Solar Energetic Particle Acceleration in Refracting Coronal Blast Waves

R. Vainio[1], J.I. Khan[2]
(1) Department of Physical Sciences, University of Helsinki, Finland
(2) Tuorla Observatory, VISPA, University of Turku, Finland

Abstract

Recent observational evidence from soft X-ray imaging data supports models of coronal shock wave propagation in the solar atmosphere as freely propagating blast waves, which refract toward the solar surface as they propagate away from the flare site. We have modeled particle acceleration in such a refracting large-scale solar coronal shock wave. The geometry of such a shock wave results in the observer in the interplanetary medium being magnetically connected with the downstream region of the shock wave. Thus, the accelerated particles escape to the observer through the region of shocked plasma behind the shock front, which may explain why the energy spectrum observed in the interplanetary medium is usually a power-law. Using parameters of upstream turbulence obtained from models of a cyclotron-heated solar corona we show that the particle acceleration model results in proton energy spectra generally consistent with those frequently observed in small, gradual solar energetic particle events. In addition, this process can serve as a pre-acceleration mechanism for further acceleration in CME-driven shocks in large gradual events.

1. Introduction

The current two-class paradigm of solar energetic particle (SEP) events divides them in two categories, impulsive and gradual, referring to the typical time scales of the particle intensity increases and the related electromagnetic emissions. Impulsive SEP events have abundance ratios and charge states that point toward their acceleration by resonant plasma waves in impulsive flares close to the solar surface. Gradual SEP events are generally correlated with coronal mass ejections (CMEs), gradual soft X-ray flares, and type II radio bursts. They are commonly thought to be diffusively accelerated by the bow shocks driven by CMEs high in the solar corona (above 2–4 $r_\odot$) and interplanetary (IP) medium.

The "standard" model seems to work well in the case of large gradual SEP events, related to the fastest CMEs with speeds greater than 1000 km/s. Here, CME-bow-shock acceleration is very rapid due to the amplification of Aflvén waves upstream of the shock by the streaming SEPs themselves [6]. In small

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gradual SEP events with peak intensities $\lesssim$ 10 protons/(cm^2 sr s MeV) at 1-MeV proton energy, however, wave generation by SEPs is a minor effect [9]. If particle acceleration in these events is due to (quasi-parallel) shock waves, the intense magnetic turbulence enabling rapid diffusive shock acceleration has to be of external type. It is, however, clear from SEP observations that the ambient scattering conditions are too weak to account for rapid enough bow-shock acceleration unless the region of strong ambient turbulence is limited to small distances ($\lesssim 10\ r_\odot$) from the Sun by, e.g., cyclotron damping of the waves by the plasma ions [10].

There is also observational evidence suggesting that acceleration in CME-related SEP events might be more complicated than the simple bow-shock picture suggests, especially, if the CME speed is not very high. Kocharov et al. [4] studied CMEs with speeds in the range 300–800 km/s. They found that all those CMEs that were associated with SEP events rapidly accelerated (i.e., within 2–4 $r_\odot$) to a constant speed measured within the coronagraph field of view. In addition, 95 % of the SEP-related CMEs were related to soft X-ray flares and 63 % to metric type II radio bursts. For all rapidly accelerating CMEs in this speed range, i.e., not only those that were SEP related, these percentages were significantly lower: 67 % were associated with soft X-ray flares and only 15 % with metric type II bursts. The authors concluded that "a typical SEP-producing CME [with a speed in the range 300–800 km/s] experiences fast acceleration close to the Sun associated with soft X-ray flare and coronal shocks." This conclusion is supported by a number of detailed case studies (e.g., [7]) suggesting that shock waves at global coronal scales (of about 1 $r_\odot$) are necessary for particle acceleration associated with moderate speed CMEs.

Recently, coronal shock waves have been observed in soft X-rays [3]. Soft X-ray images provide direct observations of coronal shock waves and, thus, of their morphology and physical properties in the corona. Hudson et al. [2] reported soft X-ray observations of a shock wave observed with high temporal and spatial resolution. Among their findings was clear observational evidence for the bending (refraction) of the coronal wave toward the solar surface as it moved away from the flare—as predicted in the blast wave model of Uchida [8]. This bending occurs because the Alfvén speed in the solar corona increases with height at distances close to the Sun ($r \lesssim 2\ r_\odot$). Here we give a sketch of particle acceleration in such refracting coronal shock waves. The full calculation is given in [11].

2. Particle Acceleration in Flare Blast Waves

The left-hand panel in Figure 1 gives a sketch of a refracting coronal blast wave. Following a strong explosion (i.e., a solar flare) in the solar atmosphere, a blast wave starts to propagate through the corona. The shock wave is not very strong, and its dispersion relation can be approximated by that of fast magne-

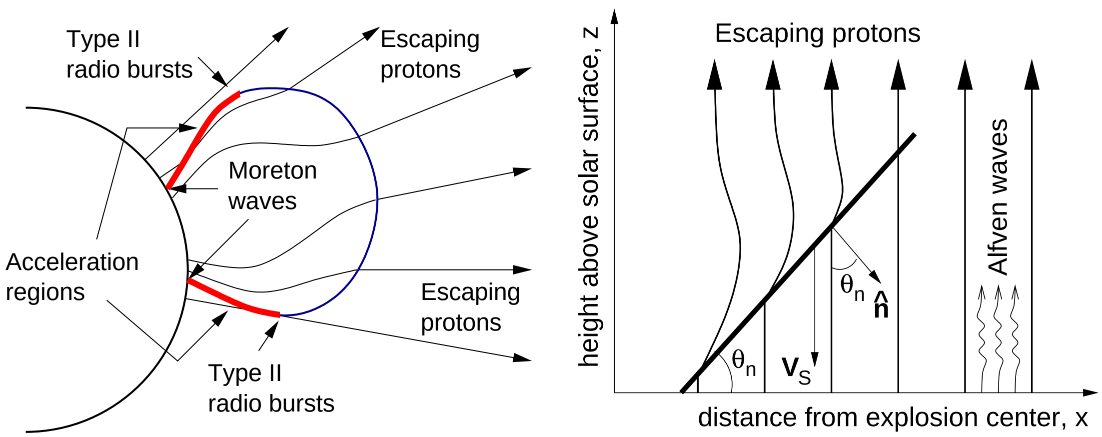

Fig. 1. The geometry of the refracting coronal blast wave (left) and a schematic of the acceleration region (right). Field lines are shown with large arrowheads. [11]

tosonic waves. Ray tracing [8] shows that the blast wave refracts toward regions of higher refractive index, i.e., lower Alfvén speed. Because the Alfvén speed close to the solar surface increases as a function of height in most models of coronal density and magnetic field, this implies that the blast wave bends toward the solar surface as it propagates away from the flare site. For the same region, the wave is also strongest in regions close to the solar surface. Thus, it is natural to assume that these regions are the strongest particle accelerators. Note that the flanks of this coronal shock wave may be observed as a chromospheric Moreton wave. The shock wave may also give rise to a type II radio burst, which we take to be emitted from the quasi-perpendicular region of the shock wave [12].

The right-hand panel of Figure 1 gives a zoomed view of the acceleration region close to the solar surface. Because the wave bends toward the photosphere, the observer in the interplanetary medium is magnetically connected to the downstream region of the blast wave. Thus, steady-state (test-particle) diffusive shock acceleration predicts a power-law energy spectrum,

$$\frac{dN}{dE} \propto \frac{p^{-\sigma}}{v}, \quad \sigma = \frac{r_{\rm sc}+2}{r_{\rm sc}-1} \tag{1}$$

of accelerated particles to be emitted from the solar corona to the interplanetary medium. Here, v and p are the particle speed and momentum, $r_{\rm sc} = u_{1n}/u_{2n}$ is the scattering-center compression ratio at the shock, and $u_{1n[2n]}$ is the scattering-center velocity component normal to the shock wave upstream [downstream] the shock wave.

The power-law spectrum extends to energies determined by the available acceleration time. This is given by $T_{\rm S} = z_0/V_{\rm S}$, where z_0 is the height of the shock from the solar surface when it first intersects the observer's field line, $V_{\rm S} = MV_{\rm A}/\cos\theta_n$ is the projection of the shock speed along the vertical magnetic field lines, $V_{\rm A}$ is the Alfvén speed, $M \gtrsim 1$ is the Alfvénic Mach number of the shock, and θ_n is the shock-normal angle (see Fig. 1). Assuming scattering downstream of the shock wave to be rapid, the momentum gain rate can be given as [1]

$$\frac{\dot{p}}{p} \approx \frac{r_{\rm sc}-1}{3\, r_{\rm sc}} \frac{u_{1n}^2}{\kappa_{1n}(p)}. \tag{2}$$

We assume that the upstream scattering centers are Alfvén waves emitted from the solar surface. Thus, $u_{1n} = (V_{\rm S} + V_{\rm A})\cos\theta_n = V_{\rm A}(M + \cos\theta_n)$. The spatial diffusion coefficient in the shock normal direction is $\kappa_{1n} = \frac{1}{3} v\lambda\cos^2\theta_n$, where the mean free path λ can be fixed assuming that the corona is heated by high-frequency Alfvén waves [10], which seems consistent with remotely-sensed coronal ion-velocity distributions on open magnetic field lines [5]. This assumption gives, roughly, $\lambda(p) = \lambda_0(p/p_0)$ with $\lambda_0 = 0.1\, r_\odot$ and $p_0 = m_{\rm p}c$ (see [11]), where $m_{\rm p}$ is the proton mass and c the speed of light. Taking $r_{\rm sc} = 2$ and $V_{\rm A} = 500$ km/s, we can integrate the momentum gain rate to get the spectral cut-off energy as

$$E_{\rm c} \sim \int_0^{T_{\rm S}} v\dot{p}\, {\rm d}t = E_{\rm c0}\frac{(M+\cos\theta_n)^2}{4M\cos\theta_n}\frac{z_0}{r_\odot} > E_{\rm c0}\frac{z_0}{r_\odot}, \tag{3}$$

where $E_{\rm c0} = (4\, r_\odot/\lambda_0)\, m_{\rm p}c\, V_{\rm A}(r_{\rm sc}-1)/r_{\rm sc} \approx 30$ MeV. Thus, particle acceleration in refracting coronal blast waves produces power-law proton energy spectra extending up to a few tens of MeVs.

Diffusive shock acceleration in refracting coronal shock waves can, thus, explain particle acceleration in small gradual (i.e., normal-composition) SEP events not associated with fast CMEs. In addition, the process can provide pre-accelerated seed particles for shock acceleration in fast bow shocks in case of larger events associated with fast CMEs.

3. References

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