ON PROTON AND ELECTRON ACCELERATION BY SHOCK WAVES DURING LARGE SOLAR FLARES

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(Received 24 May, 1978; in final form 26 March, 1979)

Abstract. The data on optical, X-ray and gamma emission from proton flares, as well as direct observations of flare-associated phenomena, show energetic proton acceleration in the corona rather than in the flare region. In the present paper, the acceleration of protons and accompanying relativistic electrons is accounted for by a shock wave arising during the development of a large flare. We deal with a regular acceleration mechanism due to multiple reflection of 'resonance' protons and fast electrons from a collisionless shock wave front which serves as a moving mirror. The height of the most effective acceleration in the solar corona is determined. The accelerated particle energy and density are estimated. It is shown in particular that a transverse collisionless shock wave may produce the required flux of protons with energy of 10 MeV and of relativistic electrons of 1–10 MeV.

The proposed scheme may also serve as an injection mechanism when the protons are accelerated up to relativistic energies by other methods.

1. Introduction

Having analysed the data on X- and gamma rays from a series of large solar flares as well as direct observations of energetic electrons and protons, Lin and Hudson (1976) arrived at the following important conclusions:

(1) The main part of the total energy of a large flare ($10^{32}$–$10^{33}$ erg) is constituted by electrons with energy $\mathcal{E} = 10–10^2$ keV. These electrons are accelerated during the flash phase.

(2) The greatest part of these electrons moves downwards from the acceleration region, generates X-ray emission and forms a shock wave as a result of explosive heating in the dense atmosphere of the Sun. Only less than $10^{-4}$ of the total number of accelerated electrons are escaping into the interplanetary medium.

(3) The energetic protons contain a very small fraction of the flare energy (of the order of $10^{-5}$). Most of the protons with energy $\geq 10$ MeV are accelerated some minutes later than energetic electrons and disappear into the interplanetary medium. This fact is supported, firstly, by the delay of the gamma emission pulse by 3–5 min as compared with that of the X-ray emission of the flare, and, secondly, by a better agreement between the $\gamma$-emission spectrum and the 'thin target' model. The foregoing implies that the main part of energetic protons is accelerated outside the flare region, for instance, in the corona.

(4) All proton flares analysed by Lin and Hudson (1976) were accompanied by shock wave formation directly observed in the interplanetary space. The conclusion has been drawn that the energetic protons originate from acceleration by a shock wave appearing during a large flare. Under this assumption, the difference between...
proton and non-proton flares is due only to the total energy release in energetic electrons.

Following Lin and Hudson's (1976) estimates, to form a shock wave and a large proton flare, a minimum energy of $10^{31}$ erg should be released in 10–20 keV electrons.

(5) The proton events, particularly the most powerful of them are also usually accompanied by the occurrence of relativistic electrons with energies of the order of several MeV (Șvestka, 1976).

Several models of proton acceleration by shock waves have been discussed (Shabansky, 1962; Parker, 1958; Wentzel, 1963). All these models are effective only in the case when the initial velocity of an accelerated proton is essentially higher than that of the shock wave. In the corona the number of such particles is exponentially small, so one meets with difficulties when interpreting the observed fluxes of accelerated protons. In addition, the maximum energy of accelerated protons is also quite insufficient since, in the models in question, the proton energy increases only a few times.

In the present paper, attention is given to a mechanism of proton acceleration by collisionless shock waves free from the two disadvantages outlined above. In other words, it provides both considerable proton fluxes for the acceleration regime and relatively large maximum energies of accelerated protons (up to tens of MeV).

Let us consider, for simplicity, a collisionless shock wave propagating across the magnetic field in a low-pressure plasma ($\beta_0 = H_0^2/8\pi n_0\epsilon_0 T$ $>> 1$). This is precisely the case realized in the solar corona. A shock wave consists of successive compression solitons with a characteristic scale of each soliton $-c/\omega_{pe}$ (Sagdeev, 1964). Each soliton has hills of the potential of the electrostatic field which is related to charge separation in the shock wave.

The maximum value of the potential is realized in the leading soliton and turns out to be equal to

$$\varphi_{\text{max}} = \frac{H_0(H_{\text{max}}-H_0)}{4\pi n_0} = \frac{H_0^2(M-1)}{2\pi n_0}. \tag{1}$$

Equation (1) takes into account that the maximum value of the magnetic field of the leading soliton is $H_{\text{max}} = H_0(2M - 1)$, where $M = u/v_A$ is the Mach number in a plasma with $\beta > 1$, $v_A = H_0/\sqrt{4\pi n_0 m_i}$; $H_0$ and $n_0$ are the unperturbed values of the magnetic field and plasma density before the shock wave front.

Let the wave propagate along the $x$-axis and the magnetic field be directed along the axis $z$ (Figure 1). Then protons with velocities close to that of a shock wave, $u$, will be reflected from the potential hill, come back again by the magnetic field to the front and then be reflected again, etc. As a result of successive reflections, a particle acquires a great velocity along the $y$-axis, namely, in the front plane and across the magnetic field $\mathbf{H}$. The path of an accelerated proton is shown in Figure 1. The velocity along the $y$-axis will increase until the Lorentz force $(e/c)v_y H$ exceeds the reflection force $-e \nabla \varphi$ in the region of the potential hill. In this case a particle is pulled through