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Rogue SEP events: Modeling

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Abstract. Rogue events (see Kallenrode and Cliver, 2001) are associated with multiple shocks and CMEs. We present a numerical model based on the focused transport equation that incorporates shocks as moving particles sources and magnetic clouds as transient modifications of the interplanetary focusing length. This model allows to simulate the effect of pairs of CMEs/shock on particle populations. Special attention is paid to pairs of converging shocks which are believed to play an important role in the formation of large events such as the August 72 SPE or the Bastille day event. We find that (a) the magnetic cloud following the leading shock is of utmost importance for the creation of high particle intensities, (b) the shocks need not to converge to create an intensity enhancement, and (c) the trailing cloud is required to reduce intensities after the passage of the shock pair.

1 Introduction

From the observation of two converging interplanetary shock waves accompanied by an energetic particle event with unusual high and long-lasting intensities in August 1972, Pomerantz and Duggal (1974) and Levy et al. (1976) proposed 1st order Fermi acceleration between converging interplanetary shocks as a fast and highly efficient acceleration mechanism. Subsequently, time periods with unusually high intensities related to multiple CME shocks as well as other particle events with high intensities between pairs of shocks have been identified (Kallenrode and Cliver, 2001, and references therein). Events of this kind are called rogue events in analogy with rogue ocean waves and are of utmost importance for space weather, such as the precipitation of energetic charged particles into the atmosphere and the resulting ozone destruction.

Although theoretically 1st order Fermi acceleration between converging shocks is an attractive picture, a fundamental question remains: what is the geometry that should lead to acceleration? In particular, how does reflection occur at or in the vicinity of the shocks?

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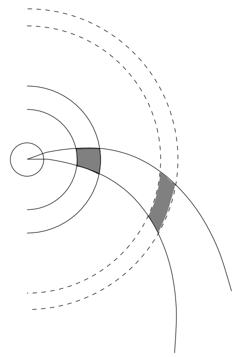

Fig. 1. Increase of the volume between two converging shocks.

In this paper, we will present some simple numerical calculations to get insight into (a) the geometrical conditions required for the generation of a rogue event and (b) its quantitative treatment. To avoid complications due to corotation and long-lasting events, we have limited our analysis to events with pairs of shocks (and magnetic clouds) and have omitted superevents (MÏler-Mellin et al., 1986).

2 Geometrical considerations

Rogue events cannot result from a simple compression of the medium between two converging shocks: although the distance between converging shocks would decrease with r as the shocks propagate outwards, the cross-section of the flux tube increases with r^2, leading to a net increase in volume between the shocks. Since the field line is not radial but curved as an archimedian spiral, the projected area of the shock (and therefore the volume occupied by the particles) in the flux tube increases even stronger than r^2, cf. Fig. 1. However, even if compression would be sufficient to explain high intensities, we still would face the problem of how compression could occur.

We can imagine different geometries for a pair of shocks and the interplanetary magnetic field, cf. Fig. 2. The left hand side shows the simplest case: two shocks and a background Archimedian field. Particles traveling from the upstream region towards the shock partly are reflected at the shock because the magnetic compression across the shock front creates a magnetic mirror. Thus particles can be swept up by the shock (e.g. Scholer and Morfill, 1977; Kallenrode, 2001b). However, reflection of particles approaching the shock from its downstream medium cannot be understood because the particle then experiences a diverging field. Therefore, although the shocks would sweep-up particles, there would be no particle storage in the volume between them and consequently no 1st order Fermi acceleration.

To avoid this problem, Levy et al. (1976) proposed the mechanism of a Gold bottle, cf. middle panel in Fig. 2: a large loop extends ahead of the shock and ones in the upstream medium particles have a chance (depending on their pitch angle) of being reflected back and forth along the field line. As the shock expands, the length of the field line in the upstream medium is reduced and the particles are accelerated by a Fermi I process. Although large loops extending beyond 1 AU have been observed, we think that this configuration might not be the only one to explain rogue events, in particular since a typical rogue event has been observed by Ulysses at a distance of 2.5 AU (Sanderson et al., 1992). Considering the calculations in Kallenrode (2001b) regarding the capability of a magnetic cloud to separate the particle populations upstream and downstream of a magnetic cloud, we suggest the scenario on the left hand side of Fig. 2: particles then are reflected repeatedly between the following shock (particles with small pitch angles passing the shock can be reflected at the cloud) and the magnetic cloud behind the leading shock. This scenario will be treated numerically.

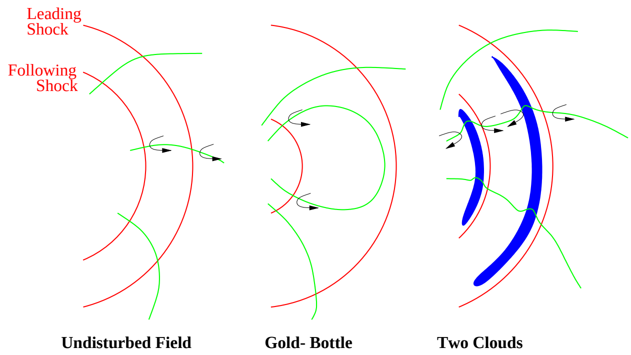

Fig. 2. Possible geometries for the acceleration of energetic particles between two converging shocks, cf. text.

3 The model

The model is based on the focused transport equation by 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 being the distribution function, t time, s distance along the archimedian magnetic field spiral, v_{p} particle speed, μ pitch cosine, $\kappa(\mu)$ pitch angle diffusion coefficient, and $\zeta(s) = -B(s)/(\partial B/\partial s)$ focusing length. Solar wind effects (Ruffolo, 1995) are not included because we are concerned with particles in the tens to hundreds of MeV range where the influence of solar wind effects is rather small, in particular, if long-lasting injections from propagating shocks are considered (Lario et al., 1998; Kallenrode, 2001a). The terms in the transport equation from left to right describe the field parallel propagation, focusing in the magnetic field, and pitch angle scattering. The source on the right hand side is allowed to propagate along the magnetic field line to simulate the continuous injection of energetic particles from a shock (Kallenrode and Wibberenz, 1997). Particle transport through the shock is treated under conservation of pitch angle as described in Kallenrode (2001a), a magnetic cloud is added as the variation in the focusing length as described in Kallenrode (2001b). In addition, a second shock with or without magnetic cloud can be started at a later time with its own characteristics but described by the same processes.

It should be noted that the model gives a first crude approximation only because it does not consider changes in momentum: thus particles can be reflected from the shock but do not gain or lose energy. However, as an approximation this approach is sufficient because the particles we are interested in are fast and thus the energy gain compared to their total energy is relatively small under typical scattering conditions in interplanetary space (cf. simulations in Scholer and Morfill, 1977). The ’normal’ anisotropies in the events observed so far do not give any indication for abnormally strong scattering. In addition, the consideration of transport in momentum space would increase calculation time by a factor of 200.

4 Numerical results

4.1 Shock/cloud pairs

Figure 3 shows numerical simulations for a particle event associated with a pair of shocks. The general parameters are an observer at a radial distance of 1 AU, a particle speed v_{p} of 1 AU/h corresponding to a proton energy of about 10 MeV, and a radial particle mean free path λ_r of 0.1 AU. Both shocks accelerate the same number of particles with the acceleration efficiency decreasing as r^{-2}, the average value reported in Kallenrode (1997). Magnetic clouds have a distance to the shock of $0.1 \cdot r_{\mathrm{shock}}$ and a diameter of $0.2 \cdot r_{\mathrm{shock}}$, their passage at the observer is marked by rectangular boxes.

Two scenarios are considered: in the upper set of curves, two shocks, both with a speed of 800 km/s, follow each other. The first one starts at time $t = 0$, the second one starts 24 h later, its start is visible as the second small increase in intensity. The shock arrival is marked by arrows. As discussed in Kallenrode (2001b), the cloud passage leads to an (unre-

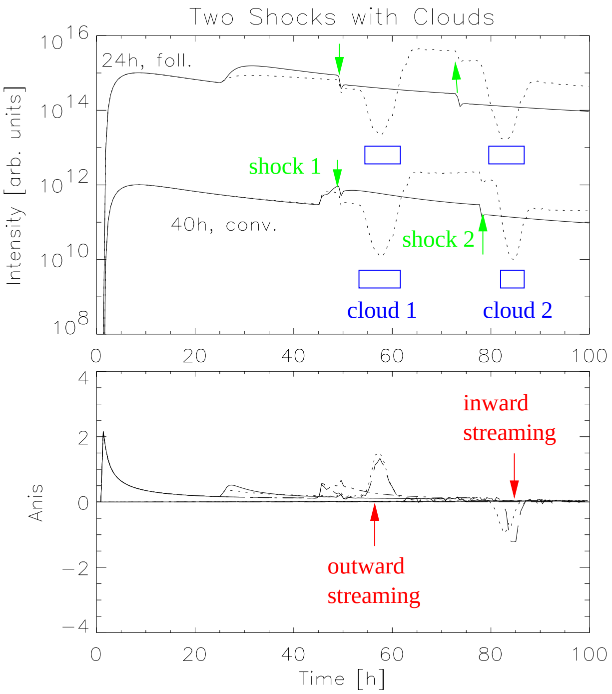

Fig. 3. Storage region between two consecutive same-speed shocks (upper set of curves) and two converging shocks (lower set). Solid lines are without consideration of the magnetic clouds, dashed ones include the magnetic clouds.

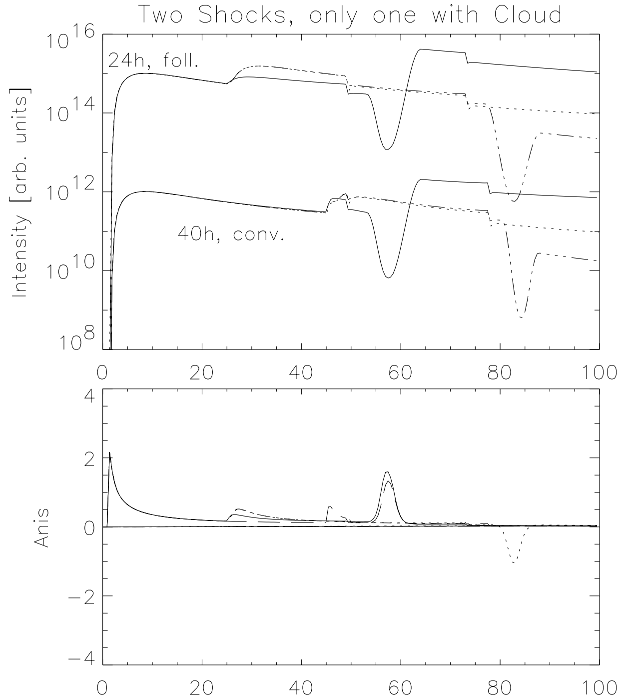

Fig. 4. Pairs of following and converging shocks as in Fig. 3 but only either the leading shock is followed by magnetic cloud (solid lines) or the following one (dashed lines).

alistic) decrease in intensity because the model follows the field line draped around the cloud but not the satellite cutting right through the cloud. The most important feature in the figure, however, is the strong enhancement in intensity by about an order of magnitude between the two magnetic clouds. Note that in this case the geometry of a pair of shocks with magnetic clouds on the observers field line leads to such an enhancement although the shocks are not converging but maintain a constant separation.

The lower set of curves is for a pair of converging shocks: the first starts at $t = 0$ with a speed of 800 km/s while the second one starts 45 h later (again visible as renewed increase in intensity) with a speed of 1200 km/s. Again, between the two magnetic clouds the intensity is markedly enhanced. Owing to the special choice of the radial development of the particle acceleration, the intensity enhancement is slightly smaller than in case of the following shocks discussed above. The main difference to that case, however, is a slight increase in intensity towards the following shock.

In both cases, anisotropies at the time of cloud passage indicate a slow leaking of particles out of the storage region.

4.2 Shock pairs, one cloud only

In Fig. 4 the same scenario has been used, however, only one of the shocks is followed by a magnetic cloud: the dotted line gives the reference run without magnetic clouds (corresponding to the solid line in Fig. 3), the solid line is for the leading shock followed by a magnetic cloud while in the dashed line the following shock is with cloud. Basic results are: (1) if the leading shock is not followed by a magnetic cloud (dashed and dotted scenarios) no region of enhanced intensity results. The leading cloud therefore is crucial for the storage of energetic particles, as already suggested in Kallenrode (2001b). (2) if the leading shock is followed by a cloud but the following shock is without cloud, intensities are enhanced, however, there is no rather sharp drop in intensity after the second cloud. Instead, the intensity is enhanced all along the field line downstream of the leading cloud.

All the results presented here do not change qualitatively with shock speed, the amount of interplanetary scattering, the properties of the magnetic cloud (geometry, compression at its flanks), or the radial evolution of the shock acceleration efficiency. Quantitatively, these parameters can have a marked influence on intensities, however, we could not identify simple rules because the system is too complex and behaves very nonlinear.

4.3 The Bastille day event

A recent example for a rogue event is the Bastille day event observed on 14 July 2001. The particle event led to unusual high fluxes of energetic particles at the orbit of Earth and was accompanied by two interplanetary shocks followed by magnetic clouds. Figure 5 shows intensities of 8.7–14.5 MeV protons observed by GOES together with a fit (solid line). Fit parameters are as follows: radial mean free path λ_r of

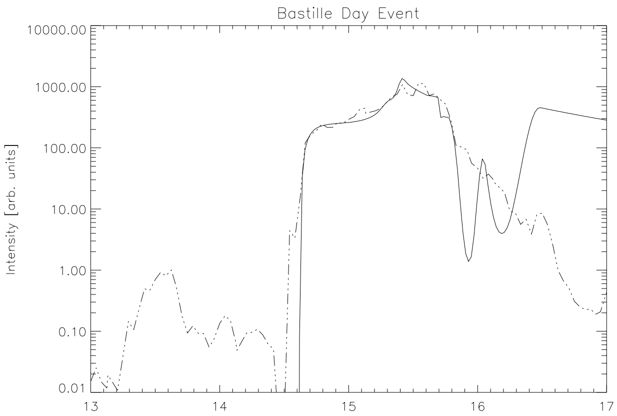

Fig. 5. $\sim$ 10 MeV protons observed by GOES (dashed lines) and fit (solid) for the 14 July 2000 event.

0.1 AU (typical value), evolution of the shocks acceleration efficiency as r^{-2} corresponding to the decrease in solar wind density (also a typical value), the injection from the second shock is five orders of magnitude larger than that from the preceding shock (in fact, GOES only sees a rather indifferent hump during the travel time of the first shock) and shock/CME starting times from the observations. The geometry of the magnetic clouds is the same as in the numerical calculations.

Although not an exact description of the intensity time profile, the fit in Fig. 5 allows the reproduction of a rather complex time profile with simple assumptions and a parameter set which is in agreement with the parameters normally used in fitting particle events. It should be noted that an exact fit is not possible because at least at Earth's orbit there are no anisotropy data available for this event.

5 Conclusions

A numerical model containing a pair of traveling shocks with magnetic clouds is able to reproduce particle events with unusual high intensities due to storage of particles between the magnetic clouds. It is important to note that

1. the intensity increase does not require converging shocks but just the creation of a storage region by two mirrors (the magnetic clouds) and a continuous particle injection into that medium (from the following shock). However, it should be noted that in the really large rogue events the following shock always was extremely fast (and thus shocks were converging).

2. the magnetic cloud behind the leading shock is crucial for the storage of particles and thus the build-up of high intensities.

3. the magnetic cloud behind the following shock is crucial for the creation of a drop in intensity after the shock pair.

These points certainly require special attention. So far, all runs presented here are performed under the assumption that both shocks and magnetic clouds intersect the observer's magnetic field line during the entire time of the particle event. In reality, however, the shock/cloud pair will intersect the observer's field line only for a limited time period while for the remainder of the event only one shock with cloud or even none will be on the field line. In application to data these scenarios have to be considered carefully. Nonetheless, Although the model is crude an simple, it is able to reproduce the general features of the observation in the Bastille day event.

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