PROMPT ACCELERATION OF IONS BY OBLIQUE TURBULENT SHOCKS IN SOLAR FLARES

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1. Introduction. Solar flares often accelerate ions and electrons to relativistic energies. The details of the acceleration process are not well understood, but until recently the main trend was to divide the acceleration process into two phases (1). During the first phase electrons and ions are heated and accelerated up to several hundreds of keV simultaneously with the energy release. These mildly relativistic electrons interact with the ambient plasma and magnetic fields and generate hard X-ray and radio radiation. The second phase, usually delayed from the first by several minutes, is responsible for accelerating ions and electrons to relativistic energies. Relativistic electrons and ions interact with the solar atmosphere or escape from the sun and generate gamma-ray continuum, gamma-ray line emission, neutron emission or are detected in space by spacecraft. In several flares the second phase is coincident with the start of a type II radio burst that is believed to be the signature of a shock wave (2). Observations from the Solar Maximum Mission spacecraft have shown, for the first time, that several flares accelerate particles to all energies nearly simultaneously (3). These results posed a new theoretical problem: How fast are shocks and MHD turbulence formed and how quickly can they accelerate ions to 50 MeV in the lower corona? We address this problem in this brief report.

2. Model. We consider the following model for shock formation during a solar flare. During the flare's impulsive phase, magnetic energy is transferred to plasma particles inside the energy release volume by increasing the random mean square velocity (i.e., heating the bulk plasma) and by accelerating the tail of the velocity distribution. The high plasma pressure inside the energy release expands against the external magnetic field and forms a shock nearly instantaneously (4). The angle $\bar{\Theta}_{Bn}$ between the mean upstream magnetic field and the mean shock normal $\hat{n}$ and the level of magnetic fluctuations in the shock vicinity play a crucial role in accelerating particles to high energies. Since the detailed evolution of energetic ions in a generally oblique turbulent shock is a complex process, we have designed a numerical code that integrates along energetic (i.e., $\gtrsim$ 100 keV) test ion orbits in such an environment (5).

We define K[X, Y, Z] as a system fixed with the shock, with the unit vector $\hat{X} = -\hat{n}$, such that the shock discontinuity coincides with the Y-Z plane and separates the upstream (X < 0, subscript 1) from downstream (X > 0, subscript 2) regions. The quantities $\vec{U}_1 = U_1 (\cos \delta_1, 0, \sin \delta_1)$ and $\vec{B}_{01} = B_{01} (\cos \Theta_1, 0, \sin \Theta_1)$ denote, respectively, the upstream plasma flow velocity and mean magnetic field (where $\Theta_1 = \bar{\Theta}_{Bn}$). Then, in K the mean electric field on either side of the shock is $-\vec{U}_1 \times \vec{B}_{01}/c$. Given values of the upstream Alfvén Mach number M_{A1} and the plasma beta β_1, the mean downstream conditions are calculated by solving the MHD jump equations (for a ratio of specific heats of 5/3).

We model magnetic fluctuations by superposing upon $\vec{B}_{0i}$ (i = 1 or 2) a zero mean, random magnetic field component $\vec{b}_i(z)$ which, in either the upstream or downstream plasma frame, varies only with the coordinate z along $\vec{B}_{0i}$, is transverse to $\vec{B}_{0i}$, and is static, so that scattering is elastic in either plasma frame. We assumed for this study that $\vec{b}_i(z)$ is a superposition of 4096 circularly polarized, parallel-propagating Alfvén waves, each with a random phase, and with the amplitude of each such Fourier component with wave number k derived from a power spectrum P(k) using a technique described by Owens (6). For synthesized realizations of $\vec{b}_i(z)$, the Lorentz force equation was solved for a particle orbit using the field $\vec{B}_i(z) = \vec{B}_{0i} + \vec{b}_i(z)$ in the appropriate plasma frame, and Lorentz transformations were performed between plasma frames at shock crossings. Each particle orbit was followed until a pre-set boundary (spatial or temporal) was crossed.

The source(s) and spectral form of Alfvénic turbulence are, of course, largely unknown in the vicinity of lower coronal shocks. Possible sources upstream include the turbulent pre-flare plasma and Alfvén waves driven by energetic (~ 100 keV) ion beams streaming upstream from the shock following reflection at the shock and/or leakage from the hot downstream plasma. Possible sources downstream include the upstream MHD turbulence convected through and amplified by the shock as well as turbulence excited by the flare release mechanism. We assumed the spectral form P(k) of Alfvén waves shown in Figure 1. The spectrum extends from k_S to k_L, with correlation length $z_c = 10^5$ cm, and slope -5/3 for $k >> z_c^{-1}$. The integrated power or variance σ^2 assumed was $\sigma_1^2 = 0.19\ B_{01}^2$ upstream and $\sigma_2^2 = 0.38\ B_{02}^2$ downstream. Figure 1 is the upstream spectrum for $B_0 = B_{01} = 50$ G. This spectral form was chosen because it provides power for resonant scattering (gyroradius ~ k^{-1}) of protons (top scale) with energies spanning the range of flare-associated energies from 100 keV to 10 GeV.

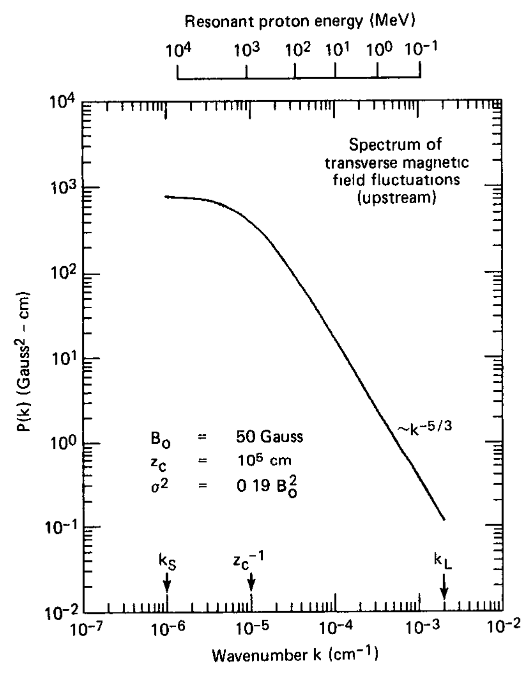

Fig. 1 Power spectrum P(k)

3. Results. Figures 2 and 3 show results for $\delta_1 = 0°$, $U_1 = 3.3 \times 10^8$ cm/s, $B_{01} = 50$ G, $M_{A1} = 3$, $\beta_1 = 0.1$, various values of Θ_1 from 0° to 75°, and protons injected upstream of the shock with energy $E_0 = 100$ keV. We define the scale time $\tau_{01} = eB_{01}/m_0c = 1.3 \times 10^{-5}$ sec (nonrelativistic upstream proton gyroperiod). Figure 2 shows the energy E versus acceleration time t/τ_{01} after a total

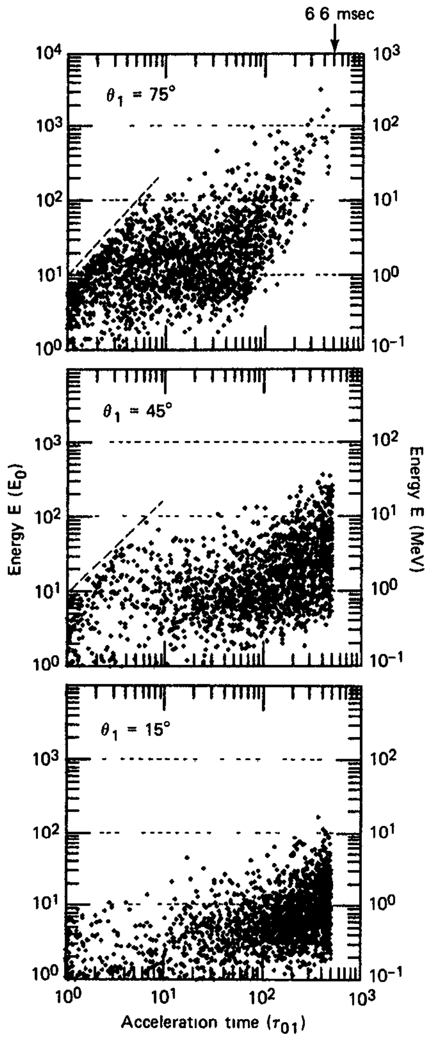

Fig. 2 Energy versus acceleration time

elapsed time of 500 τ_{01} = 6.6 msec for each of 2200 protons injected at shocks with Θ_1 = 15°, 45° and 75° (all other parameters held fixed). Plotted is the total energy of each particle against the time taken to reach that energy, or equivalently, the time of the particle's last shock crossing. Points with t/τ_{01} < 500 imply that these particles spent the time 500 - t/τ_{01} diffusing without net energy change in the upstream or downstream regions.

Particles injected into our turbulent oblique shock model gain energy through both the shock drift and diffusive acceleration processes. Shock drift acceleration, relatively fast and most effective at quasi-perpendicular (45° $\lesssim \Theta_1 \leq$ 90°) shocks, results as particles undergo an effective grad-B drift along the $\vec{U} \times \vec{B}$ electric field during shock encounters (7). Diffusive acceleration, relatively slow and most effective at quasi-parallel (0 $\leq \Theta_1 \lesssim$ 45°) shocks, results as particles diffuse back and forth across the shock and are compressed between the converging upstream and downstream flows (8). Reference (5) shows a sample orbit.

Figure 2 reveals the following. (a) An increase in Θ_1 from 15° to 75° increases the fraction of protons above 10 MeV within 6.6 msec. This results from the increasing contribution from the drift acceleration with increasing Θ_1. (b) For Θ_1 = 15° most particles are still available for further acceleration (note the high density of points near the 6.6 msec cutoff), whereas for Θ_1 = 75° most particles have been convected far downstream and will undergo no further acceleration. (c) For Θ_1 = 75° and, to some extent, for Θ_1 = 45° the shock drift process produces a spectrum extending from 100 keV to ~ 10 MeV during a super-prompt acceleration phase lasting ~ 0.1 msec, with an apparent upper energy limit indicated by the dashed diagonal lines. Particles in this separate population are those that, through an interplay between pitch angle scattering and drift, remain at the shock and undergo an intensive period of drift acceleration.

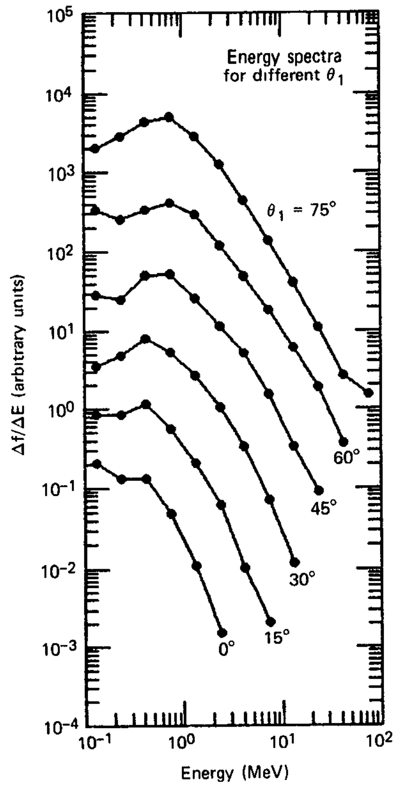

Fig. 3 Energy spectra for various Θ_1

In Figure 3 we show energy spectra for values of Θ_1 from 0° to 75° (all other quantities held fixed), again for a total elapsed time of 6.6 msec. The quantity $\Delta f(E)/\Delta E$ is the fraction of particles with energy E within ΔE centered at the logarithmically spaced plot points. The spectra are separated for clarity and statistical standard deviations are within twice the size of the plot points. Because the drift process produces relatively large and fast energy gains, quasi-perpendicular shocks are clearly most effective in producing power law spectra above ~ 2 MeV (spectral slope ~ 2.1 for 75° and ~ 1.9 for 60°) within ~ 7 msec. Because of the decrease in the drift contribution as well as the slowness of the diffusive acceleration process with decreasing Θ_1, quasi-parallel shocks yield spectra that are steeper and extend to successively lower energies as Θ_1 decreases.

4. Conclusions. We have shown that in solar flares oblique turbulent shocks can accelerate an initial population of 100 keV protons to 50 MeV in less than 7 msec (well below the instrumental resolution of existing instruments) through a combination of diffusion and the shock drift acceleration process. The implication of this prompt acceleration for the overall flare problem is beyond the scope of this brief report.

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