ACCELERATION OF IONS AND ELECTRONS TO NEAR-COSMIC RAY ENERGIES IN A PERPENDICULAR SHOCK: THE JANUARY 6, 1978 EVENT

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ABSTRACT

Acceleration of energetic ions to ~ 200 MeV and electrons to ~ 2 MeV were detected by the Low Energy Charged Particle (LECP) instrument on Voyager 2 in association with a quasi-perpendicular shock of $\theta_{Bn} = 87.5°$ at 1.9 AU. The measurements, obtained at a time resolution of ~ 1.2 sec, reveal structure of the energetic particle intensity enhancements down to a scale of the order of the particle gyroradius, and suggest that acceleration takes place within a gyrodiameter of the shock. The observations are consistent with the predictions of the shock drift acceleration (SDA) mechanism. The absence of any fluctuations in the magnetic field during the shock passage suggests that turbulence is not essential to the shock acceleration process in the interplanetary medium.

1. Introduction. It is a well documented observational fact that even weak ($M_A \simeq 1.5$) quasi-perpendicular shocks readily accelerate ions to relatively high energies (up to ~ 50 MeV, Sarris et al., 1976), while quasi-parallel shocks rarely accelerate ions to rather modest (~ 200-300 keV maximum) energies, if such shocks are more or less supercritical ($M_A \simeq 2.8$, Kennel et al., 1984). Surprisingly, theoretical work on shock acceleration of cosmic rays has concentrated on quasi-parallel shocks (Axford et al., 1977; Blandford and Ostriker, 1978), despite the fact that such shocks are demonstrably incapable of producing high energy particles in the interplanetary medium. In an earlier paper (Sarris and Krimigis, 1985) we reported the details of a high mach number shock ($M_A \simeq 3.4$) observed by Voyager 2 at 1.9 AU. In this paper we examine further the development of the energy spectrum and the time variability of the intensity at the time of shock passage. For details of the detector system and instrument operation see Krimigis et al., 1977.

2. Results. Figure 1 shows the count rate profile of several channels from the LECP instrument from January 1 - 7, 1978, following a 2N flare at 2145 UT on January 1, 1978. The shock wave intercepted the Voyager 2 spacecraft on January 6, 1978 at 00:01:30 UT, as is evident from the intensity-time profile in the figure. The energy extent of the enhancement can be seen from the fact that the iron channel in the range ~ 2-12 MeV/nuc (i.e. a total energy > 112 MeV) increased in intensity by well

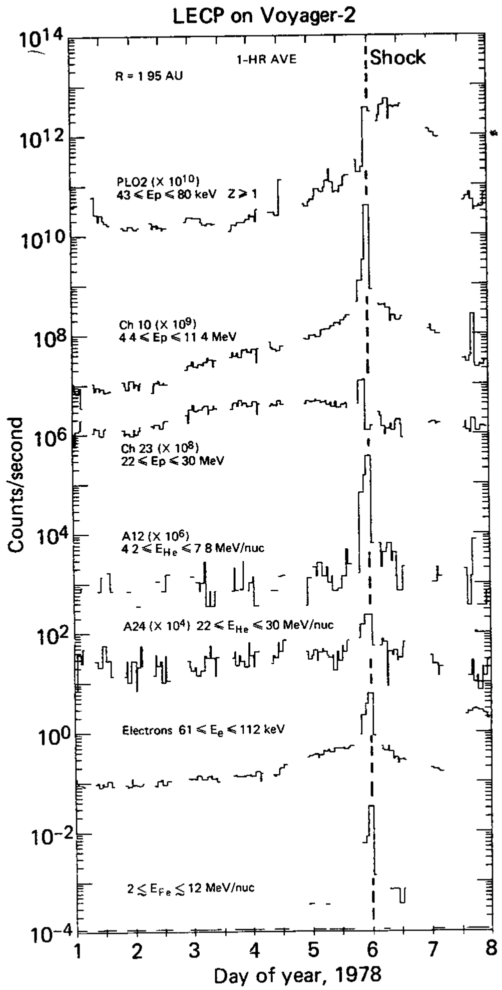

Fig 1

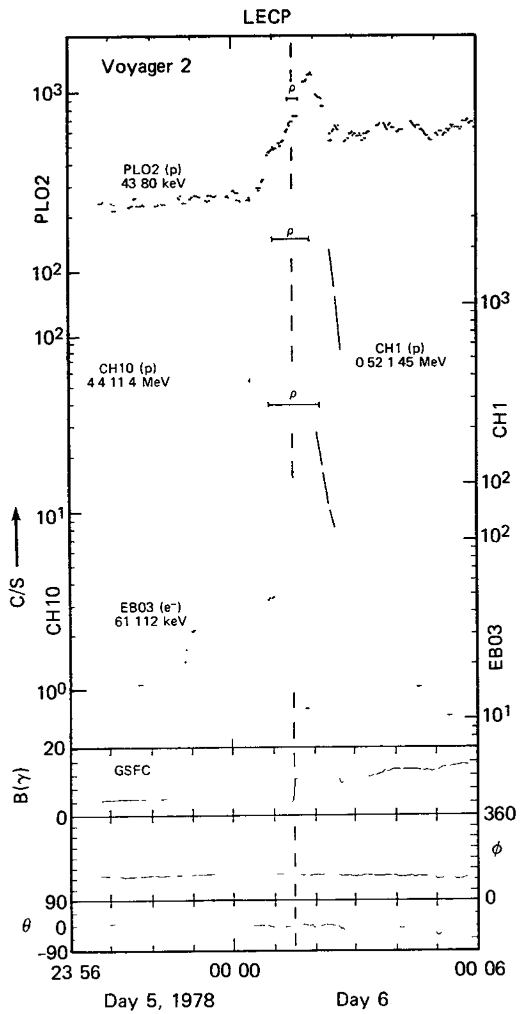

Fig 2

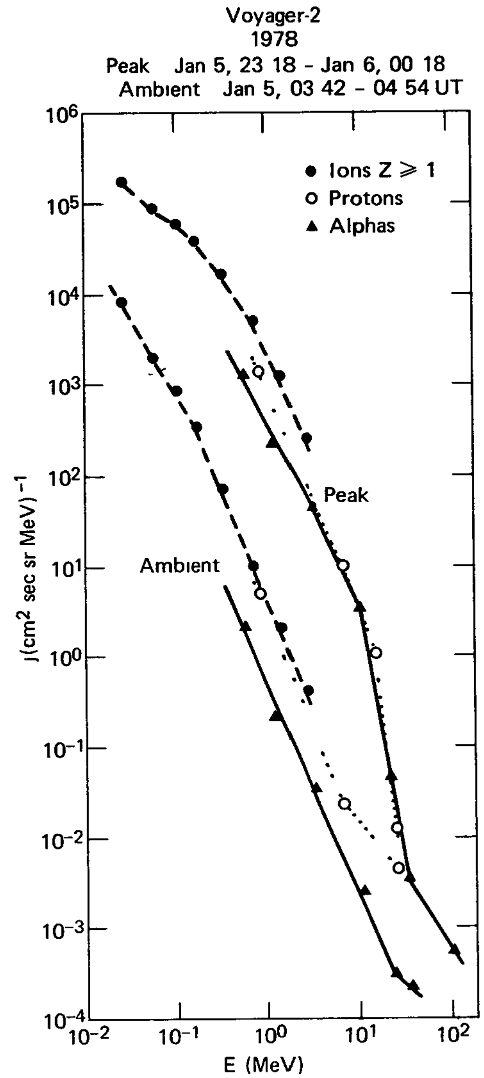

Fig. 3

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Figure 1 Hourly averages of the responses of selected channels from the LECP instrument on Voyager-2 following the January 1, 1978 solar flare event; the shock wave (dashed line) encountered the spacecrarft on January 6, 1978 at 00:01:30 UT.

Figure 2 Expanded time scale of ion and electron counting rates with a time resolution of 1.2 sec. for channels PL02 and EB03 and ~ 10 sec. for Channel CH1 and CH10. The length of time corresponding to the particle gyroradius as convected past the spacecraft is marked for each channel with the exception of EB03. The magnetic field measurements are shown in the bottom three panels (Courtesy of Drs. N. F. Ness and R. P. Lepping).

Figure 3 Energy spectra of ions $Z \geqslant 1$ at lower energies and protons and He at higher ($\gtrsim$ 100 MeV) energies, when shock effects were weak (ambient) and around the shock (peak).

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over 2 orders of magnitude.

The detailed time interval to within ± 5 minutes of the passage of the shock is shown in Figure 2. The magnetic field parameters (courtesy of N. F. Ness and R. P. Lepping) are shown in the bottom three panels. The top curve in the upper panel shows that the enhancement for the lowest energy ions (~ 40 keV) occurs immediately after the passage of the shock; at an energy about a factor of 10 higher (second curve), however, the intensity peaks at the shock passage with more of the increase upstream rather than downstream of the shock. At an energy one order of magnitude higher still (third curve from the top) the increase is most notable upstream of the shock while the intensity drops by well over an order of magnitude downstream within a gyro-diameter of the shock. We also note that the energetic electrons are essentially attached to the shock itself with the intensity being higher upstream than downstream. It is important to note that this energy separation effect is distinct in both the general large scale structure of the energetic particle intensity enhancements seen in Figure 1, as well as in the fine scale intensity structure which is attached to the shock. The peak intensities of the fine structure are found downstream (low energies) or upstream (high energies) at distances from the shock of the order of the particle gyroradius. It is essential to note that measurements of the magnetic field with a time resolution of 1.92 sec. indicate that the magnetic field is very quiet upstream from the shock front and show no evidence for the presence of significant magnetic turbulence in the frequency range from ~ 0.2 Hz to ~ 10^{-3} Hz.

Figure 3 shows the energy spectra of ions with $Z \gtrsim 1$ up to ~ 3 MeV, and of protons and alpha particles at energies $\gtrsim$ 0.5 MeV where the elements can be clearly separated (Sarris and Krimigis, 1985). The ambient population some twenty hours prior to the passage of the shock is shown for comparisons. It is evident that the enhancements were largest for helium ions, especially at the higher energies (~ 10 MeV). Although not shown here, the enhancements for the heavier elements extended to total energies ~ 200 MeV (Sarris and Krimigis, 1985).

3. Discussion. The shock acceleration event described above is remark-

able in that not only did it accelerate nuclei and electrons to almost cosmic ray energies, but that it did so in the absence of any discernible level of turbulence in the magnetic field. Further, the data demonstrate that all intensity enhancements and fine structure occur within a gyrodiameter of the shock from the lowest ($\sim$ 40 keV) to the highest ($\gtrsim$ 20 MeV) energies. This event and many other similar ones (Armstrong et al., 1985) demonstrate that turbulence is not a necessary condition for particle acceleration in shocks, to the highest energies observed in the interplanetary medium.

Recent simulation work on quasi-perpendicular and quasi-parallel shocks in the presence of turbulence (Decker and Vlahos, 1985) shows that magnetic fluctuations have a tendency to cause a test particle to encounter the shock more than once. In each of these encounters, however, the energy gain is mostly through drift acceleration along the shock surface, rather than compression. This result helps to explain the observation that maximum energies attained in quasi-parallel shocks are at most $\sim$ 300 keV. The apparent maximum energy gain is likely due to the fact that the time during which the instantaneous magnetic field-shock normal geometry is near-perpendicular is rather small and consequently the energy gain through shock-drift is low. This energy gain "saturation" effect at relatively low energies suggests that the particle escapes the shock turbulence region after only a few encounters with the shock.

Similarly in the astrophysical case, quasi-perpendicular shocks would energize the ions to several hundred MeV. Such particles would then become the seed population; further energization would obtain through scattering in magnetic field fluctuations which may cause the ions to undergo additional encounters with the shock for further energy gains. At some point (relativistic energies?) compression may begin to become an appropriate description for the process.

4. Acknowledgements. We are grateful to Dr. A. Vinas of GSFC for providing us with the shock parameters. This work was supported by NASA under Task I of Contract N00024-83-E-5301.

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