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The Halloween Shock of 2003 as it Reached Voyager 2 at ~73 AU - Two Separate Acceleration Zones and Two Different Spectra for Energetic Protons

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Abstract. Motivated by the recent observation that two separate periods of enhanced intensities of solar wind ions at ~2 times the normal solar wind energy were observed at times of the shock arrival and at the magnetic field maximum at Voyager 2 at 73 AU, arising from the 2003 Halloween event at the Earth, we have re-examined the higher energy proton data from 0.06 to 20 MeV from the LECP and CRS instruments on V2 for this event. We find that there are two separate regions of particle acceleration in this outward propagating merged interaction region. The one near the shock has a much harder proton spectrum extending up to ~20 MeV, but with a relative paucity of particles below ~1.0 MeV. The other, near the time of maximum magnetic field fluctuations, is dominated by protons at energies ~1 MeV or less with a sharp cutoff above 2 MeV. The two regions are separated spatially and the half width of the respective radial intensity distributions at each energy can be used to estimate a local diffusion coefficient. The composite spectrum from these two regions is a power law with a spectral index ~-1.4 below 1 MeV steepening to -3.2 above ~2 MeV. This observation has important implications astrophysically, beyond what is seen locally, because most astrophysical observations of accelerated spectra cannot resolve the two components and therefore miss the clues that help identify the particle acceleration mechanisms.

Keywords: Voyager, Interplanetary Shocks, Acceleration
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INTRODUCTION

The well known Halloween shock of 2003 has been followed outward in the heliosphere to its encounter with Voyager 2 at 73 AU approximately 6 months later [1,2,3], and its further encounter with Voyager 1 and then shortly afterwards the HTS. This arrival time at the HTS in late 2004 is coincident with the onset of kHz emission observed by the Iowa group [4]. The details of this shock and the associated magnetic field, plasma and galactic cosmic ray/interplanetary proton intensity-time profiles at V2 have been discussed in a number of publications [1,2,3]. In summary these studies have shown that this shock provided some of the most striking effects at the V2 spacecraft in the outer heliosphere observed to that date. These include a sudden change in solar wind speed of nearly 100 $km \cdot s^{-1}$ at 2004.32, to the large changes in magnetic field amplitude and direction at about 2004.37, and the intensity change ~10% in high energy cosmic rays occurring at between 2004.35 and 2004.37. This event was identified as a classic MIR, later upgraded to a GMIR after its effects at V1 ~18 AU further out in the opposite hemisphere were recognized.

The study of this event took a new twist when Intriligator, et al., [5,6] identified bursts of what can be interpreted as high energy solar wind ions (HET's) at roughly 2

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times the average solar wind energy, occurring only at two separate times, the time of the main shock at 2004.32 and again at 2004.37 at the time of the largest magnetic field variations. As a result of this observation we have examined the intensity time profiles of energetic protons at several energies between ~0.06 and 20 MeV using both LECP and CRS particle data. We have also constructed spectra for protons between 0.06 and 20 MeV and He nuclei between 2-8 MeV/nuc, at the two times, 2004.32 and 2004.37 when separate intensity peaks are observed for both nuclei.

We find that: 1) Two separate acceleration regions apparently exist, one associated with the time 2004.32, the other with the time 2004.37; 2) These two regions have greatly different spectra. The one at 2004.32 associated with the shock, which we call region S, has a spectrum which dominates above ~2 MeV; the one at 2004.37, associated with the rapid magnetic field variations and magnetic field maximum, called region M, has a spectrum which dominates below ~0.5 MeV.

We will describe these temporal and spatial effects in more detail

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THE DATA

1) Temporal Variations: The 5 period running average of intensities are shown at several energies in Figures 1A and 1B. Figure 1A shows data from the CRS experiment [7], Figure 1B from the LECP experiment [8]. The presence of two intensity peaks for low energy protons is clear. At the lowest energies, <1.0 MeV, the M peak at 2004.367 is dominant. At high energies, above ~2 MeV, the S peak is dominant with a peak time at 2004.322, ~15-16 days earlier. At intermediate energies, both peaks are present with comparable intensities. The intensity minimum between the two peaks offers the possibility of determining the diffusion coefficient in this region at the various energies. From the timing difference of the two peaks of 0.045 year, we find that the two source regions are physically separated by ~4.3 AU for an outward disturbance moving at a speed ~500 km·s^{-1}, the maximum plasma speed measured by [2] after the shock arrived.

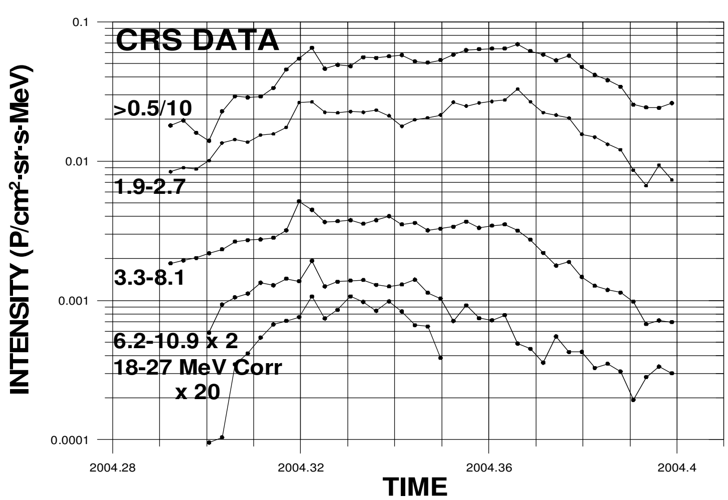

FIGURE 1A. Intensity-time profiles of protons and He nuclei observed by the CRS instruments at higher energies. Data are 5 day running averages. Times of the shock intensity maximum S and the magnetic field intensity maximum M are shown as vertical lines. Simple intensity vs. time profiles for the two intensity peaks are shown by the dashed red line.

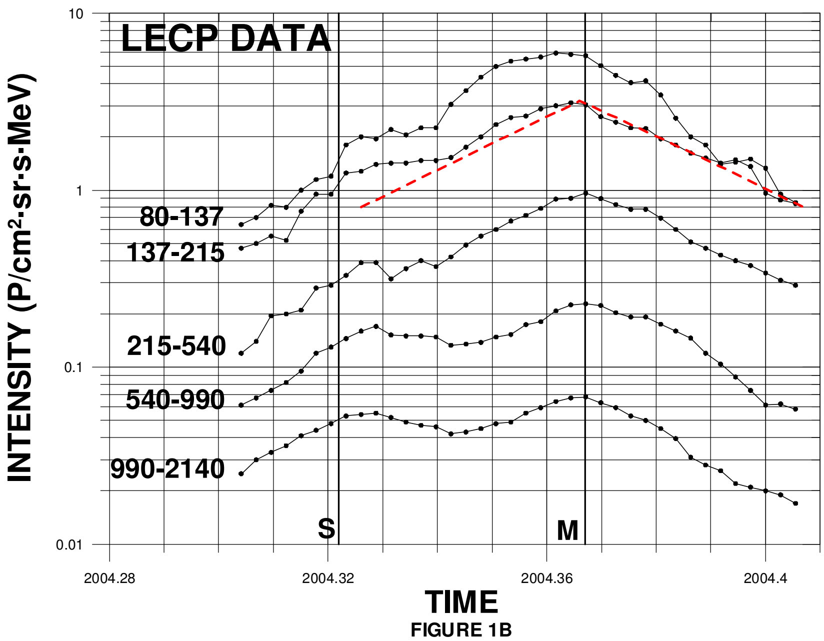

FIGURE 1B. Same as Figure 1A but for the proton intensity-time profiles from the LECP instrument at lower KeV energies.

The 5 period running averages of intensities of three galactic cosmic ray (GCR) components, >70 MeV nuclei, 132-242 MeV protons and 6-14 MeV electrons is shown in Figure 1C.

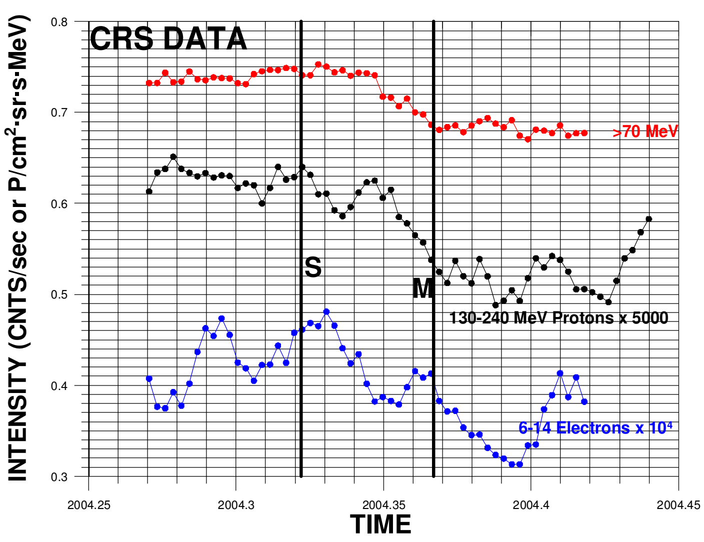

FIGURE 1C. Same as Figures 1A and B but for the intensity time profiles of GCR nuclei >70 MeV, protons between 130-240 MeV and electrons between 6-14 MeV.

2) Energy Spectra: The energy spectra of H nuclei (and He nuclei) in the two separate regions obtained from the LECP data at lower energies and the CRS data at higher energies are shown in Figure 2 with the spectrum in the S region in red and the M region in black. The intensities are xE^2 (in MeV) to show better the differences in the spectra. The composite S and M region spectrum is also shown.

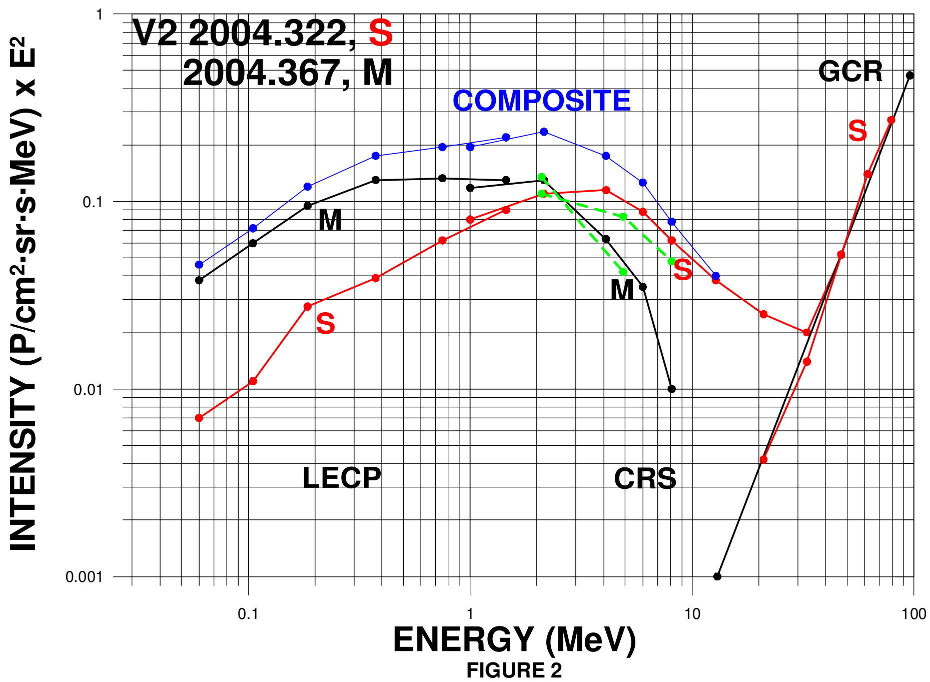

FIGURE 2. Energy spectra for protons (x E^2) obtained at the times of the two intensity peaks, S (in red) and M. The GCR background for protons, which has a spectrum ~$E^{1.0}$, is shown at higher energies. The He nuclei intensities (x 18) are shown as dashed lines for the times S and M at the same energy/nuc as protons. The composite S and M proton spectrum is shown in blue.

DISCUSSION OF THE VARIOUS FEATURES OF THE HALLOWEEN EVENT AS IT PASSES V2 AT ~73 AU

Temporal Variations of Interplanetary Protons

The time variations of protons >1 MeV from the CRS experiment are shown in Figure 1A. Figure 1B shows these variations for the lower energy protons from LECP. The existence of two intensity peaks, one at about 2004.322 dominant at higher energies, the other at ~2004.367, dominant at lower energies, is clearly evident. The observed intensity time curves can be well fit by the two distributions shown by the dashed red lines in Figure 1A. Both distributions have a FWHM between ~0.035-0.040 year = 12-14 days and have approximately equal peak intensities in the 1.9-2.7 MeV interval. The observed peaks at 2004.322 and 2004.367 have a separation of 0.045 year = 16.5 days. This separation is larger than the FWHM of the two distributions so the two source regions can be spatially resolved. This separation in time is equivalent to a radial distance of 4.3 AU for an outward disturbance moving at 500 $km{\cdot}s^{-1}$. The FWHM corresponds to a radial distance of 3.33 AU which can be used to determine the diffusion length in a specific model for the acceleration of these particles (see [9]).

The >0.5 MeV protons in Figure 1A also show the presence of two peaks each of roughly the same amplitude and at the same times as the 1.9-2.7 MeV peak. The later time peak is not visible in the data at energies above 6.4 MeV.

For the lower energy protons in Figure 1B we use the 0.137-0.215 MeV intensity time curve from LECP as a template. The data at this energy has essentially only one peak at 2004.367, the same time as the higher energies, with a FWHM = 0.044 year (16 days), about the same or slightly longer than at higher energies. The intensity-time curves at still lower energies also show only one peak. At higher energies, between ~0.3 and 1.0 MeV, a second peak begins to appear at 2004.322.

We should note here that [1], have shown that any residual population of previously accelerated protons near the Sun would have lost most of their energy by Betatron deceleration in the expanding solar wind so that their intensities at 73 AU would be less than ~0.1 of those observed at V2. So the protons we are describing are most likely being accelerated locally.

The GCR data in Figure 1C does not show the presence of accelerated particles. Instead the data for >70 MeV nuclei shows a sudden decrease ~9% occurring about half-way between the S and M times (see e.g., [3]). The lower rigidity protons and still lower rigidity electrons in Figure 1C show periodic variations and much larger overall intensity decreases, which are ~20% for 130-240 MeV H and ~32% for 6-14 MeV electrons. The typical peak-to-peak time of these variations is 9-10 days for each component, a fraction of the nominal 27 day solar rotation periodicity. The electron and nuclei peaks are also out of phase. These periodicities occur during the times of “planer magnetic structures” in the radial component of the magnetic field that are reported by [10]. These variations are superimposed on a very structured total B field which peaked at 2004.37

The Energy Spectra of the Interplanetary Protons and Helium Nuclei

The energy spectra in the two regions, S and M, are shown in Figure 2. These spectra are from both the LECP and CRS experiments and it would not be possible to study the full details of these spectra without using the data from both experiments.

In the region, S, associated with the IP shock, the spectral exponent of protons is ~-1.1 below ~1 MeV. At energies above 2-3 MeV it is a power law with exponent – 2.8. In the region, M, associated with the peak magnetic field strength, the spectrum is a power law with exponent = -1.7 at lower energies with a sharp cut-off at ~2 MeV.

Overall the composite proton spectrum has a power law exponent = -1.4 up to 1.0 MeV, steepening to -3.2 above 2 MeV. In most astrophysical situations, both locally and near shocks throughout the galaxy, this is what would be seen by an observer, unaware of the finer details of the acceleration process.

The He nuclei are observed at energies >2 MeV/nuc where their intensity time profile and their spectral index are very similar to that of protons. The ratio of intensities at the same energy/nuc is 18 ±2 in both regions.

SUMMARY AND CONCLUSIONS

We have re-examined the energetic particle features of the giant MIR connected with the Halloween events of 2003 as it reaches the V2 spacecraft at 73 AU. Data from both the LECP and CRS instruments are used to cover the energy range from 0.06 to 20 MeV for protons. The intensity-time profile shows two distinct peaks, the 1st near the time of arrival of the shock at 2004.322 and the 2nd at the time of peak magnetic field fluctuations and field strength at 2004.367. This separation in time is equivalent to a radial distance ~4.3 AU for a disturbance moving outward at a speed of 500 $Km \cdot s^{-1}$. The two intensity peaks have a FWHM width ~0.040 year or 14 days which is slightly less than the peak separation time of ~16 days.

At the higher energies the intensity peak associated with the shock itself dominates the overall spectrum. At energies below ~1.0 MeV the intensity peak associated with the magnetic field maximum dominates the overall spectrum. As a result the two regions have distinctly different energy spectra. At energies below 1.0 MeV the spectrum in region M has a power law index of -1.7 and this spectrum has an abrupt cut-off above 2 MeV. At energies above 2.0 MeV the spectrum in region S has a power law index of -2.8, but at energies below 1 MeV the power law index is only ~-1.1.

The composite spectrum for H nuclei from both regions has a power law index of -1.4 below 1-2 MeV which steepens to -3.2 at energies between 2 and 20 MeV. This is the spectrum that would be seen by an observer who could not resolve the individual acceleration regions, as is the case in most astrophysical situations.

Helium nuclei between 2 and 8 MeV/nuc are also observed. These nuclei have a similar intensity time profile as protons of the same energy. They also have approximately the same energy spectrum. Their intensity is 18 ±2 times less than that of protons at the same energy.

We believe that this identification of two regions of energetic particle acceleration, near what is basically a single outward propagating interplanetary shock, has important theoretical implications in both heliophysics and astrophysics in general.

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