The energetic storm particle event of October 20, 1989

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[1] The energetic storm particle event of October 20, 1989 has often been cited as an example of high-energy ($\gtrsim$500 MeV) proton acceleration by CME-driven shocks near 1 AU. We examine high-time resolution solar wind and magnetic field data from the IMP-8 spacecraft and energetic particle data from the IMP-8 and GOES-7 spacecraft. We show that the high-energy particle population in this event is not a locally shock-accelerated population, but rather a population of particles confined to a plasma structure with depressed magnetic field and solar wind density. This structure was bounded by enhanced densities and strong magnetic fields. Energetic protons within this structure supplied the pressure needed to prevent the structure from collapsing. The intensity and evolution of this energetic storm particle event were shaped mainly by this spatial structure rather than by the CME-driven shocks. *INDEX TERMS:* 2114 Interplanetary Physics: Energetic particles, heliospheric (7514); 2111 Interplanetary Physics: Ejecta, driver gases, and magnetic clouds; 2139 Interplanetary Physics: Interplanetary shocks

1. Introduction

[2] Intensity increases of energetic ions associated with the passage of shocks have historically been called Energetic Storm Particle (ESP) events. The earliest studies of these events suggested two possible origins. *Axford and Reid* [1962] proposed that intensity increases resulted from particle acceleration at shock fronts, while *Bryant et al.* [1962] suggested that particles were trapped in the vicinity of shocks. Although self-generated Alfvén waves can trap particles around the shock [*Lee*, 1983], other processes, such as complex magnetic and plasma structures in the vicinity of the shock, can also contribute to spatial confinement. In general, intensity-time profiles of ESP events depend not only on shock-acceleration efficiencies and levels of locally generated waves, but also on how transport conditions are affected by ambient structures in the regions upstream and downstream of shocks [*van Nes et al.*, 1985].

[3] Intensities of ESP events observed at 1 AU vary from event to event and decrease with increasing energy [*van Nes et al.*, 1984; *Kallenrode*, 1995]. Typical ESP events have significant proton intensity increases at energies from a few tens of keV to some tens of MeV. Shock-associated increases in the $\gtrsim$100 MeV range are rare [*Reames*, 1999]. The ESP event of October 20 (DOY 293), 1989 was exceptional because of: [1] its intensity (the highest observed by IMP-8 throughout solar cycle 22; [*Lario et al.*, 2001]), [2] its energy (proton intensity increases were observed at energies >685 MeV; [*Sauer*, 1993a]), and [3] the complexity of plasma and magnetic field structures observed during its development (including a previous shock wave not related to the ESP event itself; [*Cane and Richardson*, 1995]).

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2. Instrumentation

[4] We use energetic proton data from the Energetic Particle Sensor (EPS) [*Sauer*, 1993b] on GOES-7 (in geosynchronous orbit) and from the Charged Particle Measurement Experiment (CPME) [*Sarris et al.*, 1976] on IMP-8 (in near-circular earth orbit at $\sim$35 R_E). The EPS data have been corrected for background counts due to galactic cosmic rays and their secondaries, for the out-of-aperture responses, and for counts due to particles entering through secondary energy passbands [R. Zwickl 2001, private communication]. This correction algorithm works best when the energy spectrum of the differential proton intensity is close to a power law in energy (E^{-3}) [*Vainio et al.*, 1995]. The lowest energy channel of the GOES-7/EPS may be occasionally affected by trapped ions and by geomagnetic cutoff effects. From the IMP-8/CPME we use exclusively the channel P9 that measures 48–96 MeV protons. Unlike several other CPME proton channels, P9 does not suffer significant saturation during very high-intensity particle events [*Lario et al.*, 2001]. We also use IMP-8 solar wind plasma and magnetic field data from the Massachusetts Institute of Technology (MIT) Faraday cup plasma experiment and the Goddard Space Flight Center (GSFC) magnetometer [*Scearce et al.*, 1976]. IMP-8 was in the solar wind throughout the ESP event and therefore unaffected by the earth's magnetosphere.

3. Observations

[5] The ESP event on 1989 DOY 293 was superimposed on one of the largest solar energetic particle (SEP) events observed during the solar cycle 22 [*Lario et al.*, 2001]. This SEP event was associated with the occurrence of an X13/4B solar flare on DOY 292 in NOAA active region 5747 at S27°E10° with H-alpha onset at 1229 UT and maximum at 1259 UT. The SMM coronagraph was not operating at that time and no CME was observed [*Klein et al.*, 1999]. However, the arrival of ejecta material at earth on DOY 294 (identified by *Cane and Richardson* [1995]) suggests that an earth-directed CME occurred at the time of the flare. Figure 1 shows five-minute averaged proton intensities from GOES-7/EPS during this SEP event. We have included the IMP-8/CPME P9 data to show the similarity between intensity structures at IMP-8 and GOES-7. Energetic particle data for this SEP event have been analyzed by others [see for example *Shea et al.*, 1991; *Klein et al.*, 1999]; we refer the reader to these papers for further details. Henceforth, we focus on the analysis of the ESP event, and denote energetic proton intensities by j.

[6] Figure 2 shows GOES-7 and IMP-8 data during DOY 293 (see caption for details). A first shock (dashed line in Figure 2 named S1) was observed at 0916 UT [*Cane and Richardson*, 1995]. This shock had no significant effect on the already elevated j($\gtrsim$15 MeV), as seen in Figure 1. Behind this weak shock, the magnetic field magnitude B increased gradually and peaked at 35 nT on $\sim$1320 UT. During this period the solar wind proton density N and the flow speed V showed less pronounced increases. An abrupt decrease of B coincided with the simultaneous increase by a factor of $\sim$5 of j(48–96 MeV) (dotted line in Figure 2). All the GOES-7 proton channels (Figure 1) showed abrupt and simultaneous increases at the time of this discontinuity arrival at GOES-7 (based on V, there is a

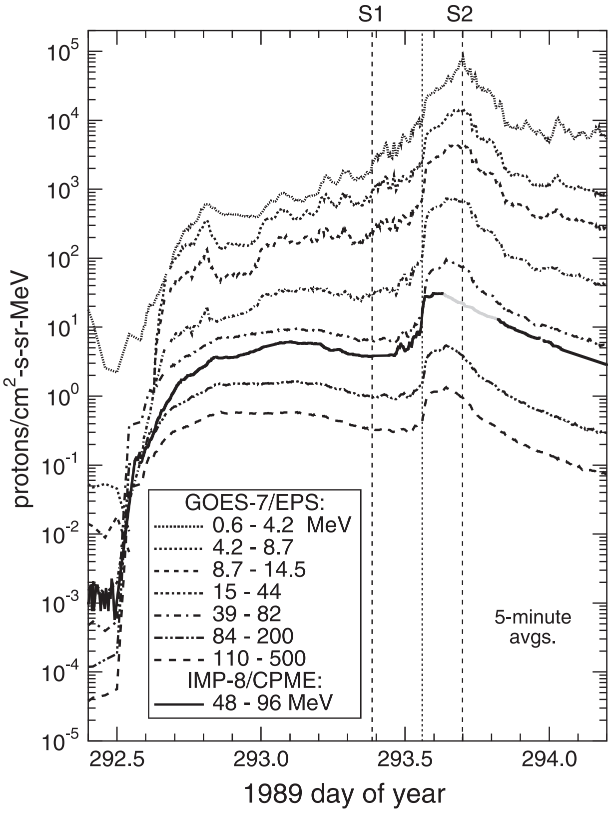

Figure 1. GOES-7/EPS and IMP-8/CPME channel P9 proton observations for the 19–21 October 1989 SEP event. The dashed vertical lines identify the arrival of interplanetary shocks and the dotted line the onset of the ESP event. The gray interval in the IMP-8/CPME P9 trace indicates the period with possible CPME saturation. DOY 293 corresponds to October 20, 1989.

~4 minute delay between the arrival of solar wind structures at IMP-8 and GOES-7). Depressions in N, T_p, and B occurred shortly after this discontinuity, with both reaching minima at 1619 UT (DOY 293.68), when j(>39 MeV) was already decreasing. The similarity between the N, T_p, and B profiles throughout this period (including the small increase observed at 1536 UT) shows clearly that magnetometer and plasma experiments were indeed observing the same plasma structure. Note that in Figure 1, the CPME P9 intensity and those of the high-energy EPS channels evolve similarly up to the peak in these EPS channels at 1521 UT (DOY 293.64). This peak is absent in CPME P9, most probably due to P9 saturation (the likely duration of which is indicated by the gray interval in the P9 trace in Figures 1 and 2); if so, this is the only large particle event during which we have discerned a saturation effect in CPME P9. On the other hand, we have checked energetic particle data from the GSFC instrument on IMP8 which show intensity maxima at the same time as at GOES-7 except for a 4 minute delay between IMP-8 and GOES-7. In our subsequent analyses we use only GOES-7 energetic proton data.

[7] The slow increase of N and B at ~1650 UT was classified as an interplanetary shock by *Cane and Richardson* [1995] (denoted in Figures 1 and 2 by S2). If S2 is indeed a shock, we can estimate its local strength r and speed V_S as follows. Within ±one minute of S2's passage, N increases by, at most, a factor ~2. This density jump is the shock strength (or compression ratio) r, which satisfies $1 \leq r \leq 4$ for a ratio of specific heats of 5/3. Across S2, V increases from $V_u \sim 700$ to $V_d \sim 800$ km s^{-1} (u = upstream, d = downstream). Conservation of normal mass flux across S2 implies that $V_S = (rV_d - V_u)/(r - 1)$, or $V_S \sim 900$ km s^{-1}. Thus, if S2 is a shock, it is neither exceptionally strong nor fast (relative to the ambient flow speed), and therefore unlikely to have locally accelerated protons to hundreds of MeV. Also note that solar wind and magnetic field parameters increased in a gradual and slow transition; shocks observed at 1 AU usually show abrupt and rapid transitions. Although j(≲8 MeV) peaked with the arrival of S2 (looking as a typical ESP event), high-energy (≳39 MeV) proton intensities were already decreasing. Thus, neither S1 at 0916 UT nor S2 at ~1650 UT produced local signatures on the high-energy proton population.

[8] *Cane and Richardson* [1995] analyzed the IMP-8 particle and plasma data together with the neutron monitor data and concluded that S2 was associated with the solar event on DOY 292. A CME structure arrived at earth on DOY 294 which was identified as the driver of S2. *Cane and Richardson* [1995] concluded that the first shock S1 at ~0916 UT was followed ~5 hours later by a region indicative of CME material with a duration of only ~2 hours [see Figure 5 in *Cane and Richardson*, 1995]. Their classification of this structure as ejecta was based exclusively on the anomalous depression of solar wind proton temperature with

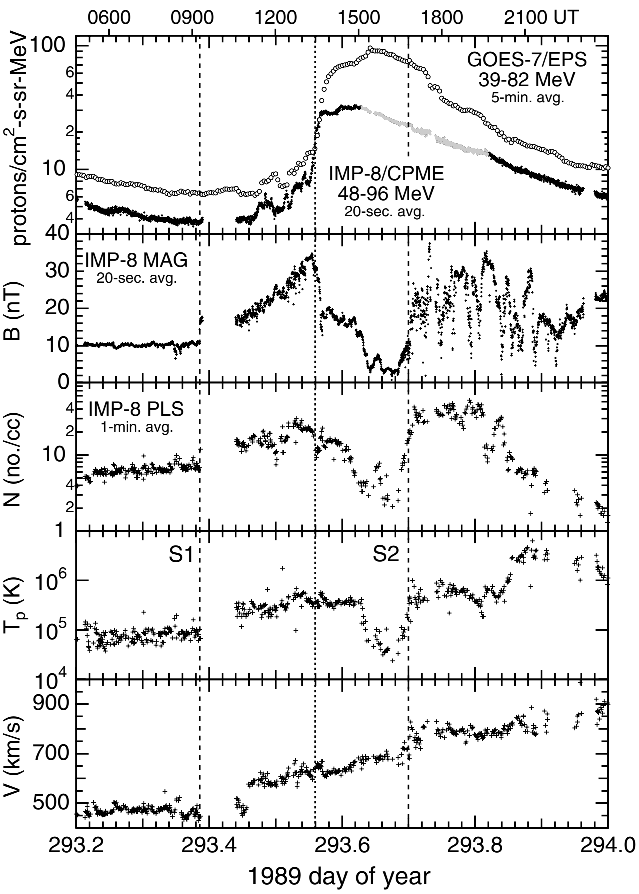

Figure 2. From top to bottom: proton intensity j(39–82 MeV) measured by GOES-7/EPS (open circles) and j(48–96 MeV) measured by IMP-8/CPME instrument (black dots); magnetic field magnitude B as measured by the IMP-8/GSFC magnetometer; solar wind density N; solar wind proton temperature T_p; and solar wind speed V as measured by the IMP-8/MIT plasma experiment. Dashed vertical lines identify the arrival of interplanetary shocks at IMP-8 and the dotted line the magnetic field discontinuity which marks the onset of the ESP event. The gray interval in the IMP-8/CPME P9 trace (top panel) indicates the period with possible CPME saturation.

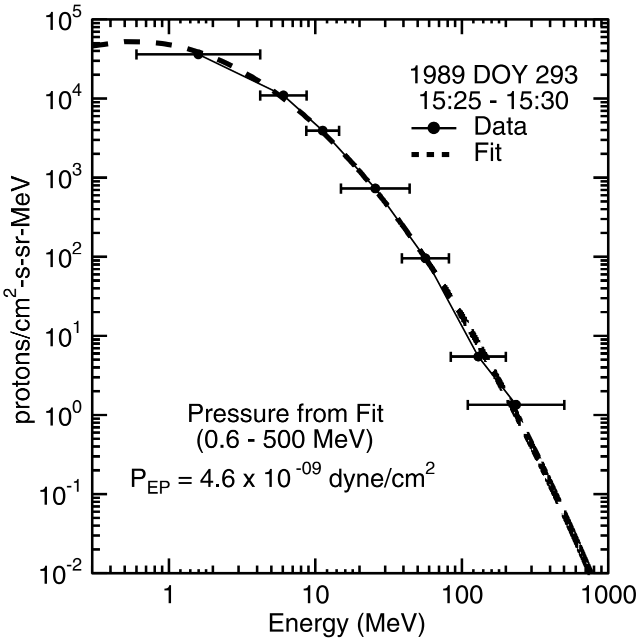

Figure 3. Energy proton spectrum as measured by GOES-7 during the 5-minute interval 1525–1530 UT (points) and the corresponding fit (dashed line). This proton spectrum is typical of those observed during the magnetic field and solar wind cavity.

respect to the normal temperature expected from solar wind expansion. As we discuss below, the sum of the thermal plasma and magnetic pressures within this structure indicates that it should collapse in response to the pressure exerted by the surrounding medium, with its enhanced *N* and *B*. However, energetic particles within this structure may supply enough pressure to support the structure against collapse or even to drive its outward expansion.

[9] We estimate the pressure contributed by the energetic protons, P_{EP}, using the GOES-7/EPS differential intensities. We represent the differential intensity from 0.6 to 500 MeV by a 3-parameter function as $\log j(T) = \log j(T_0) + a_1 \log T + a_2(\log T)^2$, where $j(T_0)$ is the intensity at the reference energy T_0. Figure 3 shows a typical proton energy spectrum observed during the depressed region and the fit obtained with this expression. Note that the spectrum at high energies (>4 MeV) follows to a very good approximation a power law dependence E^{-3} considered to be the situation when the correction algorithm used for the GOES-7/EPS data works best [*Vainio et al.*, 1995]. If the energetic protons are well represented by an isotropic pressure tensor, then the pressure in solar wind flow frame is

$$P_{EP} = \left(\frac{4\pi}{3}\right)(2m)^{1/2} \int_{T_1}^{T_2} dT\, T^{1/2} j(T)$$

where *m* is the proton mass. The finite energy range covered by GOES-7/EPS channels limits our estimated P_{EP} to protons within $T_1 = 0.6$ to $T_2 = 500$ MeV. The actual pressure that includes protons <0.6 MeV as well as other ion species will exceed this estimate.

[10] Figure 4 shows the magnetic pressure $P_B = B^2/8\pi$, the solar wind plasma thermal pressure $P_{PLS} = Nk\ (T_p + T_e)$ (where k = Boltzmann constant, T_p = proton temperature, T_e = electron temperature), and the sums $P_{PLS} + P_B$ and $P_{PLS} + P_B + P_{EP}$ as compared with the P_{EP}. In the case shown we have assumed that $T_e = 2\ T_p$, which is reasonable based on statistical surveys of proton and electron temperatures in post-shock plasmas [*Gosling et al.*, 1987]. The energetic protons enhance the total pressure precisely where the P_{PLS} and P_B reach minimum values. Thus, the structure with depressed *B* and *N* is sustained by the pressure carried by the energetic protons. An increase of P_{EP} by a factor of $\sim$2 (which may well be contributed by protons <0.6 MeV and other ions that we have neglected) would lead to a pressure balance between the depressed structure and its surroundings. Our pressure estimates will change by small factors if other conditions are assumed. For example, if $T_e = T_p$ in the post-shock plasma, then P_{PLS} is reduced by a factor of $\sim$3/2. Also, since the GOES-7/EPS 0.6–4.2 MeV channel could be affected by trapped protons and/or by geomagnetic cutoff effects, we have repeated the calculation of P_{EP} without this channel, which reduces P_{EP} by a factor $\sim$2. We have also computed P_{EP} neglecting the high energy channels of the GOES-7/EPS channels (P5-P7) which are most affected by the correction algorithm used on GOES-7 data [*Vainio et al.*, 1995]. In all considered cases the pressure within the cavity was always dominated by P_{EP}.

4. Discussion

[11] A closer inspection of the October 20, 1989 ESP event reveals that the high-energy proton component of this event did not result from local shock-acceleration. The arrival of S2 at $\sim$1650 UT had no effect on the high-energy ($\gtrsim$39 MeV) proton intensities. On the contrary, the main effect on the high-energy ($\gtrsim$39 MeV) protons was not associated with a shock, but rather with the presence of a cold tenuous plasma and depressed magnetic field region formed in front of S2 (or in the downstream region of the shock S1). Trapping of energetic particles within this depressed structure was also invoked by *Struminsky* [2001] to relate GOES-7 and neutron monitor data. On the other hand, numerical simulations by *Kallenrode and Cliver* [2001] show the necessity of this kind of structures behind a first leading shock S1 to produce high

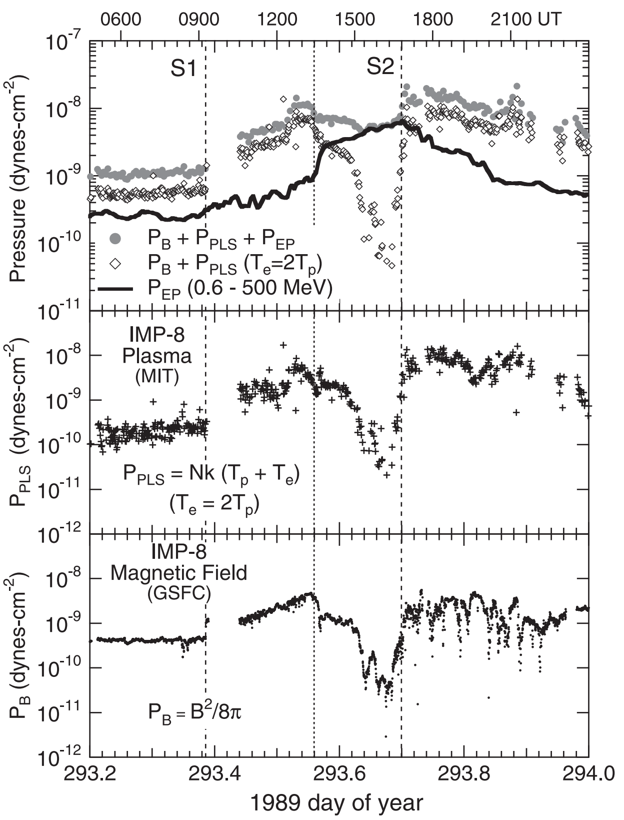

Figure 4. From bottom to top: Magnetic field pressure P_B; thermal pressure P_{PLS}; energetic proton pressure P_{EP} (black line) and the sums $P_{PLS} + P_B$ (open diamonds) and $P_{PLS} + P_B + P_{EP}$ (gray dots). See text for details.

energy particle intensities in front of CME-driven shocks. We have shown that the pressure within this structure was dominated by the pressure carried by the energetic protons. We cannot determine how this cavity originated. It may have convected from the Sun in the same form as observed by IMP-8, or some process (perhaps mediated by the same energetic protons) may have rarefied and cooled this region as it moved away from the Sun. The most plausible scenario suggests that this structure might be part of an ejecta driving the shock S1. This structure provided the initial closed magnetic field topology to trap the particles injected by the solar event on DOY 292. Had the CME on DOY 292 propagated in an undisturbed medium (without any complex structure in front of it), the resulting ESP event would most likely have shown a more typical behavior in terms of its proton peak intensity and the high energy extent of its proton spectrum.

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