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Post-Impulsive-Phase Acceleration of >10 MeV Protons

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Abstract

We review first several hours of post-impulsive-phase acceleration of high-energy particles in 9 different solar eruptions. Interplanetary proton and electron observations are employed along with data on secondary neutrons and γ-rays. Also employed are extreme ultraviolet, microwave and low frequency radio observations. We conclude that the post-impulsive-phase acceleration takes place close to Sun, at heliocentric distances about or below two solar radii, and may be associated with CME lift-off.

1 Introduction:

It is generally accepted that the energetic protons can be rapidly accelerated during a flare at the Sun or, on much longer time scales, by the CME-driven shock waves traveling in the interplanetary medium (Reames 1996 and references therein). Continual acceleration at intermediate time and spatial scales cannot be ruled out either (Klein et al. 1996). Traveling interplanetary shocks are frequently associated with enhancements in solar energetic particles. While these observations indicate that shocks are capable of energetic proton production, the scenario and other properties of the acceleration are not completely understood. In particular, interplanetary shock acceleration may not be efficient enough to accelerate ions from the solar wind, and a seed population may be needed. Potentialities of CMEs to produce energetic particles in the interplanetary medium may also crucially depend on the previous evolution of solar eruption at heliocentric heights of less or about two solar radii (Torsti et al. 1999a and references therein). If so, more attention should be paid to the early phase of CME-associated solar particle events.

2 Flares with Extended Production of Neutrons and Gamma-Rays:

We start with analysis of two powerful solar flares, impulsive and gradual, for which not only interplanetary but also interacting protons were comprehensively covered.

2.1 The 24 May 1990 flare: An outstanding high-energy neutron event and west flare of 24 May 1990 have been studied in a number of papers (for a comprehensive reference list see Kocharov et al. 1996). That was an impulsive flare, but much more powerful in production of high-energy particles than a typical impulsive solar flare. The flare started with a short impulse of X- and γ-ray emissions. A simultaneous impulsive production of high-energy neutrons was responsible for a fast rise of the Climax neutron monitor count rate. This impulse of nuclear interactions was followed by a more prolonged production of neutrons detected also by the Mexico City neutron monitor. Concurrent injection of interplanetary protons during ~1–1.5 hours was responsible for the first peak in the GOES proton count rates (Fig. 2). The number ratio for concurrently produced interplanetary and interacting >600 MeV protons was estimated to be not very large, ~1–2. This ratio may be considered as indication that protons were accelerated not very far from the Sun, at heliocentric distances below 3 solar radii. The first proton production was accompanied by a concurrent Type IV radio burst. Observed Moreton wave velocity suggests that acceleration of the first interplanetary protons started below 2 solar radii. Neither near-Sun shock nor stochastic acceleration can be ruled out as a source of this first component of interplanetary protons (see also reports by L. Kocharov & G. Kovaltsov and by R. Vainio & L. Kocharov in this volume). About 2 hours later, a second injection maximum occurred. A CME-driven bow shock acceleration is a generally accepted source of this second interplanetary proton component.

2.2 The 15 June 1991 flare: In June 1991 the Sun produced a famous series of six powerful flares. For the gradual flare on 15 June 1991 there exists a rich set of measurements, including in particular γ-ray and neutron observations of the COMPTEL instrument on board the CGRO satellite (Kocharov et al. 1998 and references therein). The γ-ray and neutron emissions indicate prolonged acceleration of protons well after the impulsive phase of the flare. Some accelerated particles interact with solar matter and produce γ-rays and neutrons at the Sun, others escape into the interplanetary medium. The low-energy γ-ray and neutron results of COMPTEL are consistent with a proton power law spectrum with index 3.3 ± 0.1. To simultaneously fit the high-energy γ-ray measurements on board the GAMMA-1 satellite, the spectrum must steepen at a few hundred MeV and then become harder again to produce a detectable amount of GeV photons. Although the degree of steepening is composition dependent, the deduced spectrum of interacting protons is qualitatively invariant in the entire parameter region $\alpha/p \leq 0.5$ (in the gradual phase at E~100 MeV/nucl.). Deduced hard-steep-hard energy spectrum of interacting protons suggests for us presence of two proton components in corona during at least one hour period after the impulsive phase. A number of CME signatures has been also reported for this flare.

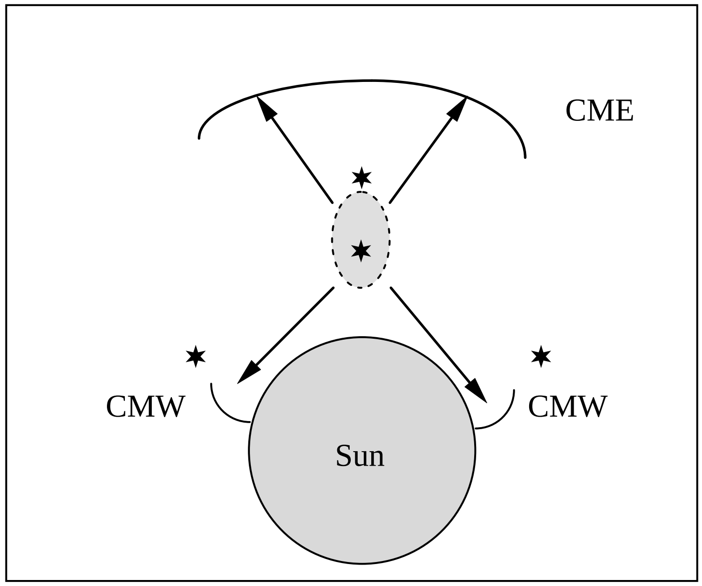

Figure 1: Illustration of EIT observed coronal Moreton waves (CMW), compression fronts caused by an impulse delivered during CME lift-off. Asterisks mark possible post-impulsive-phase acceleration sites.

3 SEPs From Angle-Distant Solar Eruptions:

Near-Earth observations of interplanetary particle events caused by east, central meridian or beyond the west limb eruptions (flares and/or CMEs) revealed that the proton acceleration at the root of the interplanetary magnetic field (IMF) line well-removed from the eruption center often starts in ~0.5–1 hour time, and properties of this first acceleration differ much from the later major proton production.

3.1 Eruptions near the central meridian in January-May 1997: During the period from January through mid-May, 1997, four large Earth-directed CMEs were observed by LASCO on board SOHO. These CMEs were associated with long-lasting fluxes of ~1 to 50 MeV protons detected by the Energetic and Relativistic Nuclei and Electron instrument (ERNE) on board SOHO. However, the magnitudes of energetic proton events differed dramatically on different occasions. In strong proton events, production of >10 MeV protons was associated with soft X-ray flares and Type II/IV radio bursts, and started during expansion of the EIT observed coronal Moreton wave in the western hemisphere of the Sun. The new SOHO observations suggest that potentialities of CMEs to produce energetic particles in the interplanetary medium crucially depend on the previous evolution of solar eruptions below two solar radii (Torsti et al. 1998).

3.2 Behind the limb event on 13 August 1996: The onset of the >10 MeV proton event of August 13–14, 1996 revealed a velocity dispersion which is a signature of its solar origin, but no associated soft X-ray flare was observed. The LASCO CME observations and the presence of AR 7981 beyond the west limb indicate that the parent solar eruption may be centered on the back side of the Sun, at about 150°W. In such a case, expanding CME–associated coronal Moreton wave (Fig. 1) can reach the Earth-connected IMF line in about one hour and so give rise to the >10 MeV proton event observed with the ERNE instrument onboard SOHO. We verified this hypothesis against observational data and concluded that a solar back side eruption is the most plausible explanation of the August 13, 1996 event (Torsti et al., 1999b). Comparison of the August 13, 1996 event with events associated with Earth-directed CMEs, shows that the August 13, 1996 event revealed many properties common to >10 MeV proton events originating from solar eruptions centered ~90° away from the root of the Earth-connected IMF line. In such events, the first injection spectrum is essentially harder than the spectrum at the intensity maximum, *i.e.* the hard but less intensive proton production is followed by the major soft-spectrum production when CME expands farther away from the Sun.

3.3 The 24 September 1997 event: The EIT and ERNE observations of this event (Torsti et al. 1999a) revealed the first injection of >10 MeV protons at the root of Earth-connected IMF line during the period when the coronal Moreton wave was traversing the western hemisphere of the Sun, being an early signature of the CME launch. Acceleration of the CME-associated protons starts during the CME lift-off, while the main proton production occurs several hours later, when the CME expands in the interplanetary medium. Development of proton spectrum and anisotropy indicates that the proton production starts with a less intensive but hard-spectrum injection which is followed by a more intensive but soft-spectrum injection farther from the Sun (see Fig. 3). Our observations lend a new support to the early finding by Cliver et al. (1995) that a rapid proton access to well-removed coronal longitudes (>100°) occasionally corresponds to the visible chromospheric Moreton waves.

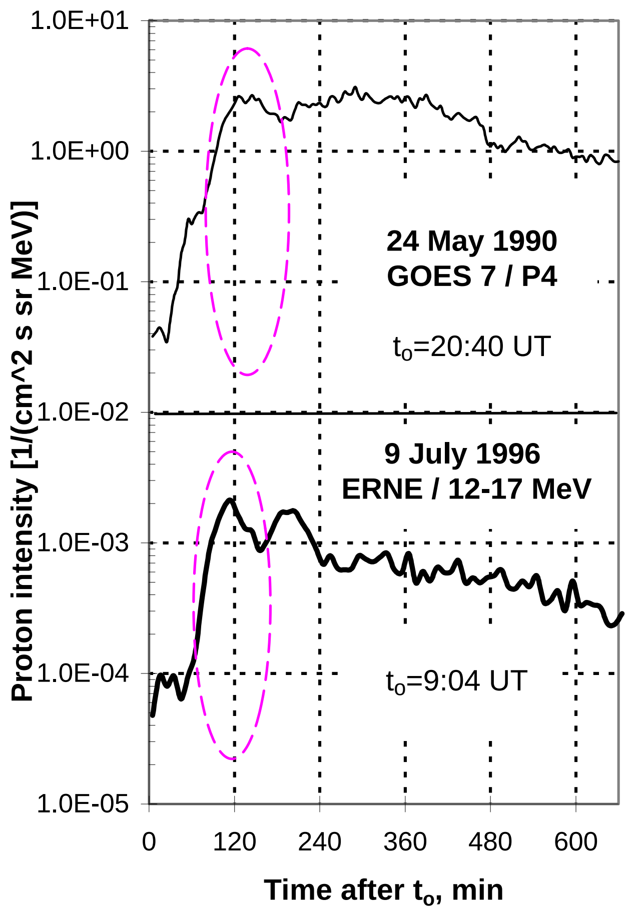

Figure 2: Development of ~ 15 MeV interplanetary proton intensity for two west flares. The first period production is encircled.

4 The 9 July 1996 Flare:

Figure 2 shows intensity of 12−17 MeV interplanetary protons associated with a west flare of 9 July 1996 observed by the ERNE/SOHO instrument. The intensity-time profile is similar to that for the 24 May 1990 flare, but the 9 July 1996 event was almost three orders of magnitude weaker. Almost scatter-free proton transport in this event essentially reduces uncertainties in the proton injection scenario. A study of the first period of acceleration in this event indicates that (1) a majority of ~0.5 MeV electrons registered by COSTEP on board SOHO was impulsively accelerated ≈0.3 hour after the start of impulsive phase, simultaneously with one of the Type III radio bursts detected on board WIND, while (2) the >10 MeV proton acceleration peaked nearly 0.5 hour later than the major electron acceleration, and (3) a CME distance from the flare cite (Pick et al. 1998) at the time of the first proton injection maximum did not exceed ≈1.5 solar radius.

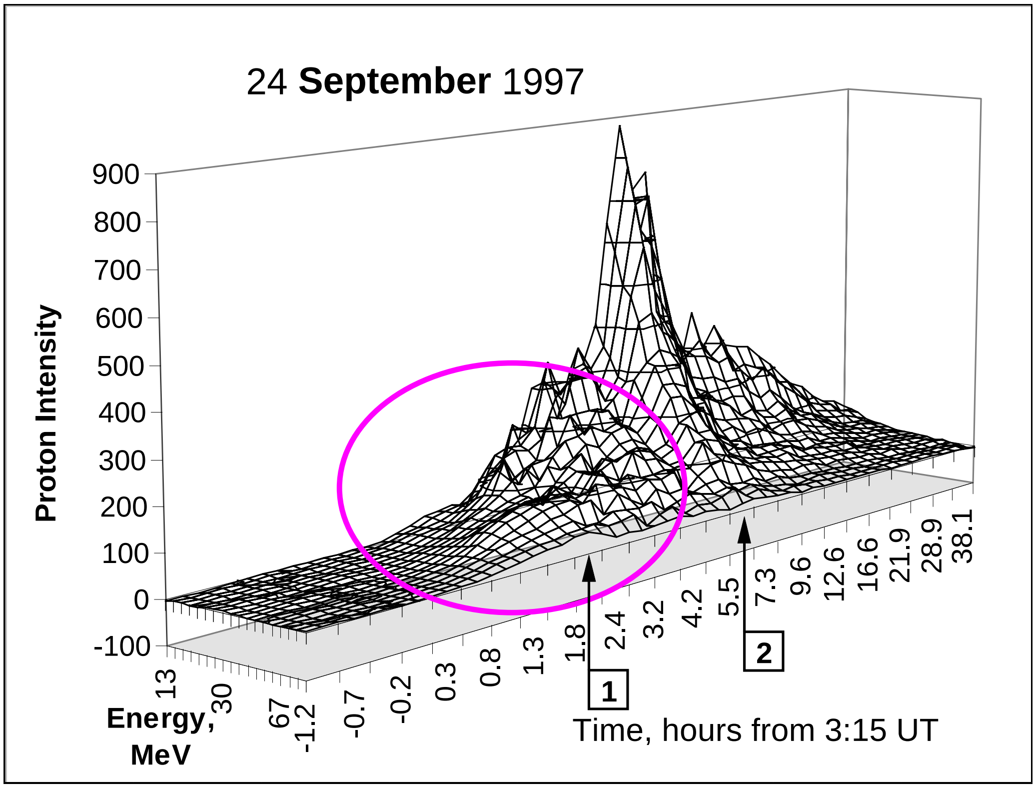

Figure 3: Illustration of the event caused by an angle distant solar eruption. Arrows 1 and 2 indicate peak anisotropy times in the 14−35 MeV proton channel (Torsti & Sahla, 1998). Ellipse encircles the first component of proton production associated with EIT observed coronal Moreton wave. The time axis is not uniform.

5 Conclusion:

Interplanetary particle observations as well as observations of high-energy neutrons and γ-rays suggest that >10 MeV proton are continuously accelerated during the first hours after impulsive phase of many solar flares. This acceleration precedes a major CME-driven interplanetary shock acceleration. The first period production is often not weaker than the latter one, especially for high-energy protons. The first acceleration is accompanied by coronal radio emissions, especially Type IV bursts, and associated with EIT observed Moreton waves expanding in longitude and latitude in solar corona. It suggests for us that this acceleration may be associated with CME launch and takes place close to Sun, at heliocentric distances about or below two solar radii. An extended and fragmented acceleration region seems necessary to explain a variety of proton and electron productions actually observed as a solar eruption develops in solar corona and farther into the interplanetary medium

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