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Differences in proton and anti-proton modulation in the heliosphere

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Abstract. The modulation effects for different local interstellar spectra for anti-protons and protons, as computed with a numerical modulation model including drifts and the latest diffusion coefficients are illustrated. The influence of heliospheric modulation on anti-proton to proton ratios and spectra, and the effect of the solar magnetic field polarity reversals are shown and discussed. It is found that the anti-proton modulation is quantitatively different than for protons.

1. Introduction

Although the differences in the proton and anti-proton local interstellar spectra (LIS's) are more subtle and perhaps not as controversial as those in the electron and positron LIS's, neither their absolute fluxes nor their exact spectral shape are known with adequate precision. Knowledge of the absolute abundance and the exact spectral shape of the proton and anti-proton spectra are of particular astrophysical and heliospheric importance. Because the LIS's have not been known well enough, and because the heliospheric modulation parameters are quite uncertain, not much work has been done on the modulation of anti-protons and positrons in the heliosphere. In this study the effects of new proton and anti-proton LIS's (e.g., Strong et al., 2000; Moskalenko et al., this conference) on the heliospheric modulation of galactic cosmic rays (CRs) are shown and discussed, using improved heliospheric diffusion coefficients. Furthermore, the peculiar modulation of anti-protons is illustrated, and the anti-proton to proton ratios are calculated for the two magnetic field polarity modulation epochs. Positron and electron modulation is discussed by Potgieter and Langner (SH3.1, this volume).

2. Modulation model and parameters

In this study the two-dimensional model developed by Hattingh and Burger (1995) was used. It is based on Parker's (1995) transport equation given by:

$$\frac{\partial f}{\partial t} = \nabla.(\mathbf{K}.\nabla f - \mathbf{V} f) + \frac{1}{3P^2}(\nabla.\mathbf{V})\frac{\partial}{\partial P}(P^3 f), \qquad (1)$$

that was solved in a spherical coordinate system assuming azimuthal symmetry and a steady-state for solar minimum modulation, that is $\partial f/\partial t = 0$. Here **V** is the solar wind velocity, and $f(\boldsymbol{r},P)$ the distribution function of the CRs at position $\boldsymbol{r}$, and with P the rigidity in GV. Numerical solutions for the A > 0 and A < 0 heliospheric magnetic field (HMF) polarity cycles were obtained. In the diffusion tensor **K**, gradient and curvature drifts were specified by

$$K_A = (K_A)_0 \frac{K_{drift}(P)}{3B}. \qquad (2)$$

Full drifts are given with $(K_A)_0 = 1.0$. Here B is the averaged magnitude of the HMF, and $K_{drift}(P)$ is a function given by

$$K_{drift}(P) = \beta P \frac{10P^2}{10(P^2+1)}. \qquad (3)$$

(See e.g., Burger et al., 2000).

The parallel diffusion coefficient is given by:

$$K_{\|} = (K_{\|})_0 \beta\{0.04\frac{P}{P_c} + 0.04(\frac{P}{P_c})^2 + 0.3(\frac{P}{P_c})^{1/3} + 0.8\frac{r_c}{r^{r/(r_c h)}}\}M, \qquad (4)$$

$$\text{with } h = 140.0 + 10.0(\frac{P_c}{P})^{1/3} \quad \text{and} \quad M = \frac{r}{r_c}, \quad \forall\, r.$$

Here r is the radial distance in AU, $P_c = 1$ GV, $r_c = 1$ AU, $(K_{\|})_0 = 30.0 \times 10^{20}$ cm^2 s^{-1} and $\beta = v/c$ is the ratio of the particle speed to the speed of light in vacuum. According to Eq. (4), $K_{\|}$ is assumed independent of the polar angle.

For the perpendicular diffusion coefficient in the radial direction it is assumed that:

$$(K_{\perp})_{rr} = a\, K_{\|} \qquad (5)$$

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with $a = 0.009$. For the perpendicular diffusion coefficient in the polar direction:

$$(K_{\perp})_{\theta\theta} = b\, K_{\parallel}\, f(\theta) \tag{6}$$

Here,

$$f(\theta) = A + B \tanh \{\frac{1}{\Delta\theta}(\tilde{\theta} - \frac{\pi}{2} - \theta_F)\}, \tag{7}$$

with parameters: $A = (d + 1) / 2$, $B = (d - 1)/2$, $\theta_F = 35\pi/180$ radians, $\Delta\theta = 1/8$ radians, and

$$\tilde{\theta} = \begin{cases} \theta & ;\theta \geq \frac{\pi}{2} \\ \pi - \theta & ;\theta < \frac{\pi}{2} \end{cases} \tag{8}$$

with θ in radians. Here, $d = 11.0$ determines the value of $(K_{\perp})_{\theta\theta}$ at the heliospheric poles and $b = 0.009$ determines its value in the equatorial plane. Because $f(\theta) = 1$ when $\theta = 90°$, $(K_{\perp})_{rr} = (K_{\perp})_{\theta\theta}$ if $b = a$.

The diffusion coefficients described above are similar to those used by Ferreira et al. (2001) (see also Hattingh, 1998, Fichtner et al., 2000, and Potgieter, 2000). Theoretical motivation for these diffusion coefficients are given by Burger et al. (2000). They are new in the sense that the rigidity dependence changes with radial distances.

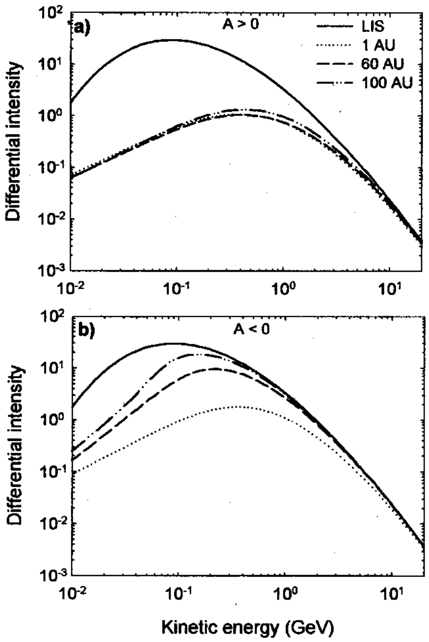

Fig. 1. Modulated proton spectra computed for the Webber LIS (private communication, 2000) in the equatorial plane at radial distances of 1 AU, 60 AU and 100 AU, for both HMF polarity cycles with $\alpha = 15°$. LIS is specified at 120 AU.

The proton and anti-proton LIS's were chosen to ensure that the modulated spectra at 1 AU in the equatorial plane with the tilt angle $\alpha = 15°$ for the $A > 0$ HMF polarity cycle were compatible with available data for both species. The data are summarized by Moskalenko et al. (this conference) and are not shown here. For the anti-protons we concentrated on two LIS's, one obtained from Moskalenko (private communication, 2000 - for the latest LIS, see Moskalenko et al. - this conference; also Moskalenko et al., 2001), and a second one from Bieber et al. (1999). For protons we used LIS's obtained from Webber (private communication, 2000) and from Strong et al. (2000), respectively. For all the LIS's, we use $(K_A)_0 = 1.0$ in Eq. (2), but for the Strong et al. LIS we used $(K_A)_0 = 0.8$, in order to fit the observations at Earth. The rest of the parameters were kept unchanged.

3. Differences in the modulation of protons and anti-protons

The modulation produced by the Webber proton LIS and the Strong et al. proton LIS are shown in Fig. 1 and 2, for the two HMF polarity cycles, respectively. The spectra converge to the same slope at low kinetic energies for both polarity cycles at 1 AU due to strong adiabatic energy losses, but remarkably less for the $A < 0$ cycles in the middle to outer heliosphere. For the $A < 0$ cycle the effect also happens at lower energies than in the $A > 0$ cycle. This is because the protons enter through the equatorial plane in the $A < 0$ cycle; the closer an observer gets to the outer boundary, the lesser the energy losses become. For $A > 0$ the protons drift primarily through the heliospheric polar regions and then outwards along the wavy HCS. It is therefore expected that at larger radial distances the energy losses will be somewhat larger in the equatorial plane for this cycle. The extent of this effect is however parameter dependent. Comparing Fig. 1 and Fig. 2 one notices that below ~ 100 MeV the Webber LIS is significantly less than

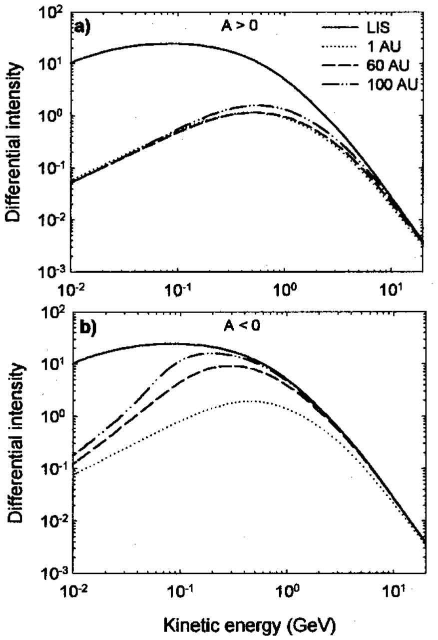

Fig. 2. Similar to Fig. 1 but obtained for the proton LIS of Strong et al. (2000). Note the difference with the LIS in Fig. 1 at energies below 300 MeV.

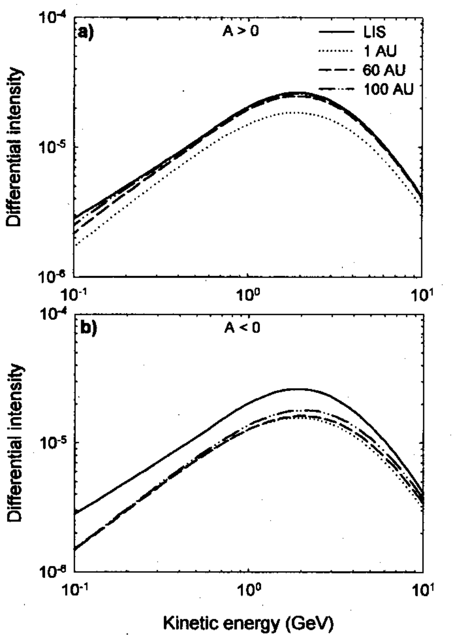

Fig.3. Modulated spectra computed for the Moskalenko anti-proton LIS in the equatorial plane at radial distances of 1 AU, 60 AU and 100 AU for both HMF polarity cycles with α =15°.

the Strong et al. LIS. But despite this difference, the modulation at Earth looks the same for both LIS's, and very similar for larger radial distances. The ratios of the LIS's and corresponding modulated spectra for the two cases also confirm that protons at low energies experience large adiabatice energy changes and that the shape of the LIS does not matter the deeper the observation is made inside the heliosphere. Modulation of protons is thus hiding the shape of the LIS very effectively at low energies. This effect is more pronounced in the A > 0 cycle. This means that a spacecraft will probably have to reach 100 AU and beyond in the equatorial plane before this kind of difference in the low-energy (< 300 MeV) proton LIS will be detected during A > 0 cycles but closer in for the A < 0 cycles. Note the large radial gradient at these energies between the outer boundary and the modulation at 100 AU in the A > 0 cycle. Although *$(K_A)_0$* was changed when using the different proton LIS's, the modulation differences between the two cases are primarily due to the different spectral indices of the two LIS's at higher energies. For more detail, see Langner (2001).

We also used two LIS's to study anti-proton modulation. The modulation produced by the Moskalenko anti-proton LIS and the Bieber et al. LIS are shown in Fig. 3 and 4, respectively. Although the model parameters and diffusion coefficients are the same for anti-protons and protons, the total modulation shown in these figures is obviously different due to the difference in the shape (spectral indices) of the proton and anti-proton LIS's. The slope of the anti-proton LIS at energies < 500 MeV is essentially the same as the slope of the corresponding modulated spectra as produced by the adiabatic energy losses, while the slope of the proton LIS at these energies is much less. This causes significantly smaller computed radial gradients for the anti-protons, especially in the outer heliosphere, and accordingly much less modulation is produced in total for the anti-protons. The differences between the two LIS scenarios seem negligible and will only be detected at ≤ 100 MeV if a spacecraft would approach the interstellar medium. Compared to observations at Earth for anti-protons (not shown) we determined that the Moskalenko LIS seems too low. This has already been modified by Moskalenko et al. (this conference). The ratios of the modulated spectra produced with the Bieber anti-proton LIS to the modulated spectra produced with the Moskalenko anti-proton LIS are shown in detail by Langner (2001). As for the protons, the ratios are also independent of the shape of the LIS at low energies (< 300 MeV), due to adiabatic cooling, but this is significantly less pronounced for the anti-protons because of the shape of the anti-proton LIS's below 1 GeV. The modulation produced is quantitatively the same for the two considered anti-proton LIS's. The qualitative effects of the modulation produced in the A > 0 cycle for anti-protons is also in accordance with the modulation produced in the A < 0 cycle for protons and *vice versa* for the other cycle. The radial gradients for anti-protons are thus smaller in the A < 0 cycle than in the A > 0 cycle but this feature is not nearly as pronounced as for protons.

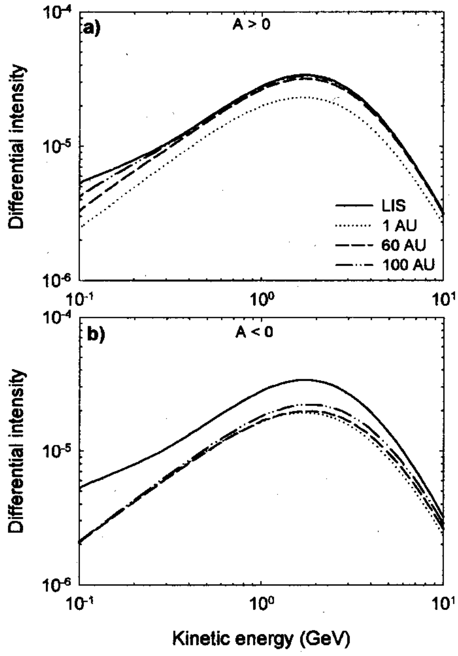

Fig. 4. Similar to Fig. 3 but obtained for the Bieber et al. (1999) anti-proton LIS specified at 120 AU.

In Fig. 5 the anti-proton to proton ratios at different radial distances are shown as a function of kinetic energy in the equatorial plane, with α = 15° for both polarity cycles. This is done for the Bieber et al. anti-proton and Strong et al

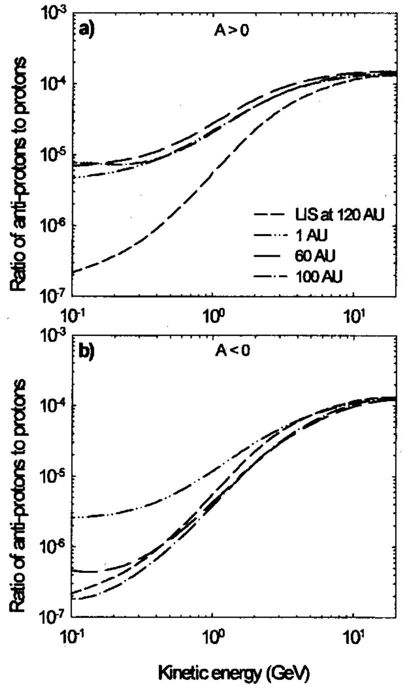

Fig. 5. Computed anti-proton to proton ratios as function of kinetic energy for the Bieber anti-proton and Strong et al proton LIS's, at radial distances of 1, 60, 100 and the LIS ratios at 120 AU in the equatorial plane, with $\alpha = 15^0$ for both polarity cycles.

proton LIS's. The difference between the A > 0 and A < 0 cycles are remarkable. For the A > 0 cycle the modulated ratios differ significantly from the corresponding LIS ratio, even at large radial distances. For the A < 0 cycle the ratio at 60 AU already has almost the same slope as the ratio at 120 AU, except for lower energies (< 200 MeV). For both polarity cycles the ratios at Earth are in good accordance with those calculated by Bieber et al. (1999). These ratios also look qualitatively the same for the different LIS's considered in this work.

5. Conclusions

We studied the differences in the modulation of protons and anti-protons as described by a drift model. We used new calculations for the proton and anti-proton LIS from Strong et al. (2000) and Webber (private communication, 2000), and Bieber et al. (1999) and Moskalenko (private communication, 2000), respectively. These were specified at a modulation boundary of 120 AU. New calculations for the various diffusion coefficients were also used (e.g., Burger et al., 2000; Ferreira et al., 2001). Solutions were obtained for the two HMF polarity cycles A > 0 and A < 0.

We found that for both protons (A > 0) and anti-protons (A < 0) that the radial gradients are small in the inner to middle heliosphere but large in the outer heliosphere. This drift characteristic is however significantly less pronounced for anti-protons because of the spectral shape of the anti-proton LIS below 1 GeV. The shape of the anti-proton LIS already has the typical spectral shape of the modulated spectra due to adiabatic energy losses. The radial gradients are therefore rather small during both polarity cycles for the anti-protons. This might indicate that the LIS's for the anti-protons are too low. See Moskalenko et al. (this conference) for updated calculations of the proton and anti-proton LIS's. The predicted large radial gradients between the outer boundary and ~100 AU for protons (modulation 'barrier') in the A > 0 cycle implies that spacecraft will probably have to penetrate the interstellar medium to determine the true value of the LIS during this period. But, spacecraft may already get close to the value and spectral shape of the proton LIS at ~80 AU in A < 0 cycles. Conversely, for anti-protons spacecraft may get close to the value of the LIS already at ~60 AU in the A > 0 cycle. Due to adiabatic cooling spacecraft will probably have to penetrate the interstellar medium to determine the true value and spectral shape of the proton and anti-proton LIS's below ~100 MeV. We also found that even if the anti-proton to proton ratio is well known as a function of energy at 1 AU, not much can be deduced about the LIS's for anti-protons or protons.

According to this model, the anti-proton to proton ratio at mid-radial distances already contains useful information about the ratios of the LIS's, but only during an A < 0 polarity cycle. It is clear that no unambiguous conclusions could be drawn regarding any preferences for the LIS's for the protons and anti-protons. This was expected because of the uncertainty in the LIS's and the uncertainties of the heliospheric modulation parameters. This may be solved only when a spacecraft is sent to explore the outer heliosphere and the very local interstellar medium. However, the results of this model do show the clear differences in proton and anti-proton modulation in the heliosphere.

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