Post-Eruption Particle Acceleration in the Corona: A Possible Contribution to Solar Cosmic Rays

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Abstract

We argue that the post-eruption energy release following large coronal mass ejections at the late phase of complex flares appears to be an effective source of prolonged particle acceleration up to high energies side by side with the primary flare energy release and coronal/interplanetary shock waves. It may give a visible contribution to the 10–30 MeV proton fluxes in the interplanetary space as well as to the solar cosmic ray ground level enhancements with a complicated time profile. This statement is grounded in particular by the analysis of recent measurements of prolonged and high energy γ-ray and neutron flare emissions.

1 INTRODUCTION

Only two acceleration processes are considered usually as sources of solar energetic particle (SEP) events at 1 AU: 1) an impulsive (primary) flare energy release in the upper chromosphere or lower corona; 2) a gradual acceleration in coronal/interplanetary shocks driven by large and fast coronal mass ejections (CMEs). Moreover, a point of view exists that in ground level events (GLEs) the escaping high-energy particles are produced in shocks only, but not in a region of the primary energy release (see [1] and references therein). Meanwhile, there is one more plausible source of the energetic particle acceleration on the Sun also closely associated with CMEs.

A large CME, propagating through the corona, strongly disturbs the coronal magnetic field in an extended region. After the passage of a CME, the disturbed magnetic field relaxes to its initial state via magnetic field reconnection in a quasi vertical current sheet. This process is accompanied by the prolonged post-eruption (PE) energy release, the effective particle acceleration, the generation of long-duration emissions in the X-ray, microwave and other ranges, the formation of the post-flare loops, giant arches, and so on (e.g. [2]).

In this paper we will outline some results of analysis of the recent high-energy γ-ray and neutron measurements revealing that the post-eruption energy release appears to be accompanied by a prolonged particle acceleration including protons up to GeV energies. Then some evidences will be presented testifying that the post-eruption particle acceleration can give a visible contribution to interplanetary and ground-level cosmic rays.

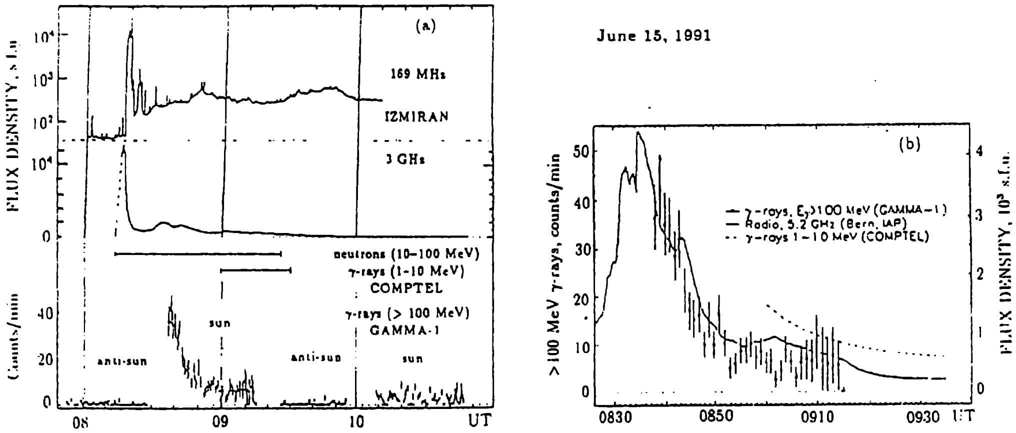

Fig. 1. Temporal development of the June 15,1991 flare: (a) a general sketch of the radio and neutral emissions; (b) the enlarged γ-ray and microwave time profiles of the delayed component (see [4]).

2 PROLONGED HIGH-ENERGY PARTICLE ACCELERATION

Six very powerful homologous flares occurred during the first half of June, 1991 in the NOAA AR 6659, and in three of them the unusually long and high-energy neutral emission was measured (e.g. [3]). A pion decay γ-ray emission with energies up to 1–2 GeV and duration of 2 and 8 hours was observed on 15 and 11 June (Figure 1,2a) aboard the GAMMA and CGRO satellites [4,5,6]. In the event of 4 June (Figure 2b), a long-duration emission of 0.1–3 GeV neutrons was recorded on the Norikura neutron monitor [8]. Besides, all these flares were accompanied by the prolonged γ-ray line emission.

The time profiles, in particular of microwaves, reveal that the energy release in these flares includes two main components: the very strong impulsive one and the relatively less intense, but sufficiently large, delayed component separated by a time interval of 15–70 min. The features of the delayed components allow us to identify them with the PE energy release [3].

One can see that in each of these flares a notable similarity takes place between time histories of the different emissions, in particular for the delayed components. This means, that the various emissions observed well after the impulsive phase, appear to be initiated by the prolonged nonstationary acceleration of electrons and ions up to high energies directly during the late phase of the flares rather than by a long-term trapping of particles accelerated at the flare onset [3,4,7,9].

The PE energy release is the most probable source of such acceleration [3,4]. The theoretical study [10] also shows that a direct electric field in a reconnecting current sheet, which forms in the corona at the PE phase, can indeed result in a prolonged particle acceleration, in particular of protons to GeV energies.

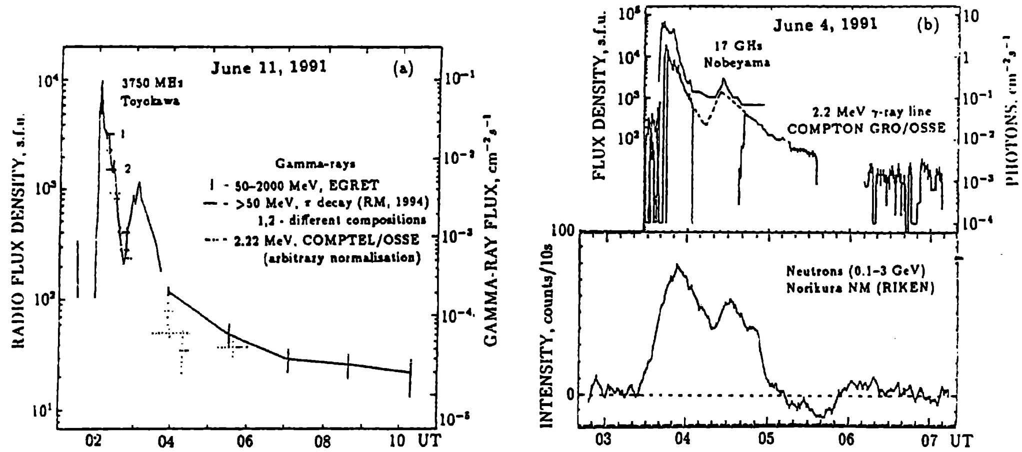

Fig.2. Time profiles of the microwave bursts and the neutral emissions: (a) the June 11, 1991 flare [3,6,7]; (b) the June 4, 1991 flare (adapted from [8]).

3 SIGNATURES OF THE PE ACCELERATION IN COSMIC RAYS

According to [11,12], there are so called surplus SEP events in which the 10–30 MeV proton flux in the interplanetary space is considerably enhanced in comparison with the average particle flux for a given electromagnetic emission of a parent flare. Many of such events display also a large time delay ($\Delta t \geq 10$ h) of the 10 MeV proton flux maximum relatively a flare. Basing on these and other characteristics, it was argued that SEP events of this class are closely associated with the PE particle acceleration. An important additional effect should be taken into account: particles accelerated in the process of the PE energy release may be trapped inside a propagating CME and then leak out gradually into the interplanetary space.

Regarding high-energy GLEs, the June 4, 1991 flare (Figure 2b) give a clear evidence that the PE acceleration can produce energetic ions contributing to the neutral (i.e. neutron) component of solar cosmic rays. Essentially, the estimations [8] showed that the second (we mean the post-eruption) component of neutrons had a harder spectrum than the first (impulsive) one.

A.Belov (see [4]) obtained the similar result for protons. Analyzing the June 15, 1991 event, he showed that a sufficiently good agreement between observed and calculated differential time profiles of protons is obtained for relatively low energies (up to ~200 MeV), if an ejection function is identified with the whole microwave burst including both the impulsive and delayed components. However for GeV energies, the best agreement takes place when the delayed component only is considered as the ejection function.

The microwave burst of the famous flare of Sept. 29, 1989 indicates that in this case also the energy release included the impulsive and post-eruption

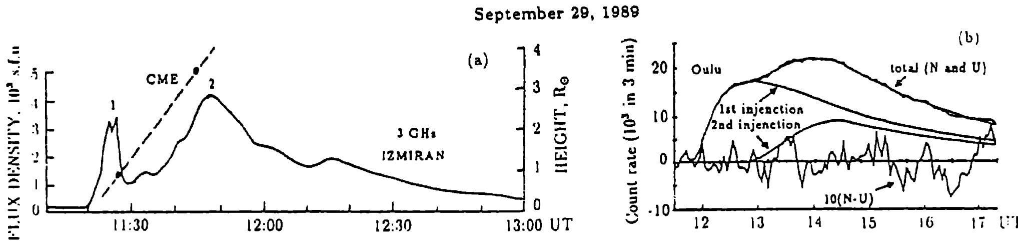

Fig. 3. Time history of the Sept. 29,1989 flare: (a) the high-time trajectory of the CME and the microwave burst with the impulsive (1) and post-eruption (2) components; (b) the two-component profile of the GLE [13].

components (Figure 3a). According to [13], the GLE, associated with this flare, also seems to reveal two subsequent particle ejections from the Sun with a time difference of several tens of minutes (Figure 3b). It is reasonable to associate these ejections with the impulsive and PE particle accelerations.

Thus we may conclude that the PE energy release following a CME is important not only for various phenomena on the Sun but also for solar cosmic rays. It should be taken into account in studies of the both SEP events and GLEs alongside with the impulsive and shock wave acceleration. Some additional illustrations of such an approach are given in [14].

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