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On the perpendicular diffusion of solar energetic particles

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The multitude of recent multi-point spacecraft observations of solar energetic particle (SEP) events have made it possible to study the longitudinal distribution of SEPs in great detail. SEPs, even those accelerated during impulsive events, show a much wider than expected longitudinal extent, bringing into question the processes responsible for their transport perpendicular to the local magnetic field. In this paper we examine some aspects of perpendicular transport by including perpendicular diffusion into a numerical SEP transport model that simulates the propagation of impulsively accelerated SEP electrons. We find that: (i) SEP intensities are generally asymmetric in longitude, being enhanced towards the west of optimal magnetic connection to the acceleration region. (ii) The maximum SEP intensity may also be shifted (parameter dependently) away from the longitude of best magnetic connectivity at 1 AU. We also calculate the maximum intensity, the time of maximum intensity, the onset time and the maximum anisotropy as a function of longitude at Earth's orbit and compare the results, in a qualitative fashion, to recent spacecraft observations.

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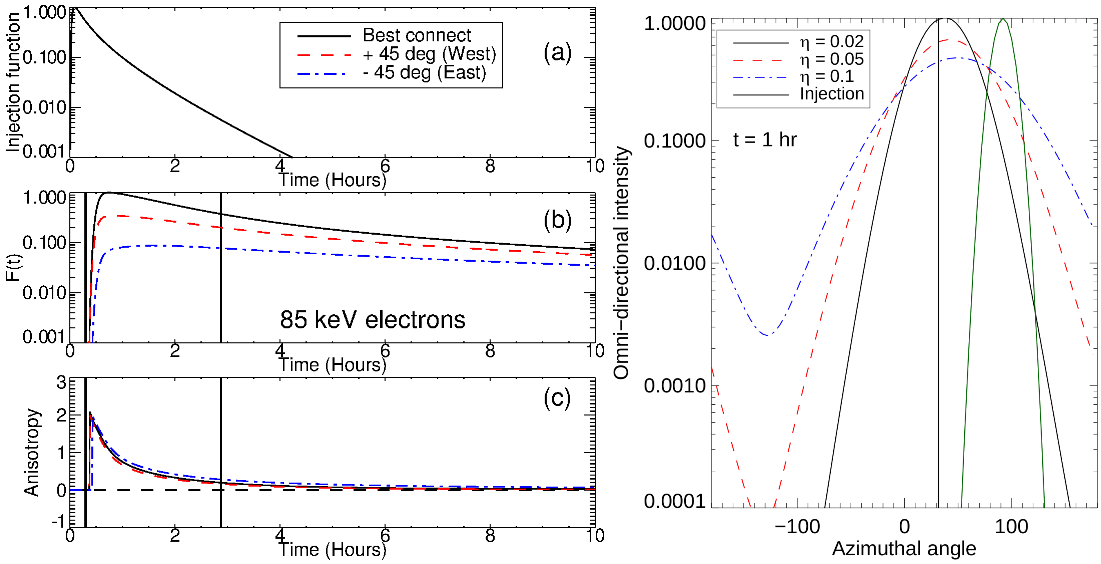

Figure 1: Left: The top panel shows the assumed injection function, while panels (b) and (c) show the resulting omni-directional intensity and anisotropy, as a function of time, at $r = 1$ AU. The solutions are shown at an angle of optimal magnetic connection and two points $\pm 45^\circ$ away from it, as indicated in the legend. **Right:** The calculated omni-directional intensity as a function of azimuthal angle at $t = 0.5$ hrs for the different choices of $D_\perp$. The green Gaussian curve shows the injection function, while the vertical black line shows the azimuthal position of best magnetic connectivity to the source. Solutions are shown for different levels of perpendicular diffusion as determined by η.

1. Introduction

Recent observations by e.g. [1] and [2] have shown that, even for impulsive SEP events, the longitudinal spread of the particles are much larger that previously thought, even extending to almost 360° in longitude at 1 AU. A possible process responsible for the observed strong longitudinal transport of these SEPs is effective diffusion perpendicular to the mean Parker heliospheric magnetic field. In this proceeding, we present model solutions of simulated impulsive SEP events in the ecliptic plane of the heliosphere, where perpendicular diffusion of SEPs in an undisturbed Parker HMF geometry is included.

2. Modelling results

We briefly summarize the modelling results of [4] and the reader is referred to this paper for more details. Fig. 1 (left panel) shows the assumed injection function (panel a), the calculated intensity (panel b) and anisotropy (panel c) as a function of time at 1 AU. Three solutions are shown, corresponding to different azimuthal positions: Optimal magnetic connection (solid black lines) and two points $\pm 45^\circ$ away from it (dashed red and dash-dotted blue lines respectively). The intensity plot illustrates the fact that the intensity is not symmetric about the point of best magnetic connection, with the flux enhanced towards the west (higher values of ϕ), as compared to an equivalent point towards the East (a negative shift in ϕ). Fig. 1 (right panel) shows the inten-

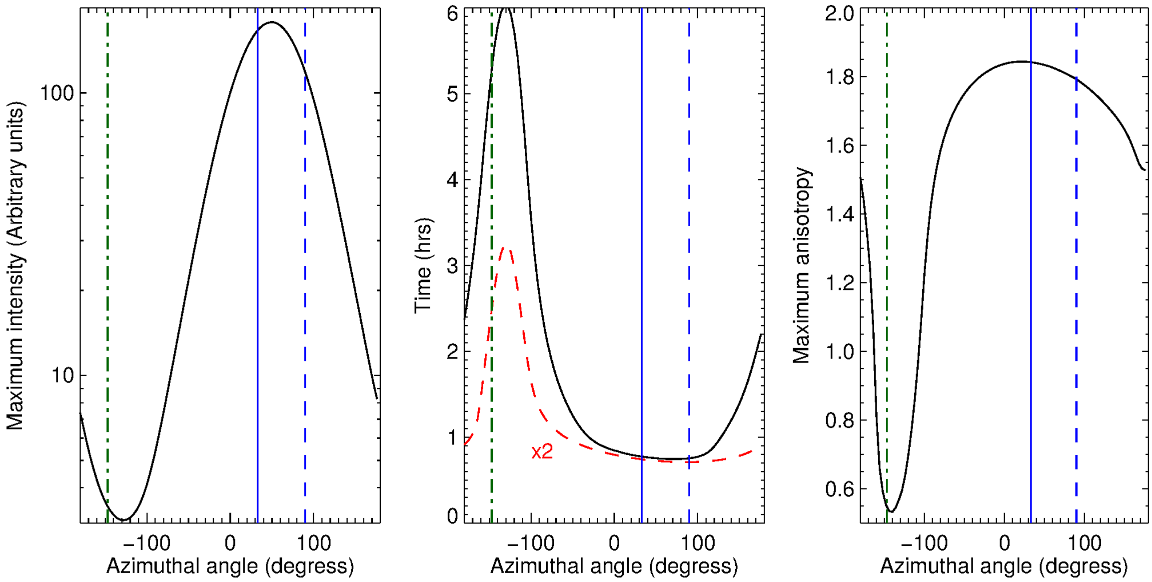

Figure 2: The figure shows, from left to right, the following quantities as a function of azimuthal angle at $r = 1$ AU: The maximum intensity, both the time of maximum intensity and the onset time (note that the onset time is multiplied by a factor of 2) and the maximum anisotropy. The dashed blue line indicates where the injection function obtains its maximal value at the inner boundary, the solid blue line the position of optimal magnetic connectivity at 1 AU and the dash-dotted line the position of worst magnetic connectivity.

sity as a function of ϕ (azimuthal angle) at $t = 1$ hr and $r = 1$ AU. Three solutions are shown, corresponding to different assumptions of η (defined by $\lambda_\perp = \eta\lambda_{||}$; a larger value of η thus corresponds to more effective perpendicular diffusion), as indicated in the legend. It is clear that the distributions are neither symmetrical about their maxima (again, enhanced towards the west), nor does the azimuthal position of the maximum flux at 1 AU occur at the position of optimal magnetic connectivity. The latter quantity is also shifted towards the west, while this shift is larger for larger values of η. Assuming $\eta = 0.1$, calculations of observable quantities are shown in Fig. 2, again as a function of azimuthal angle at $r = 1$ AU. The solid vertical line shows the position of optimal magnetic connectivity at 1 AU to the source, the green dash-dotted line the angle of worst magnetic connection and the dashed black line the position where the injection function reaches a maximum at the inner boundary. In the left panel, the maximum intensity is shown for each ϕ. The maximum of this distribution is shifted towards the west of best magnetic connection. The middle panel shows the time of maximum (solid curve) and the onset time (multiplied by a factor of 2; dashed red line). Both of these time scales are roughly anti-correlated with the maximum intensity; a higher maximum intensity usually corresponds to a shorter propagation time and hence, a shorter onset time and a shorter time needed to reach this maximum intensity value. The right panel shows the maximum anisotropy, generally occurring close to the onset time. The maximum anisotropy is again anti-correlated with the propagation time scales. It is believed that SEPs that take longer to reach e.g. 1 AU, must suffer more (pitch angle and perpendicular) diffusion, and hence, the distribution of these particles becomes increasingly isotropic.

3. Conclusions

When perpendicular diffusion is included in a SEP propagation model, the resulting distribution is asymmetrical in terms of longitude, with the intensities enhanced towards the west of optimal magnetic connectivity to the acceleration region (i.e. the source). The results are in qualitative agreement with the observations presented by e.g. [6], [7], [9] and [5]. The maximum intensity and maximum anisotropy seems to be correlated, while both are anti-correlated to the time of maximum and the onset time. These seem to be in qualitative agreement with the results of [5]. The modelled azimuthal dependence of the maximum anisotropy seems, furthermore, to be consistent with the results of [9].

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