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Proton transport through self-generated waves in impulsive γ-ray flares

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Abstract. Energetic proton transport through self-generated Alfvén waves in impulsive (γ-ray) flares is studied using the method of Monte Carlo simulations. Protons are traced inside a flux tube after they are released from a point source located inside the loop until they hit the boundary of the 1-D simulation box and escape. As they stream from the source towards the boundaries, the particles generate Alfvén waves through the streaming instability. We consider both open and closed field lines. In the closed field line case, the escaping particles precipitate and produce observable secondary emissions; for the open field line, particles precipitate only from one end of the field line, and escape freely to the interplanetary medium from the other end. For a sufficiently large number of accelerated protons per unit area, $\gg n_0 V_\mathrm{A}/\Omega_\mathrm{p}$ where n_0 is the plasma density, V_A the Alfvén speed, and Ω_p the proton gyro-frequency, the particle flux from the source produces a turbulent trap that expands at Alfvén speed to both directions from the source. The resulting γ-ray emission from the loop legs consists of a precursor, related to the quick propagation of particles when the trap has not formed yet, and of a delayed brightening in the loop leg closer to the source, related to the opening of the turbulent trap as the self-generated waves reach the solar surface. For impulsive injections lasting $\ll L/(2V_\mathrm{A})$, the second emission may be suppressed by adiabatic deceleration in the expanding turbulent trap. For open field lines, our model is capable of producing the small ratio of the numbers of interplanetary-to-interacting protons typically observed in impulsive flares, if the proton source is located close to the Sun.

1 Introduction

The current two-class paradigm of solar particle events suggests that impulsive SEP events originate in impulsive solar flares and gradual events are linked to the coronal/interplanetary shocks (Cane et al. (Cane et al., 1986; Cliver, 1996; Reames, 1999, and references therein). Impulsive flares may produce ^{3}He-rich SEP events, which typically are not strong in terms of the total number of accelerated protons. Some impulsive flares, however, can produce a large number of protons interacting at the Sun and can be observed in the γ-ray band. In such events the ratio of the numbers of interplanetary-to-interacting protons is typically small ($\lesssim 0.1$), whereas gradual γ-ray flares show larger ($\gtrsim 1$) values of this ratio (Kocharov & Kovaltsov, 1986; Hua & Lingenfelter, 1987; Ramaty et al., 1993).

Intensive production of accelerated protons implies the potential importance of self-generated waves, i.e., waves generated by the flux of protons leaking from the accelerator (see, e.g., Ng et al., 1999) in application to gradual SEP events). In application to impulsive γ-ray flares, the role of self-generated waves was emphasized by Bespalov et al. (1987, 1991), who studied the proton transport under the assumption that the protons stream away from a source located at the top of the loop, and generate Alfvén waves. They showed that for a sufficiently strong source, the waves would become so intense that the particles would be trapped by the waves and convect with them at Alfvén speed towards the footpoints of the loop. Electrons, being coupled to higher-frequency waves, would travel much faster, at a bulk speed of $\lesssim 9\,V_\mathrm{A}$ (e.g., Vainio, 2000). This would lead, consistently with observations of impulsive flares, to a delay of the γ-ray emission relative to the X-ray emission, if electrons and protons were accelerated simultaneously near the top of the flaring loop (Bespalov et al., 1987). Note that the delay of the peak time of the γ-ray emission relative to the X-ray peak could alternatively be interpreted in terms of particle transport in flaring loops with weak external turbulence and large variation of the cross-sectional area of the flux tube (Hulot et al., 1989, 1992).

The turbulent trapping model could lead to interesting effects, if the flux tube is asymmetric with respect to the source position, and if transient processes are incorporated in the model. Scattering off self-generated waves at open magnetic field lines may also affect the interplanetary-to-interacting

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proton ratio. Vainio et al. (2000) obtained reasonable ratios for gradual flares in a model of coronal shock acceleration by arranging the turbulence around the shock in a stationary manner to mimic self-generated waves. In the case of impulsive flares the role of self-generated waves in forming the interplanetary-to-interacting proton ratio has not been studied, yet.

The purpose of this paper is to study and extend the transport model of Bespalov et al. (1987, 1991), using a time-dependent numerical method. To simplify the model at this stage, we perform the study inside a single magnetic flux tube with constant values of the magnitude of the magnetic field and plasma density, and zero bulk speed of the thermal plasma. The study includes as separate cases a symmetric loop (Case A), an asymmetric loop (Case B), and an open field line (Case C).

2 The model

Our model consist of a magnetic field with a constant magnitude along the line of force. Either one (Case C) or both (Cases A and B) ends of the flux tube are tied to the solar surface, where we assume that the density of the plasma is so large that all particles reaching this region interact producing secondary emissions. No mirroring of particles at the footpoints of the flux tube is taken into account. The basic scale length of the (1-D) system is denoted by L. In case of closed magnetic field, L is the length of the loop and in case of open field, L is the height at which the particles are assumed to freely escape into the interplanetary medium.

The plasma parameters are fixed to representative values for flaring loops (Bespalov et al., 1987): Alfvén speed $V_{\mathrm{A}} = 10^8$ cm s^{-1}, plasma electron (and proton) density $n_0 = 10^{11}$ cm^{-3}, and the length of the loop $L = 10^9$ cm. In Case C, we choose the length of the trapping region as $L = 5 \times 10^9$ cm being less than or of the order of the scale height of the magnetic field in lower corona. The magnetic field in such a flux tube (with electron–proton composition) is $B \approx 145$ gauss, and the ion skin length, $V_{\mathrm{A}}/\Omega_{\mathrm{p}} \approx 72$ cm, where $\Omega_{\mathrm{p}} \approx 1.4 \times 10^6$ s^{-1} is the proton gyro-frequency.

The Alfvén waves are assumed to propagate along the mean magnetic field. For simplicity, no absorption of the waves by the thermal plasma nor any wave-wave interactions are thought to occur. Sunward-propagating waves are absorbed and anti-sunward propagating waves are emitted at the footpoints of the flux tube. The emitted wave flux at the footpoints has to be, of course, given as a boundary condition.

We consider energetic protons of momentum $p = p_0$ emitted from a point source located inside the flux tube at $x = x_0$. Protons are followed under the guiding-center approximation along the magnetic field as they undergo wave–particle interactions with Alfvén waves of wavenumber that is assumed to be fixed and given by $k = m\Omega_{\mathrm{p}}/p_0$. This approximation to the full resonance condition, $k = m\Omega_{\mathrm{p}}/p\mu$ ($p\mu$ is the parallel momentum in the wave frame), allows us to follow a single wavenumber instead of the full spectrum of them, and makes the simulations much simpler and faster. Particles hitting the ends of the flux tube are assumed to be absorbed (by stopping at the solar surface or by escape to the interplanetary medium). The wave–particle interactions are modeled as pitch-angle scattering that is elastic in each wave frame and occurs at the scattering rates (Skilling, 1975)

$$\nu_{\pm}(x,p,t) = \frac{\pi}{4}\,\Omega\,\frac{U_{\pm}(x,t)}{U_B}, \tag{1}$$

where $U_B = B^2/8\pi$, $\Omega = \Omega_{\mathrm{p}}/\gamma$ is the relativistic gyro-frequency of the proton, and $U_{\pm}(x,t)$ is the total (kinetic + magnetic) energy density (per logarithmic bandwidth in wavenumber) of waves propagating parallel (+) or anti-parallel (−) to the field line. The scatterings lead to pitch-angle diffusion with isotropic diffusion coefficients $D^{\pm}_{\mu\mu} = \frac{1}{2}(1-\mu^2)\nu_{\pm}$.

Energetic protons interact with the waves self-consistently in the sense of conserving the total energy (as measured in the plasma frame) of waves and particles at microscopic level. Let $p_{\pm}$ and $\mu_{\pm}$ denote the momentum and pitch-angle cosine as measured in the wave frame indicated by the subscript. A particle scattering in pitch-angle cosine by an amount of $\Delta\mu_{\pm}$ (in the wave frame) suffers an energy loss of $-\Delta E = \mp V_{\mathrm{A}} p_{\pm} \Delta\mu_{\pm}$ in the plasma frame. We use isotropic scattering, so $\langle \Delta\mu_{\pm}\rangle/\Delta t = \partial D_{\mu\mu}/\partial\mu = -\mu_{\pm}\nu_{\pm}$. This leads to a growth of the waves at the rate

$$\Gamma^{\pm} = \pm\frac{1}{U_{\pm}}\int \mathrm{d}^3p_{\pm}\,\nu_{\pm}V_{\mathrm{A}}p_{\pm}\mu_{\pm}\,f_{\pm} = \pm\Omega_{\mathrm{p}}\frac{\pi S_{\pm}}{2n_0V_{\mathrm{A}}} \tag{2}$$

where $f_{\pm}(\mu_{\pm}, p_{\pm}, x, t)$ is the distribution function of the accelerated particles and $S_{\pm} = \int \mathrm{d}^3p_{\pm}\,v_{\pm}\mu_{\pm}\,f_{\pm}$ gives their flux.

3 Results

3.1 Case A: Symmetric loop

In the first set of simulations, we study a loop which is spatially symmetric about the point source of energetic protons. We inject $p_0 = 0.25\,mc$ (corresponding to an energy of about 30 MeV) protons isotropically at rate $Q = \epsilon\, n_0 V_{\mathrm{A}} = \epsilon \times 10^{19}$ cm^{-2} s^{-1}, where $\epsilon = 2 \times 10^{-5}$ is chosen to give a large flux resulting to a rapid wave growth, but still keeping the energetic-proton pressure at least an order of magnitude below the thermal proton pressure (for $T = 10^7$ K) even if all particles are trapped by Alfvén waves inside $|x| < V_{\mathrm{A}}t$. We vary the total amount of injected particles by varying the duration of the injection between $\Delta t = 1/15$ s and $10/15$ s, resulting to a total number of injected particles between $Q\,\Delta t = 1.33\times10^{13}$ cm^{-2} and 1.33×10^{14} cm^{-2}. The background wave flux emitted from the footpoints is fixed by assuming that the wave mode emitted from each footpoint has an energy density of $U_{\pm}(\mp L/2, t) = U_0 = 10^{-4}\times U_B$. We assume that this emission of waves is steady; thus the initial condition for both wave modes is also $U_{\pm}(x,0) = U_0$.

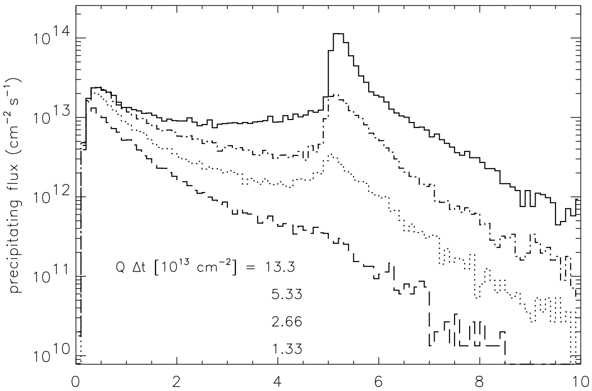

Fig. 1. Flux of precipitating particles for four values of the total number of injected protons. See text for details.

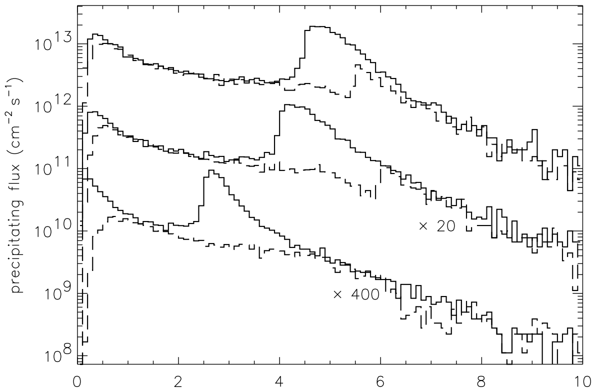

Fig. 2. The flux of precipitating protons in a loop with asymmetric source position at $x_0 = 0.05\,L$, $0.1\,L$, and $0.25\,L$ (top–down). The curves should be multiplied by the indicated constants. *Solid curves* correspond to the footpoint closer to and *dashed curves* to the footpoint farther from the source.

The results of the simulations are presented in Figure 1 in form of flux of protons precipitating to the footpoints of the loop. One can see a peak in the precipitating flux at $t \approx 5$ s corresponding to the travel time of Alfvén waves from the center of the loop to the footpoints, as predicted by the theory of Bespalov et al. (Bespalov et al. (1987), Bespalov et al. (1991)). What is not predicted by the steady-state theory is the rather intense precursor peak immediately after the particle release, that corresponds to the first phase, when the waves have not yet grown enough to suppress the diffusive particle transport. The number of particles in the precursor seems to be independent of the number of injected particles, if this number exceeds a threshold level. This can be understood as follows. Until the wave-energy density has grown to a level, denoted by U^*, that suppresses diffusive transport, the particles propagate quickly towards the footpoints adjusting the value of particle flux to $|S_\pm| \approx \frac{1}{2}Q$ (directed away from the source). The wave-energy density obeys

$$\ln \frac{U_\pm(x,t)}{U_0} \approx \pm\Omega_\mathrm{p} \frac{\pi}{4 n_0 V_\mathrm{A}} Q t \tag{3}$$

until the time t^* when the waves have reached the level U^*. This can be turned around to give the number of precursor particles per unit area, $\mathrm{d}N_\mathrm{prec}/\mathrm{d}A = Qt^*$, as

$$\frac{\mathrm{d}N_\mathrm{prec}}{\mathrm{d}A} \sim \frac{4}{\pi} \frac{n_0 V_\mathrm{A}}{\Omega_\mathrm{p}} \ln \frac{U^*}{U_0}. \tag{4}$$

A lower-limit estimate for U^* is given by equating the diffusion length, κ/V_A (where $\kappa = \frac{1}{3}v^2/\nu$ is the spatial diffusion coefficient), to the distance from the source to the footpoint, i.e., giving

$$U^* \sim \frac{8}{3\pi} \frac{\gamma v^2}{V_\mathrm{A}^2} \frac{V_\mathrm{A}}{L\Omega_\mathrm{p}} U_B = \frac{4}{3\pi} \frac{V_\mathrm{A}}{L\Omega_\mathrm{p}}\, pv\, n_0. \tag{5}$$

Inserting the numerical values gives $U^*/U_0 \sim 3.5$ and $\mathrm{d}N_\mathrm{prec}/\mathrm{d}A \sim 10^{13}$ cm^{-2}, which is seen to agree well with the number of precursor particles in the simulation.

3.2 Case B: Asymmetric loop

The majority of the particles in a powerful impulsive flare precipitate once the turbulent walls have reached the footpoints of the flux tube, at $t = L/2V_\mathrm{A}$. It is of interest to investigate, what happens if the particles are not released in the central point of the flux tube; if the trap is opened from one end, we should see a peak in the precipitating flux to this footpoint, but if the precipitation is rapid, the particle reservoir might get empty before the trap opens from the other end. We have simulated this by varying the position of the source as $x_0 = 0.05\,L$, $0.1\,L$, and $0.25\,L$ (from the center of the loop). The number of injected particles was 6.67×10^{13} cm^{-2}, and other parameters were chosen as in Case A. The results are plotted in Fig. 2. The flux towards the footpoint closer to the source resembles the symmetric case with a prompt and a delayed peak. The flux at the other footpoint, however, behaves differently. Even a slightly asymmetric position of the source can lead to a huge difference in the precipitating flux for the delayed component; in practice, we can expect a delayed brightening in γ-rays at only one of the footpoints based on our simulations. However, the observed asymmetry in the precursor brightening provides a measure of the asymmetry of the source position, if the ambient turbulence level is high enough to yield a diffusive delay in the particle flux reaching the footpoints at different distances from the source.Without a possibility to distinguish between the emission from different footpoints, the observations in the asymmetric case are very similar to the symmetric case, and the general conclusions drawn from Case A – two-component structure, importance of the total number of injected particles – are valid also for the asymmetric case.

3.3 Case C: Open flux tube

As a last study, we performed simulations in a flux tube that is connected to the solar surface from one footpoint at $x = 0$,

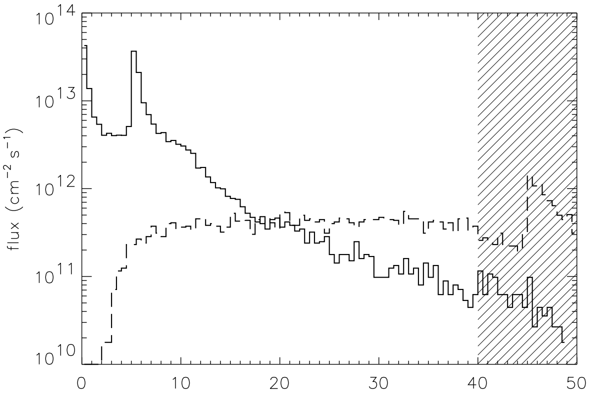

Fig. 3. The flux of particles precipitating (*solid curve*) and escaping into the interplanetary medium (*dashed curve*) in an open magnetic flux tube.

only. The other end at $x = L = 5{\times}10^9$ cm is assumed to leak the incident particles directly to the interplanetary medium, modeling a flux tube rapidly expanding above $x = L$. The source is positioned at $x = 0.1\,L$, and the total number of injected particles is 1.33×10^{14} cm^{-2}. We assume that the background Alfvén waves have a large cross helicity: the outward propagating waves have $U_+(0,t) = U_+(x,0) = U_0 = 10^{-4} \times U_B$ as in Cases A and B, but the inward propagating waves have only $U_-(L,t) = U_-(x,0) = 10^{-6} \times U_B$. Other parameters were taken as in Cases A and B.

The results of the open-field simulation are shown in Fig. 3. The precipitating particle flux again shows a double peaked structure, with a precursor well described by Eqs. (4–5). The escaping flux, however, rises more slowly to a stationary level that is destroyed by the boundary effects, when the turbulent trap hits the free-escape boundary opening it also from this end. Towards the end of the event, the escaping flux becomes dominating over the precipitating flux. The number of precipitating particles is, however, an order of magnitude larger than the number of escaping particles, which shows that energetic particles accelerated in impulsive flares can be effectively trapped near the Sun even on open field lines. This demonstrates that the small ratio of interplanetary-to-interacting protons observed in impulsive flares do not necessarily result from closed field line topology.

4 Discussion and conclusions

We have modeled the transport of energetic protons in impulsive flares through self-generated waves using the Monte Carlo method. Our model uses a scattering law that is proportional to the energy densities of single-k Alfvén waves propagating in both directions along the mean field. The energy lost (gained) by the particles in the scatterings is given to (taken from) the waves. Our simulations make use of $k \propto p_0^{-1}$, which is reasonable, if the particles approximately conserve their energies during the propagation. Because the turbulent trap is expanding along the magnetic field at constant rate, however, there exists adiabatic deceleration of the trapped particles. The simulations reveal that precipitating particles have average momenta $\ln\langle p\rangle/p_0 > -1$, so the approximative resonance condition seems acceptable for scattering estimates. Note, however, that the change in energy during trapping can be substantial in context of γ-ray production, up to a factor of ~ 5 in non-relativistic case. For a typical integral particle spectrum, $N(>E) \propto E^{-2}$, this means a factor of ~ 25 less particles capable of γ-ray production, and may suppress the delayed peak of emission completely. The problem of adiabatic deceleration is most severe in case of strong, impulsive injections.

In conclusion, the impulsive flare scenario in light of our simulations is the following: promptly ($t \lesssim 1$ s) after the start of the proton acceleration process near the loop top the footpoints will brighten in γ-rays. After this, the turbulent particle trap develops and emission from the loop legs will stay at a level that determined by the convective flux of particles. After one Alfvénic propagation time from the source, the closer loop leg will brighten in γ-rays once again, provided that the number of high-energy particles after the adiabatic losses is large enough, $\mathrm{d}N/(\mathrm{d}A) \gg 4n_0V_\mathrm{A}/(\pi\Omega_\mathrm{p}) \sim 10^{13}\, n_{11}^{1/2}$ cm^{-2} with $n_{11} = n_0/(10^{11}$ cm$^{-3})$. The footpoint farther away from the source is unlikely to show the delayed peak in γ-ray emission in any case. We also found that the small interplanetary-to-interacting proton ratios observed in impulsive solar flares do not necessarily imply closed field line topology, but can result also from the turbulent trapping on open magnetic field lines.

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