Self-consistent Monte Carlo simulations of the re-acceleration of protons in the downstream region of a coronal shock

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Abstract

In the framework of the “SEPServer” EU FP7 project, we have simulated stochastic re-acceleration of protons by enhanced Alfvénic turbulence in the downstream region of a shock wave. This effect can be important at the early (coronal) phase of gradual SEP events, when the shock propagates through closed coronal structures. The main feature of our study is that the wave-particle interactions are treated self-consistently, and thus the finiteness of the available turbulent energy is taken into account. The simulations reveal that the shape of the particle energy spectrum developed due to the re-acceleration depends on the particle injection strength from the shock into the shock's downstream region.

Model

We consider a CME-driven shock propagating through a coronal loop and simulate interactions of protons with Alfvén waves in a 1-D simulation box in the shock's downstream region (Fig. 1). The wave-particle interactions are treated under the quasi-linear approximation, i.e. as resonant interactions. We apply the full form of the resonance condition governing the interactions (for the simulation model details, see Afanasiev & Vainio 2013, ApJS, 207, 29).

Initial and boundary conditions:

- The Alfvén waves are assumed to propagate in both directions along the magnetic field and specified, at the start of simulation, by two intensity spectra of the power-law type (each spectrum corresponds to the waves propagating in one direction).
- The shock is assumed to be perpendicular and protons, at the start of simulation, are taken to be power-law distributed in the energy range 1 MeV < E < 30 MeV and isotropically distributed in coordinate space (in this way we separate the effect of shock acceleration from the one of stochastic acceleration).
- The simulation box has periodic boundary conditions and no spatial resolution (one-cell box).
- The initial state of the overall system is characterized by the ratio $\alpha = U_p^{(0)}/U_w^{(0)}$ of the initial energy density of protons to the initial energy density of waves. This parameter can be interpreted as the relative strength of particle injection into the downstream region.

Conclusions

- At a strong energetic proton production (α<<1), the power-law spectrum of shock-accelerated protons evolves due to the re-acceleration in the downstream region into a broken power-law one.
- At a weaker injection ($\alpha \gtrsim 1$), the steady-state particle energy spectrum is again a power-law. Interestingly, its spectral index does not depend on either the initial turbulence spectral index or that of the shock-accelerated proton spectrum and equals about 2.1.

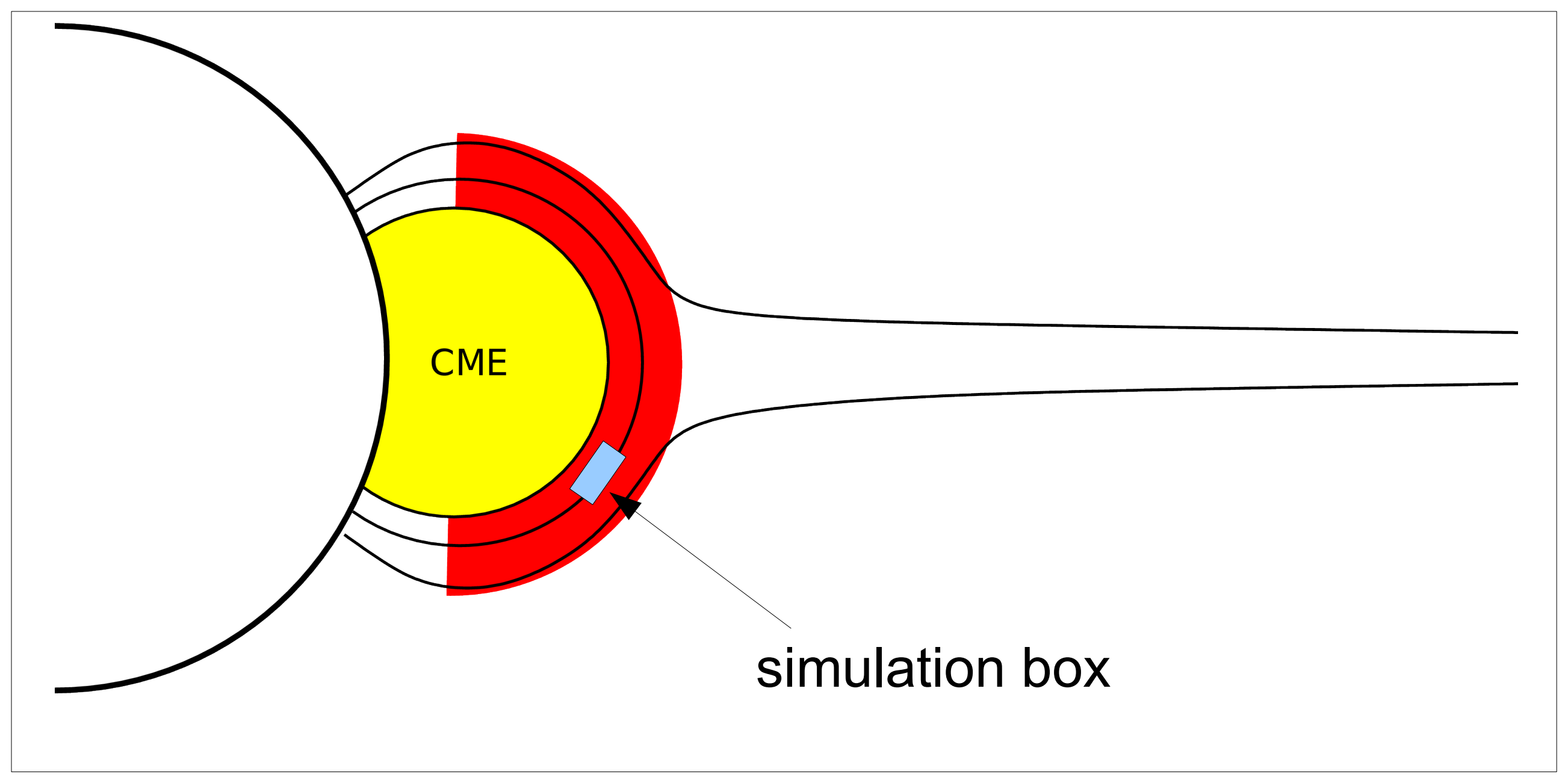

Fig. 1. Formulation of the problem: a shock driven by a CME propagates through a closed magnetic structure. The shock’s downstream region is schematically indicated in red. In this region, the shock-accelerated particles are re-accelerated by the turbulence amplified by the shock.

Simulation results

In the simulations we examined the time evolution of the spectra of waves and of the energy spectrum of protons for different values of the parameter α and of the initial power-law spectral indices.

Case α ≥ 1

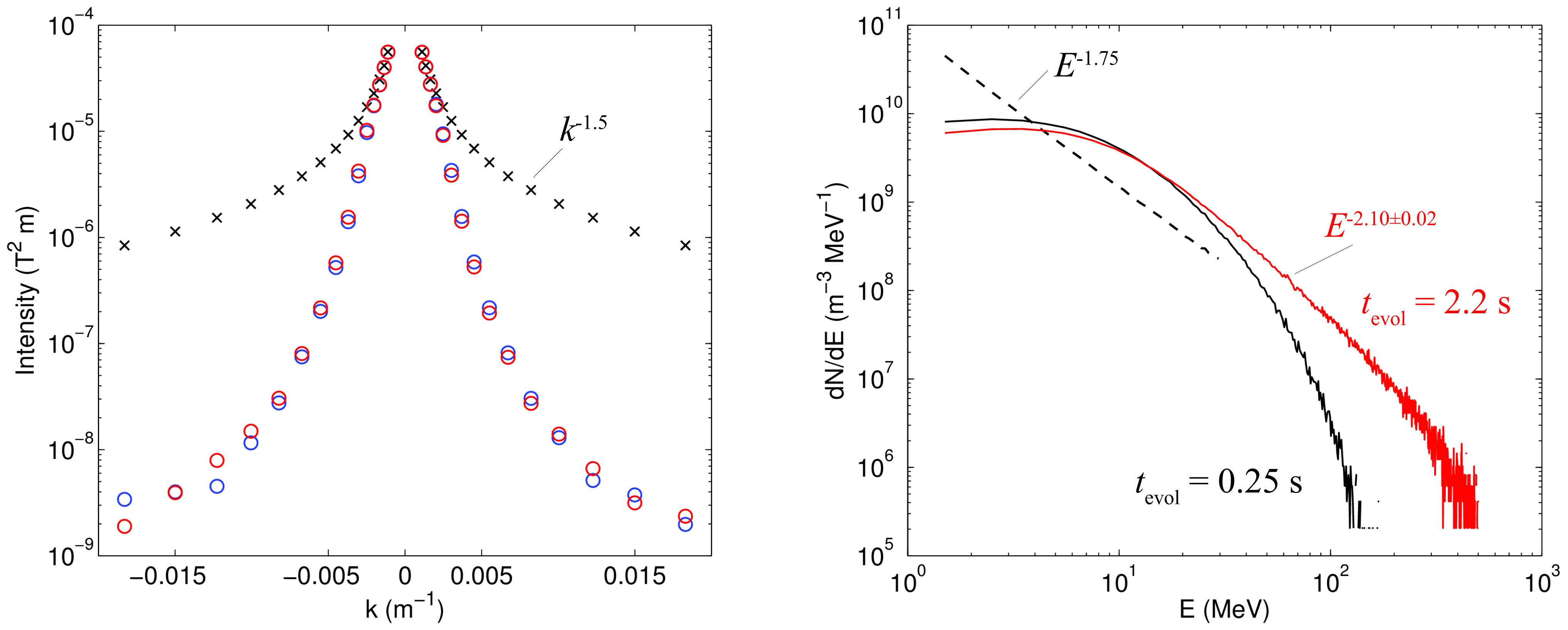

Fig. 2. *Left:* Simulated Alfvén wave spectra (blue and red circles denote forward and backward propagating waves) and the initial Alfvén wave spectrum (black crosses). *Right:* Simulated proton energy spectra (red and black curves) together with the initial spectrum (dashed black line). Note the formation of the power-law proton energy spectrum.

Case α << 1

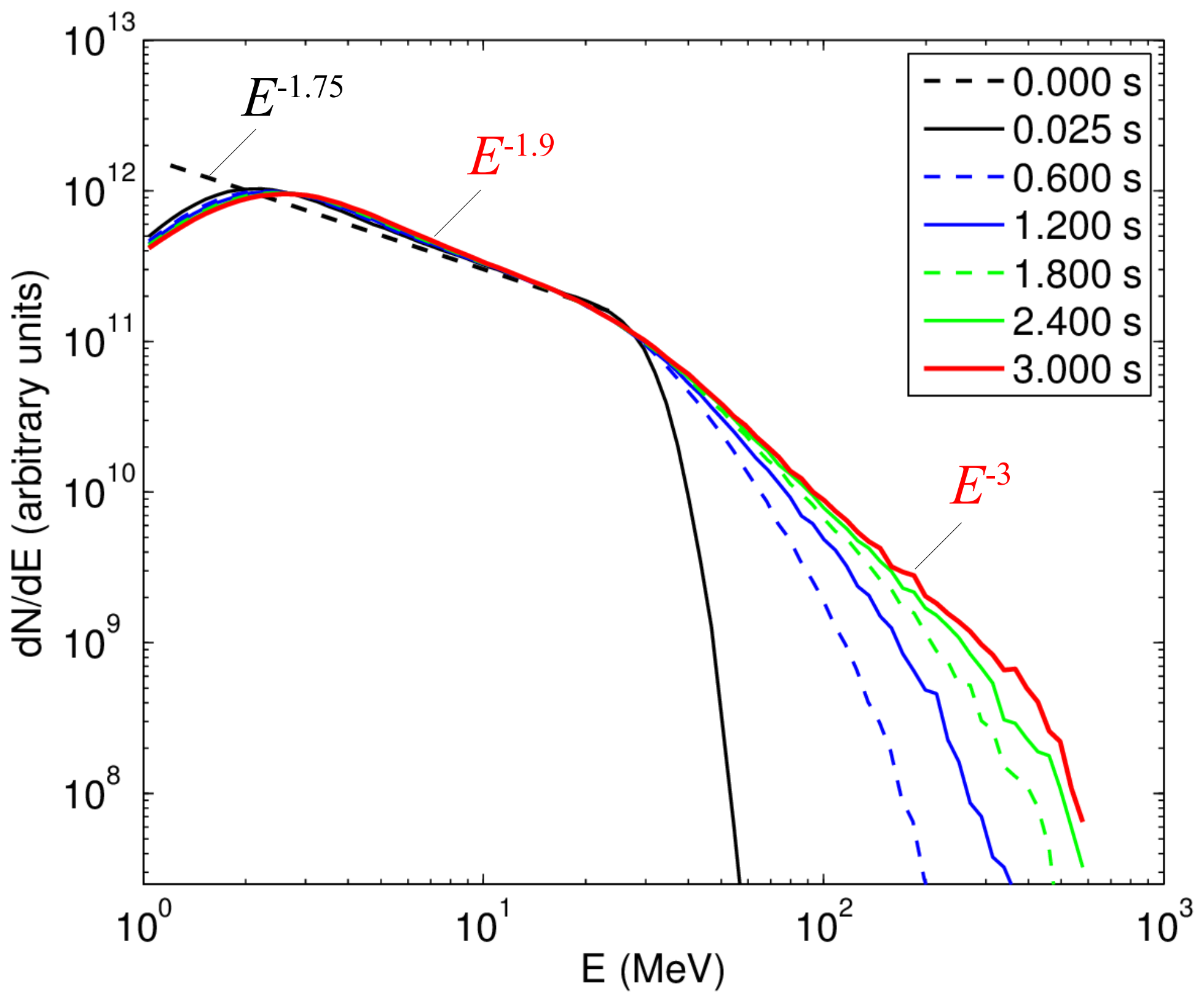

Fig. 3. Time evolution of the proton energy spectrum showing the formation of a broken power-law steady-state spectrum. The initial proton spectrum (black dashed line) spans the range [1,30] MeV. The rate of particle energy density increase corresponding to the red curve is 1.9% of the initial rate. Here logarithmic energy bins were used to suppress fluctuations.

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