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Re-examination of the October 20, 1989 ESP event

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Abstract. The energetic storm particle (ESP) event of October 20, 1989 has often been cited as an example of high-energy ($\gtrsim$500 MeV) proton acceleration at the arrival of a CME-driven shock at the earth. In this paper we re-examine high-time resolution solar wind, magnetic field, and energetic proton data from the IMP-8 spacecraft. We conclude that the high-energy proton population observed around the shock passage is not a locally shock-accelerated population, but rather a population confined and channeled by a complex magnetic field structure formed in front of the shock.

1 Introduction

Intensity increases of energetic charged particles in association with the passage of interplanetary shocks have historically been called Energetic Storm Particle (ESP) events. The earliest studies of these events indicated two possible origins for such intensity increases. While Axford and Reid (1962) suggested that these increases resulted from particle acceleration at the shock front, Bryant et al. (1962) pointed out the possibility that energetic particles were trapped in the vicinity of the shock. The present paradigm for solar energetic particle (SEP) events assumes that particles undergo continuous and gradual acceleration by shock waves that propagate outward from the Sun and are driven by fast coronal mass ejections (CMEs). Therefore, particle intensity increases observed around the time of the shock passage are composed not only of particles locally accelerated at the shock, but also of particles previously accelerated and that, by different mechanisms, remain confined around the shock.

Particle scattering by self-generated Alfvén waves has been invoked as a mechanism for trapping particles around the shock front (see discussion in Reames, 1999). However, other mechanisms, as for example complex magnetic and plasma structures in the vicinity of the shock, may also contribute to the confinement and trapping of energetic particles. Therefore, the intensity-time profiles of the ESP events are functions not only of the shock's efficiency for accelerating particles, but also of the transport conditions in the upstream and downstream regions of the shock (Kallenrode, 1995). Observations at 1 AU show that the intensity of ESP events varies from event to event and decreases with increasing energy (van Nes et al., 1984). Typically, ESP events have significant intensity increases for protons with energies from a few tens of keV to some tens of MeV (Kallenrode, 1995); being rare increases in the $\gtrsim$100 MeV range (Reames, 1999).

2 The ESP event on October 20, 1989

On October 20, 1989 an ESP event was observed at exceptionally high energies. There were abrupt and simultaneous rises in all energetic proton channels (from $\gtrsim$4 MeV to 500 MeV) of the GOES spacecraft. This ESP event was superimposed on one of the largest SEP events observed during solar cycle 22 (Lario et al., 2001). In fact, the $\sim$50–100 MeV proton intensities at the time of this ESP event were the highest observed by IMP-8 during all of solar cycle 22 (Lario et al., 2001). An X13/4B solar flare was most probably related to the origin of the SEP event (Shea et al., 1991). This solar flare occurred on October 19 in the NOAA active region 5747 located at S27°E10°, with Hα onset at 1229 UT and maximum at 1259 UT (Shea et al., 1991). The October 19 solar event produced intense electromagnetic emissions from the radio to the gamma-ray domains (Klein et al., 1999). Unfortunately, the SMM coronagraph was not operating before 1603 UT, so no CME was observed at the time of the solar event. However, the arrival of ejecta material at earth on October 21 (identified by Cane and Richardson, 1995) suggested that an earth-directed CME occurred at the time of this flare.

Figure 1 shows 5-minute averages of the proton intensities detected by the GOES-7 spacecraft (in geosynchronous orbit) during this SEP event. Proton intensities have been corrected for counts generated by particles entering through secondary energy passbands (R. Zwickl, private communication, 2000). The dotted line indicates the time of the si-

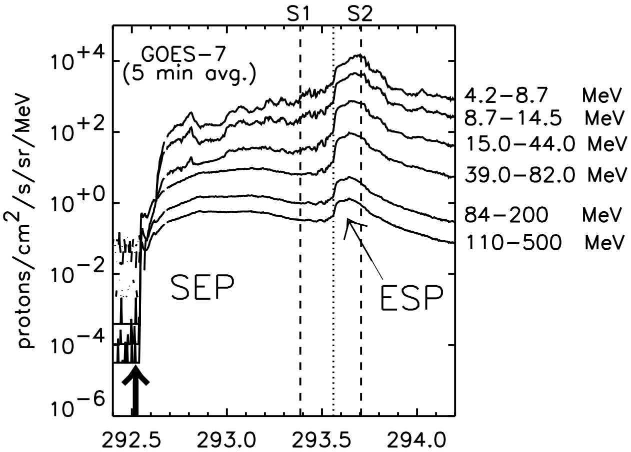

Fig. 1. GOES-7 proton observations of the 19-21 October 1989 event. The vertical arrow indicates the time of the solar event, the dashed vertical lines identify the arrival of interplanetary shocks and the dotted line the onset of the ESP event.

multaneous abrupt increase in the proton intensities that constituted the onset of the ESP event. Dashed lines mark the arrival of interplanetary shocks (S1 and S2) at the IMP-8 spacecraft (see discussion below). Although low-energy ($\lesssim$8 MeV) proton intensities peak at the arrival of the second shock S2, high-energy ($\gtrsim$39 MeV) proton intensities show a clear decrease even before the arrival of S2. Energetic particle data from the GOES spacecraft for this SEP event have been analyzed elsewhere (see for example Anttila et al., 1998; Klein et al., 1999; Reames, 1999). We refer to these papers for a global description of the SEP event; however, we are not aware of any previously published work that analyzes this ESP event in detail.

Figure 2 shows solar wind speed V_{SW}, solar wind density n_{SW}, magnetic field magnitude B, and the 48.0-96.0 MeV proton intensity measured at IMP-8 during October 20, 1989 (doy 293). IMP-8 was upstream of the earth's bow shock during this period. Energetic proton data are from channel P9 of the CPME instrument (Sarris et al., 1976). Channel P9 did not saturate even at the time of the highest particle intensity. Unlike the other CPME proton channels, P9 survived these high intensities due to a fortunate combination of energy discrimination logics as defined for each channel of the solid-state detector telescope. A first shock S1, indicated by the first dashed line in Fig. 2, was observed at 0916 UT (Cane and Richardson, 1995). This shock did not produce any significant effect on the already elevated high-energy ($\gtrsim$15 MeV) proton intensities (as seen in Fig. 1 and Fig. 2). In the downstream region of this weak shock S1, B increased gradually, reaching a maximum of 35 nT at $\sim$1325 UT. During this period, V_{SW} and n_{SW} showed a less pronounced increase. Then an abrupt decrease of B coincided with the simultaneous increase by a factor of $\sim$5 of the 48.0-96.0 MeV proton intensity (dotted line in Fig. 1 and Fig. 2). Both B and n_{SW} reached minima at $\sim$1520 UT, when the high-energy proton intensities were already decreasing. The slow increase of n_{SW} and B at $\sim$1650 UT has been identified as an interplanetary shock (Cane and Richardson, 1995), denoted as S2 in Figure 2. We note that the jump in V_{SW} during this shock was only a factor of $\sim$100 km s^{-1}, which, relative to typical shocks observed at 1 AU, is a weak shock. We also note that all the solar wind and magnetic field parameters increased in a gradual and slow transition; shocks observed at 1 AU usually show faster and more abrupt transitions. The arrival of this shock did not produce any effect on the high-energy ($\gtrsim$39 MeV) proton intensities, which were already decreasing at a rate which remained constant throughout the decaying phase of the SEP event. Thus, neither shock S1 at 0916 UT nor shock S2 at $\sim$1650 UT produced a local variation in the high-energy proton intensities.

Cane and Richardson (1995) have studied IMP-8 particle and plasma data together with neutron monitor data and concluded that the shock S2 observed at $\sim$1650 UT was associated with the solar event on October 19 (average transit speed of $\sim$1480 km s^{-1}). Following this shock a CME structure was observed on October 21. Cane and Richardson (1995) concluded that the first shock S1 at 0916 UT was followed $\sim$5 hours later by a region indicative of CME material with a duration of only $\sim$2 hours (see Figure 5 in Cane and Richardson, 1995). A sudden storm commencement at $\sim$1000 UT on October 20 was associated with the arrival at the earth of the shock S1 and its ejecta. The solar origin of this first ejecta and associated shock has not been identified (Cane and Richardson, 1995). Presumably another solar event from the same active region 5747 (which showed evidence of intense activity on October 18-19) was responsible for its origin. However, an obvious and unique association has not been found (Cane and Richardson, 1995). This solar event did not affect significantly the energetic protons observed at 1 AU, neither during its outward expansion from the Sun, nor at its arrival at earth. While the shock S1 did not affect energetic proton intensities, the arrival of the ejecta material which drove this first shock evidently had important consequences for the development of the ESP event.

The abrupt and simultaneous increase of ($\gtrsim$4 MeV) proton intensities at energies from $\sim$ 5 to $\sim$500 MeV (Fig. 1) occurred in near coincidence with the arrival of the complex plasma structure formed in the downstream region of the first shock S1 (Fig. 2). We believe that the intense ESP event on October 20 was produced by this structure, which formed in front of S2 and behind S1, and was not due to local acceleration of particles by these two shocks. In fact, the high-energy ($\gtrsim$39 MeV) proton intensity maxima were not observed at the time of the shock passages. Rather, the simultaneous increase of the proton intensities (dotted line in Fig. 1 and Fig. 2) was observed in temporal coincidence with the rapid decrease of the enhanced B downstream of shock S1. These data suggest that this magnetic field structure was acting as a barrier to energetic particles which were unable to escape from the upstream region of shock S2. These particles were most likely injected into the plasma structure downstream of shock S1 during the early stages of the SEP event, when the associated CME on October 19 started propagating

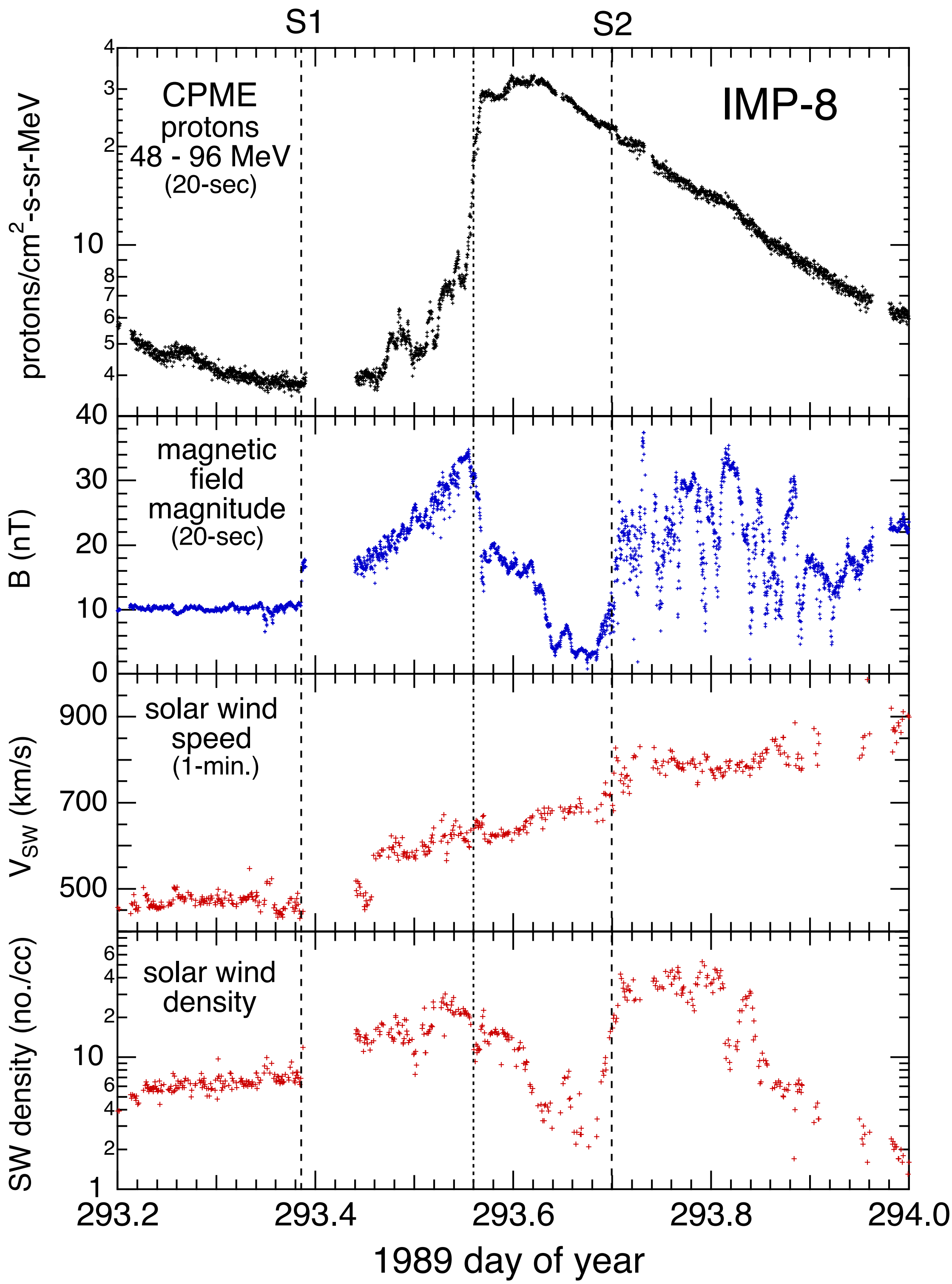

Fig. 2. IMP-8 observations for the October 20, 1989 ESP event. From top to bottom: 48.0-96.0 MeV proton intensities from the CPME instrument; magnetic field magnitude; solar wind speed and solar wind density. Dashed vertical lines identify the arrival of interplanetary shocks at IMP-8. The dotted line indicates the magnetic field discontinuity marking the onset of the ESP event.

from the Sun, and the associated driven shock was still strong enough to accelerate a large number of particles to high energies. Had shock S2 propagated in an undisturbed medium, e.g., one devoid of large and systematic B variations, the resulting ESP event would likely have shown a more typical profile, both in terms of its peak proton intensities and the high-energy extent of its proton energy spectrum. We propose that the distorted medium upstream of shock S2 acted to confine and channel the energetic particles accelerated by this shock. In fact, the region downstream of the first shock S1, enclosed between two converging structures of very high B, offers ideal conditions for confining these energetic particles (Lario et al., 1999). We suggest that particles injected by the solar event on October 19 and its associated traveling shock S2 were trapped in this confinement structure and swept ahead by the propagating shock S2. The arrival of this complex structure at 1 AU, together with the population of trapped particles, constituted this intense ESP event.

3 Conclusion

A closer inspection of the October 20, 1989 ESP event reveals that this event was not a result of local shock-acceleration. The arrival of the interplanetary shock at $\sim$1650 UT did not produce any effect on the high-energy ($\gtrsim$39 MeV) proton flux. Energetic particle profiles observed around the shock passage are not consistent with trapping by self-generated waves or any additional turbulence associated with the shock. On the contrary, we have shown that the high proton flux observed before the arrival of the October 20, 1989 interplanetary shock reflects a sequence of unique and unusual occurrences and not a reacceleration process at the shock. We suggest the following scenario: (1) during its early stages, the CME (associated with the October 19 solar event) drove the (then strong) shock S2 that accelerated particles to high energies; (2) these high-energy particles were injected into a region of converging magnetic structures lying between an earlier shock S1 (and ejecta) and CME-driven shock S2; (3) confinement behind the trailing edge of the large jump in B (at doy 293.56) kept these particles well ahead of shock S2, and produced the peculiar time-intensity profiles of this unusually energetic and intense ESP event.

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