Proceedings of ICRC 2001: 3277 © Copernicus Gesellschaft 2001

ICRC 2001

Particle injection in the 6 November 1997 SEP event: CME, radio and gamma-ray observations

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Abstract. The 6 November 1997 solar energetic particle (SEP) event exhibited charge state dependence on energy with Fe having a mean charge state of $\sim$ 18-21 at energies $>$ 10 MeV amu^{-1}. We review the CME, radio, and gamma-ray observations of the associated solar event to gain insight into the origin of this behavior. The CME was rapidly accelerated low in the corona (to speeds $\sim$ 2000 km s^{-1} within $\sim$ 4 x 10^5 km of the solar surface), consistent with the proposed picture in which the observed Fe ions are accelerated by a CME-driven shock (indicated by a metric type II burst) and further stripped as they propagate through the low corona. The situation is ambiguous, however, in that the period when the CME/shock is at the required altitude/density for the stripping scenario to occur corresponds to the peak of the gamma-ray burst and low frequency radio emission of the associated flare, providing evidence for an alternative (or contributing) source of SEPs.

1 Introduction

The 6 November SEP event is one of the more thoroughly examined events of the present cycle. Various studies have analyzed its electromagnetic emissions (radio (Maia et al., 1999; Reiner et al., 2000), X-ray (Sato et al., 2000), and gamma-ray (Yoshimori et al., 1999, 2001)) and CME characteristics (Delanée et al., 2000; Zhang et al., 2001), as well as the particle event itself (e.g., Mason et al., 1999a; Cohen et al., 1999a,b; Möbius et al., 1999; Leske et al., 1999; Mazur et al., 1999; Torsti et al., 2000; Falcone et al., 2001). The event was remarkable for its intense gamma-ray emission [one of the largest events of the current cycle], fast coronal mass ejection [peak speed $\sim$ 2200 km s^{-1}], hard particle spectrum [>5 GeV particles detected by Milagrito], and high Fe charge state at [$<Q> = 19.5 \pm 2$ at $\sim$ 10-60 MeV, unexpected in a large "gradual" SEP event (e.g., Reames, 1999)]. In this study we focus on the high observed Fe charge states. Various explanations have been suggested: (1) electron stripping of Fe ions following shock acceleration low in the corona (Reames et al., 1999); (2) the high $<Q>$ Fe ions could be flare-accelerated particles (e.g., Cohen et al., 1999a); (3) shock acceleration of seed Fe ions that were previously accelerated during impulsive flares and injected into the interplanetary medium (Mason et al., 1999b). Other processes such as rigidity-dependent acceleration (Oetliker et al., 1997), concurrent charge-changing and acceleration (Barghouty and Mewaldt (2000), and photo-ionization by flare X-rays (Mullan and Waldron, 1986) could also play a role. As a point of departure for the present study, several authors (Ostryakov and Stovpyuk, 1999; Barghouty and Mewaldt, 2000; Kocharov et al., 2000; cf., Reames et al., 1999) have used the charge state variation with energy in this event to constrain the density/altitude of the acceleration region to values $\sim 10^9$ cm^{-3} and $\sim$ 0.1-1.0 $R_\odot$ ($\sim 10^5$-10^6 km above the solar surface). We review the SOHO CME and ground-based metric radio observations for this event to see if they are consistent with shock acceleration at these heights. We then consider a potential flare source of SEPs in this event via *Yohkoh* gamma-ray and Wind/WAVES decametric radio emissions.

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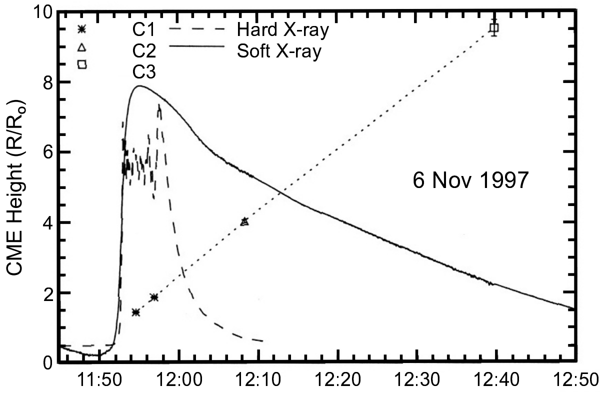

Fig. 1. Height-time plot of the LASCO observations of the 6 November 1997 CME, shown with *Yohkoh* hard X-ray (saturated at maximum) and GOES soft X-ray time profiles. (From Zhang et al., 2001.)

2 Analysis

2.1 CME and Coronal Shockwave

CME observations for this event have been presented by Maia et al. (1999) and Zhang et al. (2001). Fortuitously, the inner C1 coronagraph on LASCO with occulting disk at 1.1 $R_\odot$ was operating for this event and the cadence was optimal, with a pre-event image taken at 11:52:13 UT, only $\sim$ 2 minutes prior to the appearance of the CME above the occulting disk at 11:54:34 UT. The flare was located near the limb at S18W63. The height-time plot of the CME, along with the GOES soft X-ray and *Yohkoh* hard X-ray (HXT) flare curves, is given in Figure 1 (Zhang et al., 2001). The reported acceleration in this event was extremely large, 7,300 m s^{-2} compared with typical impulsive acceleration values of 100-500 m s^{-2}. Taking projection effects into account, we calculate that the CME leading edge reached a radial height of 10^5 km above the solar surface after 11:51.8 UT and an altitude 1 $R_\odot$ at 11:57.6 UT. Radio observations of this event from Potsdam reveal a type II like feature with a high starting frequency of $\sim$ 250 MHz starting at 1153.2 UT when the CME leading edge was at a radial height of <3 x 10^5 km, within the range required by stripping models. As we will see below, however, constraining the acceleration to low altitudes introduces an ambiguity with the flare as a source of the high-charge-state particles.

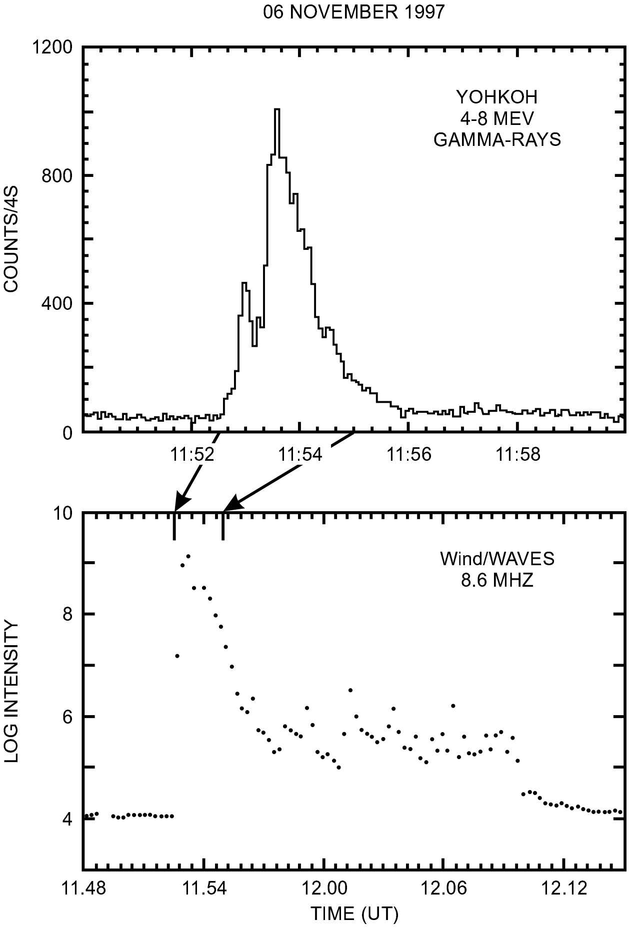

Fig. 2. Top. The 4-8 MeV gamma-ray line profile of the 6 November 1997 event from *Yohkoh*. Bottom. The corresponding 8.6 MHz radio emission measured by the Wind/WAVES experiment.

2.2 Gamma-ray and Low-frequency Radio Observations

In Figure 2, we compare the *Yohkoh* 4-8 MeV gamma-ray time profile (top panel) with the time-intensity trace at 8.6 MHz (corresponding to a nominal height of 3 $R_\odot$ from Sun center) in the bottom panel. The 4-8 MeV gamma-ray emission indicates the presence of >10 MeV protons bombarding C,N,O ions in the low solar atmosphere. The peak in the radio emission corresponds to low-energy (5-50 keV electrons) that are streaming freely outward through the corona (type III bursts). Thus there is evidence for particle escape during the time that a large population of flare-accelerated particles exists in the low solar atmosphere. Studies of the composition of the interacting (gamma-ray producing) solar particles reveals a composition similar to that observed in space following impulsive flares (e.g., Murphy et al., 1991; Ramaty et al., 1993; Mandzhavidze et al., 1999). Cohen et al. (1999b) reported an “impulsive” high-Z composition for the 6 November SEP event. Therefore it is difficult to rule out a flare contribution for this event since such particles are observed to escape from the Sun following much smaller (non-CME associated) flares. Following Cliver et al. (1989), we calculate that $\sim$ 40% of the interacting $\sim$ 10 MeV particles would have had to escape the gamma-ray source to account for the $\sim$ 10 MeV SEP event, based on: the 4-8 MeV fluence of 168 $\pm$ 27 photons cm^{-2}, the peak 9-23 MeV SEP flux of 23 protons cm^{-2} sr^{-1} sec^{-1} MeV^{-1}, and the assumption of isotropic diffusion. A more realistic propagation assumption will reduce this 40% figure, perhaps by as much as a factor of 10 (von Rosenvinge et al., 1981).

3 Discussion

For large SEP events, shock acceleration easily solves the fast propagation problem and naturally accounts for the low Fe charge states (11-14) observed at low energies. The presence of high Fe charge states ($\sim$ 19)in events such as 6 November 1997 indicates acceleration (via shocks or flare particle acceleration process(es)) much deeper in the solar atmosphere. The source densities of $\sim 10^9$cm^{-3} that have been deduced for this event correspond to heights $\sim 10^5$ above the solar surface. Radio evidence exists that a CME-driven shock was operating in this general altitude range, consistent with the notion that all large SEP events are shock-dominated. The situation is not clear-cut, however, because certain aspects of this presumably “gradual” event are more characteristic of “impulsive” SEP acceleration. In addition to the high Fe charge states at $>$ 10 MeV energies, the high-Z composition of this event was similar to that observed in impulsive events (Cohen et al., 1999b) that are attributed to solar flares. The flare itself (Figure 2) was impulsive, with a soft X-ray duration at 10% of its peak intensity of $<$ 1 hour, and the e:p ratio was high ($\sim$ 130), a further signature of impulsive acceleration (Kallenrode et al., 1992). The ^{3}He:^{4}He ratio in the 6 November event (Mason et al. 1999b) was enhanced by a factor of $\sim$ 5 above average solar wind values, but well below the 0.1 nominal cutoff for impulsive events. Reames et al. (1988) showed that the ^{3}He:^{4}He ratio in impulsive events varies inversely with flare size. Reames et al. (1994) suggested that in big events, such as 6 November, depletion of the ^{3}He ions available for acceleration might drive down the ratio. In addition, we would expect the degree of enhancement to be less in mixed events where the low energy part of the spectrum might be dominated by shock acceleration. Alternatively, the ^{3}He:^{4}He ratio enhancement could result from the pre-existing seed population picture proposed by Mason et al. (1999b), although it is uncertain that this scenario could account for the high-Z abundance variations and energy-dependent charge states observed in the 6 November event.

A SEP event that lacked charge state data but had similar composition was observed on 3 June 1982 (Van Hollebeke et al., 1990). Like the 6 November 1997 event (Mason et al., 1999a; Yoshimori et al., 1999), the 3 June event had an unusually hard proton spectrum and was associated with an intense gamma-ray burst. The type II starting frequency was 140 MHz, relatively high in comparison with all type IIs, but lower than that of 6 November 1997. For 3 June 1982 and two other GLEs, Lockwood et al. (1990) deduced that the first arriving 50 MeV protons were injected at least 5 minutes earlier than the first GeV protons. From Milagrito observations for the 6 November event, Falcone et al. (2001) obtained a GeV onset time of 12:07 ± 6 UT. Assuming a similar delay of GeV protons relative to lower energy protons for the 6 November event as inferred for the June 1982 event and a 1.3 AU spiral path length (no scattering) yields a $\sim$ 50 MeV injection onset time range at the Sun from 11:45.2 - 11:57.2 UT relative to the type II onset time of 1144.9 UT and the gamma-ray burst duration of 11:44.5 - 11:46.7 UT. Any scattering will move the injection range of $\sim$ 50 MeV protons closer to the times of the type II bursts and gamma-ray emissions, although it will not resolve the ambiguity between these possible sources. Determinations of the injection times of energetic particles for the 6 November 1997 event by Krucker et al. (1999) ($>$ 25 keV electrons at 12:16 UT) and Torsti et al. (2000) (20-30 MeV amu^{-1} particles at 12:30-12:40 UT) cannot be easily reconciled with the low source heights required by the various models that have been proposed to account for the energy-dependent charge states.

Events such as 6 November 1997 are of interest because of the constraints they place on the SEP source region. They suggest that in some cases flares may play a more important role in large SEP events than is currently thought, either through direct acceleration of SEPs or as a source of seed particles for the shock. How common are events like 6 November? To what do they owe their composition and charge characteristics? Which variables (e.g., flare location, flare duration, type II starting frequency, inferred injection onset times, gamma-ray emission) are essential to their understanding and which are red herrings? Clearly more work is needed to answer questions such as these.

Acknowledgements. O.C.St. Cyr acknowledges partial support from NSF grant ATM-9819668 and NASA contract S-86760-E. Ed Cliver thanks S. Krucker, A. Tylka, and J. Zhang for helpful discussions.

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