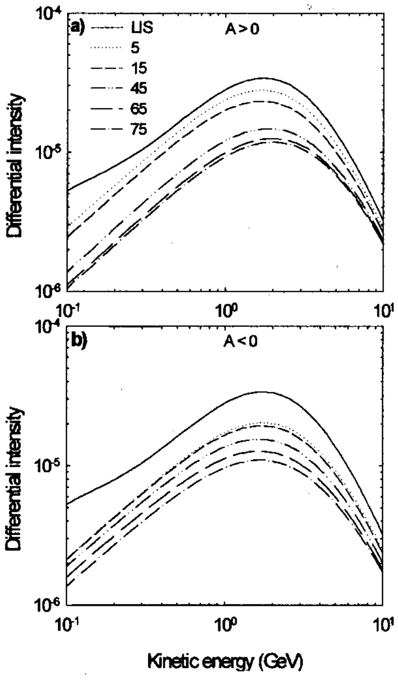

Fig. 4. Same as in Fig. 1, but for anti-protons.

polarity cycles are clearly shown and are in good accordance with previously computed ratios (see also Burger and Potgieter, 1999). The ratios for the 'V' shapes are generally higher than for the 'Λ' shapes at 1 AU due to high electron differential intensities in the A < 0 HMF polarity cycle. Note that this ratio always remains less than unity. Figure 5(a) clearly shows that there is almost no drift at low kinetic energies so that the tilt angle dependence of the $e^+/(e^+ +e^-)$ ratio dissipates for both polarity cycles. The tilt dependence and the values of this ratio becomes less with increasing radial distance (Langner, 2001).

In Fig. 5(b) the $e^+/(e^+ +e^-)$ ratios as a function of tilt angle are compared at a kinetic energy of 1 GeV between the steady-state WCS model and a TS model. The 'V' and 'Λ' shapes are clearly more pronounced for the steady-state WCS-model than for the TS-model at this energy, primarily due to the neglected acceleration process in the WCS-model. (See also Potgieter, et al., this volume). At larger radial distances the difference between the $e^+/(e^+ +e^-)$ ratios for the two models becomes less (Langner, 2001). The steady-state model evidently overestimates the effects of heliospheric modulation, in particular the effect of the changing tilt angles.

5. The anti-proton to proton ratios

In Fig. 6 the computed anti-proton to proton ratios are shown at Earth as a function of tilt angles for kinetic energies (rigidities) of 45.0 MeV (0.3 GV), 440.0 MeV (1.0 GV) and 2.2 GeV (3.0 GV), respectively, for both HMF polarity cycles. The rigidity dependence and the calculated ratios are also in good accordance with those calculated by Bieber et al. (1999). The distinctive 'Λ' and 'V' shapes are again clearly recognizable. During the A < 0 cycles the ratio may change by up to a factor of 50 from solar minimum modulation to solar maximum modulation, while for the A > 0 cycles the variation is rather mild.

The model predicts a stronger tilt dependence for the anti-proton to proton ratio during the A < 0 polarity cycles as one would expect. This dependence also has a strong energy dependence, with almost no tilt angle dependence at ~2 GeV, in contrast to the energy dependence of the $e^+/(e^+ +e^-)$ ratios. Obviously, the ratio is much less than unity for all tilt angles, or in other words, for a complete modulation cycle. Increasing the anti-proton LIS would change these ratios somewhat (Moskalenko et al., 2001).

6. Conclusions

1. The tilt angle dependence of electrons, positrons, protons and anti-protons is clearly different for consecutive solar polarity cycles due to the different drift patterns they follow. This is despite the fact that drifts are inhibited by the modification of the Parker magnetic field used in all our modeling and the introduction of enhanced perpendicular diffusion in the polar direction of the heliosphere - see e.g., Potgieter (2000) and Burger et al. (2000).
2. Drift effects do not occur for electron and positron modulation below ~100 MeV. The exact value is somewhat parameter dependent. The tilt angle dependence of the

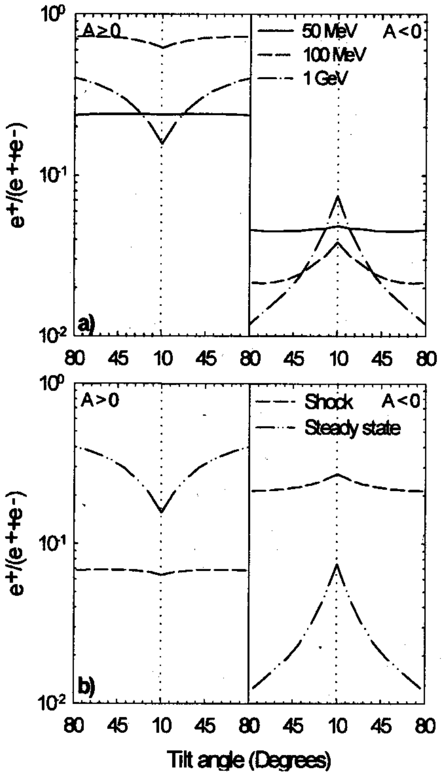

Fig. 5. a) The $e^+/(e^++e^-)$ ratio at Earth as function of tilt angle in the equatorial plane computed with the steady-state WCS model for both HMF polarity epochs at kinetic energies of 50 MeV, 100 MeV and 1 GeV, respectively.

Fig. 5. b) The $e^+/(e^++e^-)$ ratio computed with the steady-state WCS model and repeated with a termination shock model, with a shock at 80 AU, at a kinetic energy of 1 GeV - the same parameters were used as in a). The modulation region ends at 120 AU.

$e^+/(e^++e^-)$ ratio therefore dissipates below this energy. The largest effect on the $e^-/(e^-+e^+)$ ratio should occur during the A < 0 polarity cycle.

3. The total modulation, and characteristics, of anti-proton modulation is quite different than for protons, primarily because of the spectral shape of the anti-proton LIS, especially below 2 GeV.

4. The tilt angle dependence of the $e^+/(e^++e^-)$ and anti-proton to proton ratios at Earth exhibits the characteristic and distinctive 'Λ' shapes for A > 0 cycles, and 'V' shapes for the A < 0 cycles, similar to that of the e^-/p ratios shown by e.g., Burger and Potgieter (1999).

5. The tilt angle dependence of the anti-proton to proton ratios is very moderate for the A > 0 cycle, but may vary by a factor of 50 during the A < 0 cycle.

6. The steady-state model overestimates the effects of the varying tilt angle on heliospheric modulation. This was found when the steady-state model was compared with a termination shock/drift model.

7. No unambiguous conclusions can be drawn regarding any preferences for the LIS's presently available using the $e^+/(e^++e^-)$ or the anti-proton to proton ratios at Earth. These

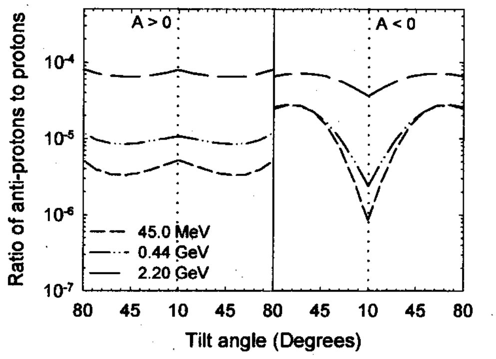

Fig. 6. Anti-proton to proton ratio at Earth as a function of tilt angle computed with the steady-state WCS model for both polarity epochs at kinetic energies (rigidities) of 0.045 GeV (0.3 GV), 0.44 GeV (1.0 GV) and 2.2 GeV (3.0 GV), respectively.

results do however illustrates what uncertainties can be expected in the ratios measured at Earth because of the uncertainties in the LIS's for the different species.

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