Modulation of Anomalous Protons with increasing Solar Activity

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Abstract

A comprehensive time-dependent modulation model including particle drifts, enhanced perpendicular diffusion, a solar wind termination shock (TS), and a heliosheath is used to study the acceleration and modulation of anomalous protons with increasing solar activity. Solar activity is represented by increasing the 'tilt angle α' from 10° to 70°, reducing global drifts, changing the effectiveness of the TS directly by decreasing the compression ratio s, and by decreasing the effective radial diffusion coefficient. Surprisingly, the effectiveness of the acceleration of the ACR protons improves with increasing α for the $A > 0$ polarty cycle but not for $A < 0$. Changing s has a profound effect on all spectra.

1. Introduction

The solar wind termination shock (TS) is one of the main features of the heliosphere. There is reasonable consensus that the TS should be between 80 and 90 AU, but the position of the outer boundary (heliopause) is uncertain, probably at least 30–50 AU beyond the TS. The TS is crucially important for the existence of the anomalous component of cosmic rays (ACR). Like galactic cosmic rays, ACR are also subjected to the four major modulation mechanisms: convection, diffusion, drifts, and adiabatic energy losses. As such a change in the diffusion coefficients and in gradient and curvature drifts over a solar activity cycle, together with a changing current sheet, should influence the acceleration and the modulation of ACR. We also assumed that the TS can be modified (mediated) because the shock structure is not only determined by what the solar wind does but also by the characteristics of the energetic particle population in the outer heliosphere — see [2] for an excellent review. In this paper we report on our study of the spectral form of anomalous protons at/close to the TS, in particular what may happen to the spectrum with increased solar activity, and when the TS is modified as mentioned above — see also [5] and [7].

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2. Model and Parameters

The Parker time-dependent transport equation (TPE) was solved as a combined diffusive shock acceleration and drift modulation model with two spatial dimensions, neglecting any azimuthal dependence. The concept and method was first described in [4]. The numerical scheme is similar to the description of [8], except for some modifications introduced by [3]. The TPE was solved with the current sheet 'tilt angle', $\alpha = 10^\circ$ and $\alpha = 70^\circ$, during so-called $A > 0$ (e.g., $\sim$ 1990 to present) and $A < 0$ (e.g., $\sim$ 1980 to $\sim$ 1990) heliospheric magnetic field (HMF) polarity cycles. The outer modulation boundary was assumed at 120 AU where the intensity of anomalous protons is assumed to become zero. A TS is assumed at $r_S = 90$ AU with a compression ratio varying between $2.0 < s < 4.0$, and a shock precursor scale length of $L = 1.2$ AU. The magnetic field 'jumps' by a factor s at the TS. The solar wind speed V changes from 400 km s^{-1} in the equatorial plane ($\theta = 90^\circ$) to 800 km s^{-1} in the polar regions; V decreases by $1/2s$ over L up to the shock, then abruptly as a step function to the downstream value, in total by V/s. Beyond the TS, V decreases as $1/r^2$ up to the outer boundary. The details of the assumed diffusion coefficients are given by [5]. The spatial and rigidity dependence of the parallel, perpendicular and 'drift' diffusion coefficients $K_{||}$, $K_\perp$, and K_T, respectively, are based on the motivations given by [1] except for minor changes. Diffusion perpendicular to the HMF was enhanced in the polar direction by assuming $K_{\perp\theta} \geq K_{\perp\mathrm{r}}$ off the equatorial plane [6]. A quantitative fitting of ACR observations will not be shown — see also [8].

3. Results and discussion

The development of solar activity is represented by changing the following: (1) Increasing α from 10°, shown in Figure 1, to 70°, shown in Figure 2 — see also [7]. (2) Decreasing global drifts, from an optimum value (which fits most data sets) to zero — not shown. (3) Changing the effectiveness of the TS directly by decreasing s in Figure 3. (4) Increased diffusion by decreasing the effective radial diffusion coefficient — not shown. Figure 1 shows that the model reproduces the basic modulation features e.g. (1) the spectra at the TS have the required slope (-1.2) corresponding to $s = 3.2$ before the spectral cut-off occurs with increasing energies. (2) This cut-off in the power law spectra occurs at a higher energy for the $A < 0$ cycle than for $A > 0$. (3) The radial distribution is clearly different for the two cycles, with a significant stronger increase in modulation between 80 and 90 AU for $A > 0$ than for $A < 0$. Between 1–60 AU the radial gradients are clearly much less for the $A > 0$ cycle than for $A < 0$. (4) At low energies the spectra obtain the same slope (spectral index) because adiabatic energy losses dominated. (5) Between the TS and 1 AU the intensity at 100 MeV drops by a factor of $\sim$900 for $A > 0$, but by a factor of $\sim$650 for $A < 0$. (6) The maximum intensity at

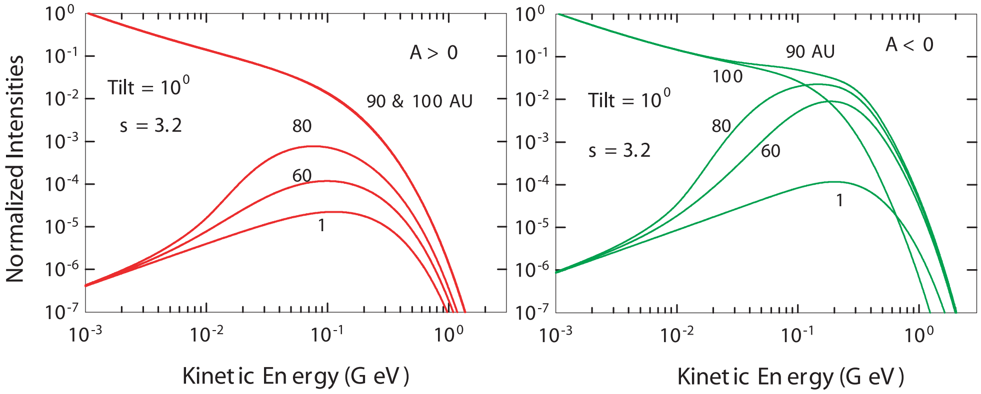

Fig. 1. Computed anomalous proton spectra at 90, 100, 80, 60 and 1 AU (top to bottom) in the equatorial plane with the TS at 90 AU, normalized at 1 MeV. Left: A $>$ 0 polarity cycle, right, A $<$ 0 polarity cycle, both with $\alpha = 10°$ and an optimal compression ratio $s = 3.2$.

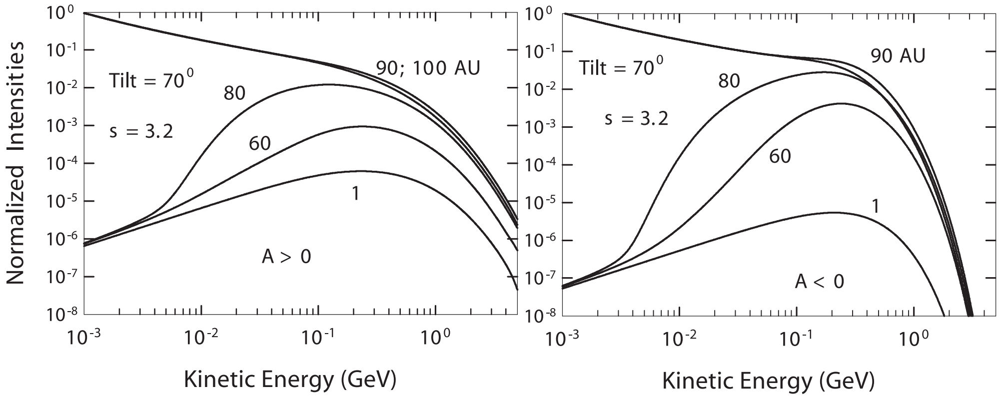

Fig. 2. Similar to Figure 1 but with increased solar activity with $\alpha = 70°$. Spectra at 100 AU are just below that for 90 AU.

1 AU occurs at ∼120 MeV for A $>$ 0, decreasing to lower energies with increasing radial distance. For A $<$ 0, the maximum intensity at 1 AU occurs at ∼200 MeV, decreasing to lower energies with increasing radial distance with about the same value. The first remarkable difference in Figure 2 is that for A $>$ 0 the cut-off occurs at significantly higher energies than for $\alpha = 10°$ in Figure 1. This makes the intensity at energies $>$ 500 MeV considerably higher. For A $<$ 0, the cut-off occurs at somewhat lower energies than with $\alpha = 10°$, in sharp contrast to the A $>$ 0 scenario. However, at 100 MeV the total modulation between the TS and

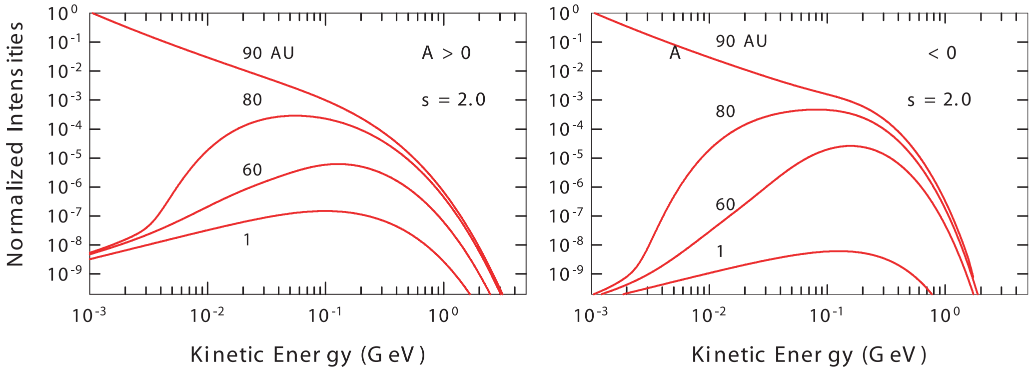

Fig. 3. Similar to Figure 2 but with $s = 2.0$. Spectra for 100 AU are omitted.

1 AU is quite close for the two α values. The radial distribution is also different from Figure 1 for both polarity cycles. Obtaining the 'adiabatic slope' has shifted to lower energy values in the outer heliosphere. As expected, and consistently, the slope of the 'shocked' spectra at 90 AU in Figure 3 is much steeper (-2.0) with a substantial drop in the intensity at all energies.

4. Conclusions

When the compression ratio s is decreased from 3.2 to 2.0 with increased solar activity the ACR proton intensity decreases significantly throughout the heliosphere. For additional effects, see [7]. If this scenario is real, the ACR intensities should drop significantly in the inner and the outer heliosphere with increasing solar activity, even as an observer approaches the TS. This scenario is by far the most dominant effect on ACRs with increasing solar activity.

5. References

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