Acceleration of ions in quasi-perpendicular coronal shocks

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***Abstract*. Gradual solar energetic particle events have been shown to be highly variable in their heavy ion abundances at the highest energies, with some events showing characteristics typical to impulsive events. One proposed solution to this variability is selective acceleration at quasi-perpendicular shock waves driven by coronal mass ejections of a compound seed population consisting of coronal / solar wind plasma and ions pre-accelerated by flares. In earlier studies, we have performed test-particle simulations in quasi-perpendicular coronal shock waves to demonstrate that this type of model is capable of explaining the variability of heavy ion abundances in SEP events. In this paper, we study the energy spectrum of the corresponding proton event and show that for parameters reproducing the heavy-ion abundance enhancements at high energies, proton acceleration can be very efficient. We show that in favourable magnetic geometries the same kind of model can explain proton acceleration to GeV energies in a matter of minutes. Typical spectral forms for protons obtained from the simulations are power laws with exponential cutoff.**

***Keywords*: Solar energetic particles, Coronal shock acceleration, Ground level enhancements**

I. Introduction

Solar energetic particle events are commonly divided into gradual and impulsive events, with diffusive shock acceleration (DSA) in coronal shocks and resonant-wave acceleration in solar flares as the proposed acceleration mechanisms, respectively. Gradual events typically have much larger particle intensities and coronal elemental abundances, while impulsive events typically show higher mean ionic charges, enhanced ^{3}He/^{4}He ratio, and enhanced heavy ion abundances [1]. However, gradual events have been shown to be highly variable in their heavy ion abundances at the highest energies, with some events showing characteristics typical to impulsive events [2].

One proposed solution to this variability is selective injection and subsequent acceleration at shock waves driven by coronal mass ejections (CMEs) of a compound seed population consisting of coronal / solar wind plasma and ions pre-accelerated by flares [2], [3]. This idea relies on quasi-perpendicular coronal shocks, which can rapidly accelerate particles to higher energies than parallel shocks, but which suffer from a high injection energy threshold. Thus, compositional signatures at the highest energies in the seed population are reflected by the highest energy part of the shock accelerated spectrum, producing the observed compositional variability at high energies in gradual events. Of course, variations in composition can be caused byvariations in shock geometry from one event to another.

In two earlier studies [4], [5], we have performed test-particle simulations of heavy ion acceleration in quasi-perpendicular coronal shock waves, and demonstrated that the semi-empirical model proposed by [2], [3] is capable of explaining the variability of heavy ion abundances in SEP events. The heavy-ion simulations were performed in a simplified but yet realistic model of the coronal magnetic field and evolving shock geometry.

In this short paper, we study the energy spectrum of a proton event produced by coronal shock acceleration in a similar global model that was use in our earlier simulations to study the high-energy abundance variations of heavy ions. We have slightly modified the coronal magnetic field model to include a bipolar active region in addition to the background unipolar radial field used in the previous studies, but otherwise the model is very similar to the ones used in [4], [5].

II. Proton simulations

We model the shock as a spherical discontinuity with a constant radial expansion speed 1000 $\mathrm{km\,s^{-1}}$ and a constant gas compression ratio $X = 3$. The center of the explosion is in the corona, which results in an evolving magnetic geometry of field lines swept by the shock (see Fig. 1). The simulation code has been presented in detail already earlier [5].

We employ an infinite Mach number approximation, i.e., assume that the shock expansion speed is much higher than the Alfvén speed in the upstream region. The upstream plasma is also assumed to be at rest. These approximations allow us to use simplified MHD jump conditions for oblique shocks that determine the downstream plasma speed and magnetic field.

In the downstream region the plasma flow is assumed to be radially outwards from the explosion center everywhere. The downstream magnetic field can then be analytically solved for a generic upstream magnetic field using the induction equation, assuming that diffusive effects can be neglegted. In the downstream region there is a convective electric field, the upstream region is at rest so the convective electric field vanishes.

The particle trajectories are computed using the full Lorentz force whenever the particles are in the down-

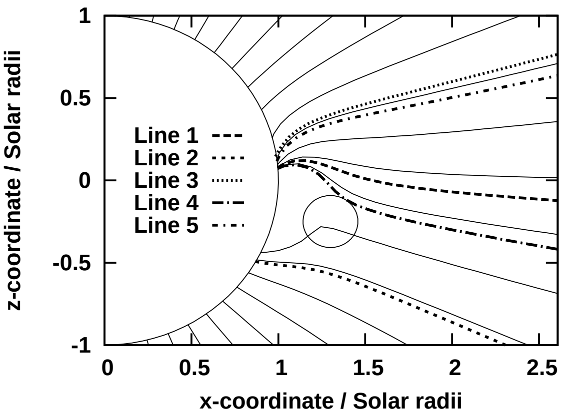

Fig. 1. The magnetic field model and the model of the shock front used in our simulations. The field is a superposition of a unipolar radial field centered at the Sun and a bipolar active region with two opposite magnetic charges embedded just below the solar surface symmetrically above and below the equator. The five different injection field lines considered in our study are marked in the figure. The circle centered in the corona represents the spherical shock front as it first intersects field line 4.

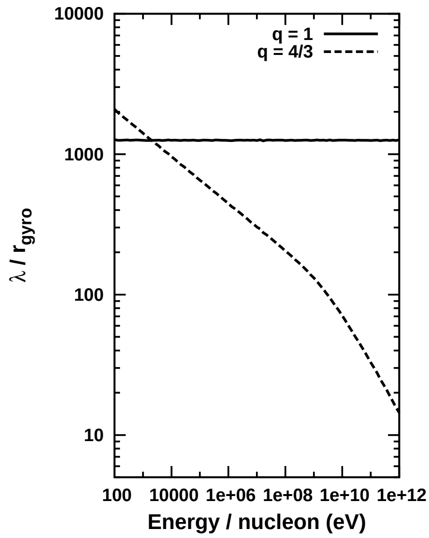

Fig. 2. The scattering mean free path of the accelerated protons in our model. The two curves correspond to two values of the spectral index of the magnetic field fluctuation power spectrum.

stream region, or near the shock in the upstream region. In the upstream region above $1.6\,R_\odot$ from the center of the Sun and far away from the shock front we assume that the ambient magnetic field is radial (from the center of the Sun), and compute the particle trajectories analytically. This approximation is done simply to reduce overall computation time.

When using the full Lorentz force to compute particle trajectories, we model pitch angle scattering by first calculating the time of the next scattering, which is chosen to be consistent with the scattering rate obtained from the quasilinear theory, then computing the trajectory until that time is reached, and finally randomizing the particle's pitch angle cosine. We take the power spectrum of the magnetic fluctuations to be a power law in wavenumber, $P(k) = P_0|k_0/k|^q$. In this paper, we concentrate on preliminary results from the simulation runs where $q = 1$ has been used, but discuss also results from simulation runs with $q = 4/3$. Figure 2 shows the mean free paths vs. energy from our model using $q = 1$ and $q = 4/3$.

1-MeV protons were injected on field lines 1–5 directly in front of the shock in the upstream region. They were removed from the simulation if the radial coordinate reached a value of $20\,R_\odot$, if the particles' distance to the shock front exceeded $0.05\,R_\odot$ in the downstream region, or the simulation time exceeded 1200 seconds, or if the particle hit the surface of the Sun.

Figure 3 shows the energy spectra obtained from the simulation runs. All particles (however they were removed from the simulation) have been included when plotting the figure. All energy spectra are power laws with an exponential cut-off. The acceleration is most efficient for injection line 5, with roughly an order of magnitude difference in intensity to the next best

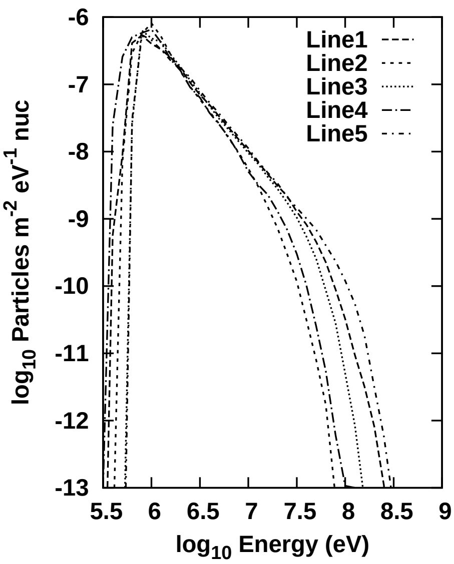

Fig. 3. Energy spectra of protons accelerated in a spherical shock front propagating on coronal field lines 1–5 depicted in Fig. 1. The power spectrum of the magnetic fluctuations is a power-law with spectral index $q = 1$ giving the scattering mean free path depicted in Fig. 2. All spectra have been normalized to 1 m^{-2}.

injection line above the cutoff energies.

Although the shock speed, the compression ratio and the turbulence amplitude were the same in all cases, the cutoff energies vary by an order of magnitude from one field line to another. This emphasizes the role of favorable magnetic geometry in the acceleration process. In our simulations, the field line producing the most energetic particles was line 5. In this case, the shock first intersects the field line close to the surface at an oblique angle, which allows an efficient injection of particles to the acceleration process. The obliquity of the shock then increases up to about 84 degrees, and the shock stays for about 50 seconds in the quasi-perpendicular configuration, after which the obliquity of the shock again decreases. (In the case of other field lines, the quasiperpendicular phase is shorter.) When studying the simulated particles, we find that the highest energies are attained by particles removed from the simulation during and right after the most perpendicular phase of shock evolution; these particles escape at the outer boundary of the simulation.

The same simulation runs were performed also for the turbulence model with $q = 4/3$, which yields more efficient scattering (see Fig. 2). The spectra in these cases (not shown) are harder than for the less turbulent conditions, as expected. The cutoff energy on line 5 extends up to the GeV range in the more turbulent case. Thus, under favorable conditions, coronal shocks can accelerate protons up to energies observed in ground level enhancements (GLEs).

III. Summary and discussion

We have studied DSA in quasi-perpendicular coronal shocks using test-particle simulations. Our model implements a realistic magnetic field geometry close to an active region in the solar corona, combined with a shock wave caused by an expanding CME. We consider particle acceleration resulting from injection on five different field lines with different shapes and at different distances from the center of explosion in the corona. We find that

- proton acceleration to relativistic energies may occur in quasi-perpendicular coronal shocks in a matter of minutes from the launch of the shock;
- field line and shock geometry have a strong effect on the maximum energy of the particles: shock-normal angle evolution is most favorable for particle acceleration if it starts from oblique and then develops toward quasi-perpendicular values; and
- turbulent conditions affect the acceleration efficiency in the usual fashion, i.e., more turbulent conditions yield more effective acceleration.

The last point needs a caveat: our particle propagation model contains very little perpendicular diffusion, and more realistic models with a finite-amplitude long-wavelength turbulent component may behave differently. Fluctuating fields may put an upper limit on the effective shock normal angle that remains below 90°. Furthermore, efficient perpendicular transport increases the diffusion coefficient in the shock normal direction, which leads to a slower acceleration rate in DSA theory. As the scattering mean free paths are still orders of magnitude above the gyroradius in our model, however, the corresponding turbulent field amplitudes are also small compared to the ordered magnetic field.

In conclusion, our simulation results implicate that quasi-perpendicular shock acceleration yields proton spectra that extend up to relativistic energies, thus resembling GLE spectra. On most coronal field lines, however, the cut-off energies in the proton spectrum are some tens of MeVs, which are more typical values during gradual energetic particle events. It seems that a rapidly expanding CME shock in the low corona is not a sufficient condition for a gradual event to become a GLE. In addition, special conditions in terms of field line geometry and turbulence are needed. This is consistent with the fact that GLEs are a relatively rare phenomenon.

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