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The influence of magnetic clouds on the propagation of energetic charged particles in interplanetary space

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Abstract. Magnetic clouds modify the structure of the interplanetary magnetic field on spatial scales of tenth of AU. Their influence on the transport of energetic charged particles is studied with a numerical model that treats the magnetic cloud as an outward propagating modification of the focusing length. As a rule of thumb, the influence of the magnetic cloud on particle intensity and anisotropy profiles increases with decreasing particle mean free path and decreasing particle speed. Special attention is paid to energetic particles running into a magnetic cloud released at an earlier time: here the cloud acts as a barrier, storing the bulk of the particles in its downstream medium.

1 Introduction

The propagation of energetic charged particles through interplanetary space normally is described by a transport equation which considers the effects of field-parallel propagation, pitch-angle scattering at magnetic field irregularities, and focusing in the diverging interplanetary magnetic field (Roelof, 1969) or, in addition to the above effects, also convection with the solar wind and adiabatic deceleration (Ruffolo, 1995). Focusing always is considered for simple geometries, in general the Archimedian spiral field, although variations in the large scale magnetic field structure, in particular propagating magnetic flux ropes (ejecta following coronal mass ejections, CMEs, also called magnetic clouds; for a review see e.g. Burlaga, 1995), modify the local focusing length and therefore also particle propagation.

This paper presents a numerical model which allows the description of the influence of a magnetic cloud on the propagation of energetic charged particles.

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2 The Model

Since we are concerned with particles with energies in the MeV and tens of MeV range, solar wind effects such as convection and adiabatic deceleration are of minor importance (Ruffolo, 1995), in particular, if we are concerned with a long-lasting injection from a propagating interplanetary shock (Lario et al., 1998; Kallenrode, 2001). For a first approach on the influence of a magnetic cloud, we therefore started from the model of focused transport (Roelof, 1969):

$$\frac{\partial f}{\partial t} + \mu v_{\mathrm{p}} \frac{\partial f}{\partial s} + \frac{1-\mu^2}{2\zeta} v_{\mathrm{p}} \frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu}\left(\kappa \frac{\partial f}{\partial \mu}\right) = Q(s,t,\mu)$$

with $f(t,s,\mu)$ being the distribution function, t time, s distance along the Archimedian magnetic field spiral, v_{p} particle speed, μ pitch cosine, $\kappa(\mu,s)$ pitch angle diffusion coefficient, and $\zeta(s) = -B(s)/(\partial B/\partial s)$ the focusing length.

The terms in the transport equation from left to right describe the field parallel propagation, focusing in a magnetic field with focusing length ζ (s) depending on distance, and pitch angle scattering. The source term is allowed to propagate along the field line, simulating the long lasting injection of energetic particles from a shock as described in Kallenrode and Wibberenz (1997), the transport of energetic particles through the shock front is treated as described in Kallenrode (2001).

The magnetic cloud is assumed to be of spherical cross section with the interplanetary magnetic field draped symmetrically around it, cf. Fig. 1. Note that the main change is a compression of the interplanetary magnetic field at the flanks of the cloud. The magnetic cloud is characterized by its diameter α as a certain fraction of the distance r_{shock} of the shock from the Sun, the distance β of its leading edge from the shock, also expressed as a certain fraction of r_{shock}, and its magnetic compression r_{B} at the flanks. For applications, these data can be inferred from the observations; for the numerical study below we use $\alpha = 0.2$ and $\beta = 0.1$ (Bothmer, 1993). With $s_1 = s(r_{\mathrm{shock}} - (\alpha+\beta))$ and $s_2 = s(r_{\mathrm{shock}} - \beta)$ this configuration than is translated into a sinusoidal variation

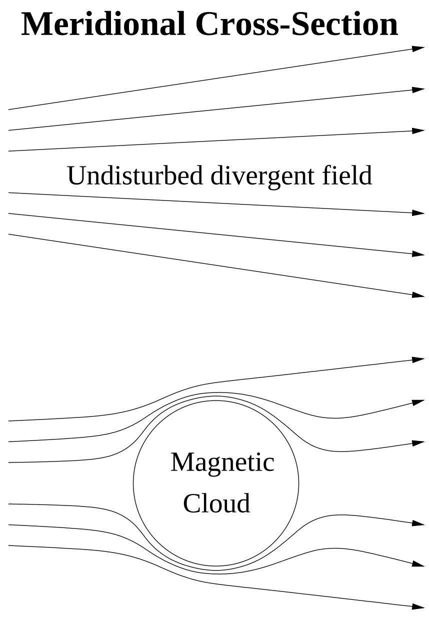

Fig. 1. Cross-section (perpendicular to the plane of ecliptic) for the undisturbed expanding magnetic field (top) and a field disturbed by a magnetic cloud. The filed converges at the flanks of the cloud.

of the focusing length ζ

$$\zeta(s) = \begin{cases} \zeta_o(s) & \text{for } s \leq s_1 \\ \zeta_o(s) \pm \zeta_o(s) \sin \frac{s-s_1}{s_2-s_1} f(r_B) & \text{for } s_1 < s < s_2 \\ \zeta_o(s) & \text{for } s \geq s_2 \end{cases}$$

and a corresponding elongation of the interplanetary magnetic field line. The $\pm$ allows for the consideration of the magnetic cloud or a void in the field instead of the cloud.

Asymmetric draping of field lines (Vandas et al., 1996) can be considered by assuming a stronger (or weaker) compression of the magnetic field with a more (or less) pronounced elongation of the field line.

Note that this approach allows us to describe the particle propagation in a flux tube draped around the magnetic cloud but not the features of energetic particles directly inside the cloud! It also does not consider the cross-field transport of energetic particles from the ambient medium into the magnetic cloud.

3 Numerical Results

Figure 2 shows intensity and anisotropy profiles for a solar energetic particle event (lower set of curves; observer at 1 AU, particle speed $v_p = 1$ AU/h corresponding to $\sim$ 10 MeV protons, radial mean free path $\lambda_r = 0.1$ AU, δ-injection on the Sun) followed by a magnetic cloud with a constant speed of 800 km/s (no shock with particle acceleration considered here). The upper set of curves is for particles accelerated at a shock with constant speed of 800 km/s and constant acceleration efficiency, followed by a magnetic cloud. All other parameters are the same as for the solar

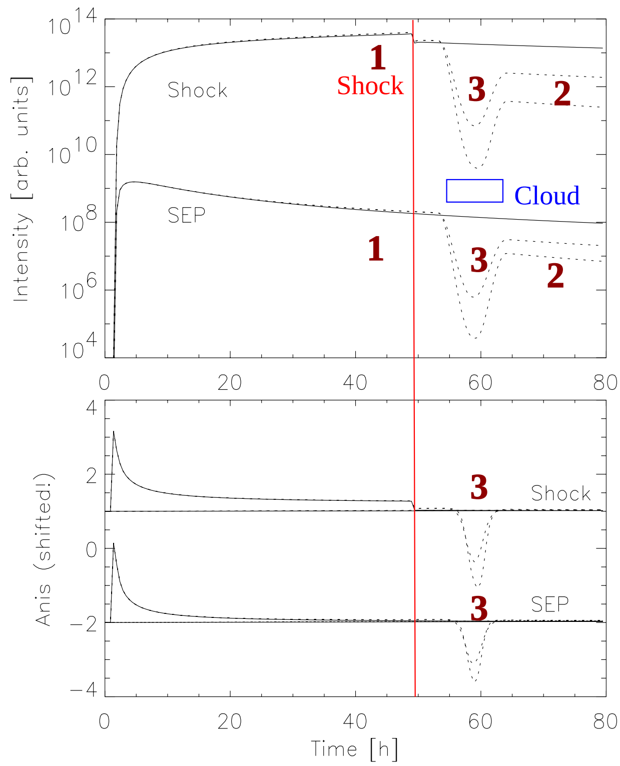

Fig. 2. Solar energetic particle event (lower set of curves) and shock accelerated particles (upper set of curves) followed by a magnetic cloud. The upper panel gives intensities for the two scenarios, the lower ones anisotropies (shifted with respect to each other).

event. The shock arrives at the drop in particle intensity around 50 h. The solid line gives the particle event without ejecta, the dotted lines are for a cloud geometry with a magnetic compressions at its flank of 1.3 (lower amplitude) and 2. The latter value is in agreement the values inferred from numerical simulations (Vandas and Romashets, 2001).

The presence of the magnetic cloud leads to: (1) a slight increase in intensities upstream of the cloud by a few percent, (2) a strong drop in intensities downstream of the cloud by about an order of magnitude, depending on the strength of the magnetic compression, and (3) a sharp drop of intensity at the time of cloud passage (remember, this is at the flanks not inside the cloud!) combined with a strong anisotropy indicating a net-streaming of particles from the cloud's upstream medium (where intensities are high) into its downstream medium (where intensities are low). Note that these effects are very similar for a simple solar injection as well as for the continuous particle injection from a propagating interplanetary shock.

Quantitatively, the influence of the magnetic cloud depends on particle speed and strength of the interplanetary scattering. With increasing scattering, the increase in upstream intensities increases while the drop in downstream intensities decreases. The intensity drop at the time of cloud passage is independent of scattering while the anisotropy decreases

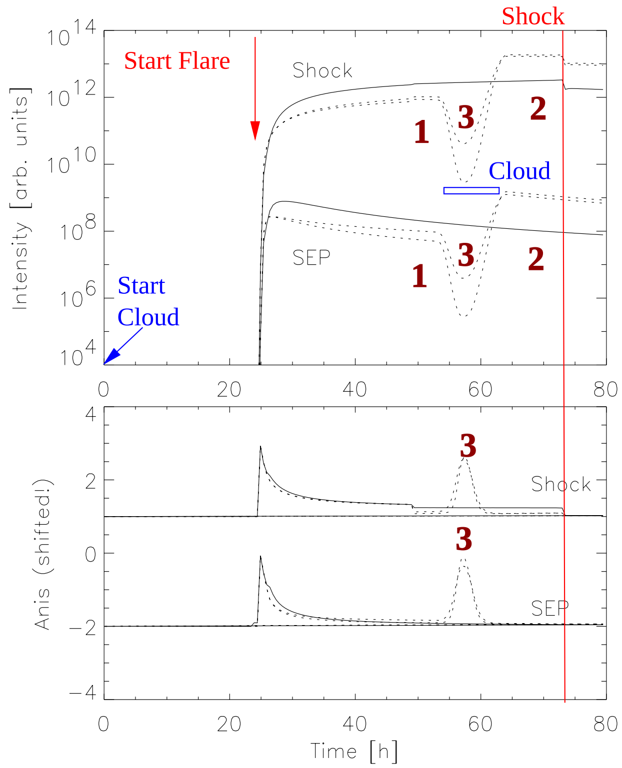

Fig. 3. Same as Fig. 2, but the magnetic cloud is running ahead of a solar energetic particle event (lower set of curves) and a shock accelerated particle event (upper).

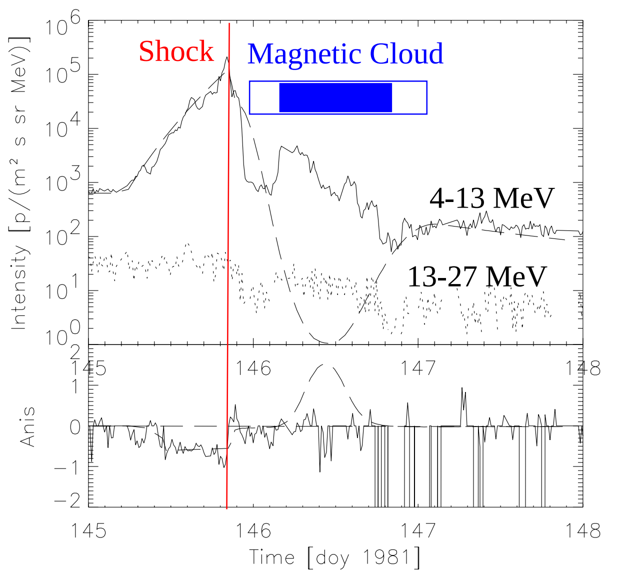

Fig. 4. Comparison between model (dashed) and observations, cf. text.

with increasing scattering. With decreasing particle speed both upstream intensity increases and downstream intensity drops increase and the negative anisotropy inside the cloud becomes more pronounced. Thus faster particles are less influenced by the presence of the magnetic cloud than are slower ones.

Figure 3 gives the same set of curves as Figure 2 except that the ejecta has started 24 hours prior to the release of the energetic particles in a different solar event. In this case the ejecta is running ahead of the particles and is at a radial distance of about 0.5 AU at the start of the particle injection. Again, solid lines are calculated without ejecta, dotted ones with.

The most important results are (1) a pronounced decrease in intensities upstream of the magnetic cloud combined with (2) a pronounced increase in intensities downstream of the cloud, and (3) a strong drop in intensity at the time of cloud passage combined with a pronounced positive anisotropy, indicating a net-streaming of particles from the cloud's downstream into its upstream medium (again following the gradient in particle intensities). Again, effects are very similar for a solar injection and a continuous injection from a propagating shock. These results strongly point to a barrier effect of the magnetic cloud for the propagation of energetic particles.

Figure 4 shows a comparison between a model run and the Helios observations in the 27 May 1981 event (for a detailed description see Kallenrode, 1997). The passage of the magnetic cloud is marked by a filled rectangle, interplanetary field lines draped around the cloud are represented by the adjacent open rectangles. These latter field lines are the ones which can be approximated in this model while the field lines inside the cloud are not considered. For modeling, this event is a challenge in so far, as it shows a rather strong increase in intensity towards the shock combined with a drop in intensity short before the arrival of the magnetic cloud. This is impossible to model in a simple transport model because particles cannot be removed fast enough to get a significant decrease in intensity. If the magnetic cloud is considered, however, not only intensities upstream of the cloud can be fitted but also the fast decrease of intensity associated with the arrival of the field lines draped around the cloud and the reduced intensity in the cloud's downstream medium can be described properly. The description fails, by definition, right inside the cloud since the model only gives intensities along the field lines draped around the cloud but not inside the cloud – the satellite, on the other hand, cuts right through the cloud.

4 Discussion

The influence of a magnetic cloud on the interplanetary propagation of energetic charged particles is treated numerically by introducing a moving bottleneck into the model of focused transport. The cloud is characterized by its speed, its distance from the shock, its width, and the magnetic compression resulting from the draping of the IMF around the cloud. Note that this method does not allow to simulate particles inside the cloud! Important results are:
(1) If the cloud follows the particle source, the upstream intensity is increased by a few percent for 10 MeV protons

under average scattering conditions ($\lambda = 0.1$ AU).
(2) This increase increases with decreasing energy and increasing scattering.
(3) The downstream intensities are reduced by about an order of magnitude.
(4) If the cloud is ahead of the particle source, it is an effective barrier for particle propagation.
(5) The model allows to fit observations, although by definition intensities and anisotropies inside the cloud are not described correctly.

All these properties can be understood from the modified focusing: viewed from the outside, the bottleneck configuration shows a converging field and thus reflects part of the particles. As a consequence, the cloud is a barrier that separates the upstream and downstream medium and allows for markedly different intensities in both of them. Intensities are higher on that side of the cloud where the source is located (upstream in case of a traveling shock, downstream in case of a magnetic cloud from an earlier event). At the bottleneck intensities are reduced because only the relatively small number of particles just in transit can propagate through. In addition, anisotropies are relatively high because only particles with small pitch angle can propagate into the bottleneck.

Changes in intensity and anisotropy related to the presence of the cloud increase with decreasing energy and mean free path because in these cases particles stay longer in the vicinity of the cloud and thus can perform multiple interactions. For weak scattering and high energies, on the other hand, once a particle has passed the cloud it has only a small return probability. The enhancement of the barrier function of the cloud with increasing scattering also had been proposed by Lario et al. (1999).

A relatively unexpected effect was the strong barrier action of a cloud ahead of the particle source. Since SOHO observations show a large number of CMEs during solar maximum (about 2/day, cf. St. Cyr et al., 2000), magnetic clouds in interplanetary space ahead of a particle source might be a relatively common feature. Fits of a transport equation on particle events neglecting the influence of a magnetic cloud might be faulty. This might explain part of the discrepancy between particle mean free paths determined from fits and particle mean free paths determined from the analysis of magnetic field fluctuations (Wanner and Wibberenz, 1993). In addition, the barrier properties of the magnetic cloud as demonstrated in Figure 3 can be used to simulate rogue events where converging shocks lead to unusual high particle intensities as described for the August 1972 event by Levy et al. (1976). First examples are described in Kallenrode and Cliver (2001).

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