Energetic Particle Observations Near the Termination Shock

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Abstract. The most recent data from Voyager 1 (V1) show that a second event (TS2), apparently associated with the termination shock (TS), is in progress, with spectral characteristics similar to the energetic particle increase observed from 2002.4 - 2003.1 (TS1) [1,2]. We concentrate on the pressure, composition, and anisotropy profiles of TS1. The magnetic field pressure [3] is significantly smaller than the particle pressure perpendicular to the interplanetary magnetic field (IMF) in the 40-4000 keV range. The composition during the interplanetary shock event (ISE) observed by V1 during 1991 is drastically different from that during TS1 (C/O ~0.2 for ISE, ~0.02 for TS1). The dominant anisotropy during TS1 is azimuthally in the outward direction for a Parker spiral field, suggesting a source inward of the spacecraft, while the radial anisotropy is consistent with zero (-0.024 ± 0.02), implying a slow (<50 km/s) plasma flow speed. We conclude that the totality of the data is consistent with V1 being in the heliosheath during TS1.

INTRODUCTION

The unusual energetic particle increases observed by V1 beginning in mid-2002 (TS1) have been interpreted either as due to crossing of the TS into the heliosheath [1] or as upstream precursors of the TS [2]. Arguments for upstream precursors included time delays from Voyager 2 of discrete particle enhancements [2], while arguments based on composition and anisotropy measurements were used to infer a decrease in the solar wind velocity to ≤50 km/s [1]. However, measurements of the interplanetary magnetic field (IMF) did not show the predicted increase in IMF expected from the solar wind slowdown [3]. The details of the anisotropy measurements, the relative pressures of the magnetic field and the particles, and the composition must be inclusively consistent for either interpretation of the TS1 event to be successful.

OBSERVATIONS

Figure 1 shows daily averages of the intensity profiles of three channels from the Low Energy Charged Particle (LECP) instrument on V1 [4], together with the spectral index γ for a power law spectrum of the form $dj/dE = KE^{-\gamma}$. The period plotted has been divided into three intervals: TS1 discussed previously, TSU (upstream), and TS2, as marked by the three vertical lines. The first interval (TS1) shows substantial structure over periods as small as a day, with fluctuations that are coherent over a factor ~20 in velocity. Short-duration, lower intensity spikes characterize the second interval (TSU); these are reminiscent of increases upstream of interplanetary shocks and planetary bow shocks [5]. Note that intensities generally return to pre-event background in between spikes. Note also the absence of significant electron increases. The third episode (TS2) is still in progress and bears striking resemblance to TS1, including a strong relativistic electron component. The spectral parameter γ, plotted in the top panel, gives a clear discriminator of the differences in the three regions. During TS1, the value is ~1.5; during TSU, the spectrum is softer with γ~2, while during TS2 the spectrum hardens again with γ~1.5.

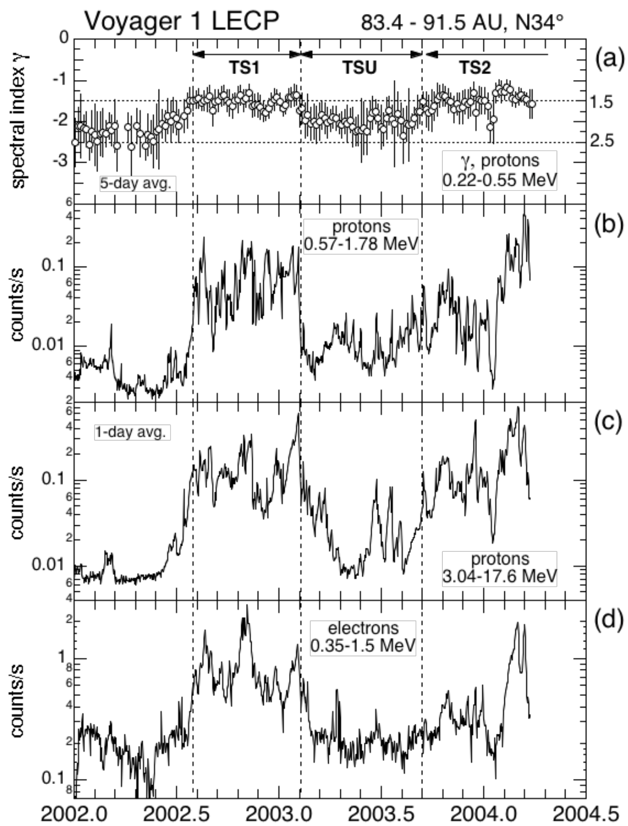

Figure 1. Count rate profiles of three characteristic LECP channels from 2002 to the present. Note the coherent fluctuations in the top two panels, and the major peak coincidence of protons and electrons (bottom panel). The spectral index exhibits characteristic values during periods TS1 and TS2, but a different value during TSU, when the spacecraft is thought to be upstream of the TS.

The full spectra and ion composition during TS1 are contrasted in Figure 2 with the interplanetary event of 1991. The right panel shows the power law enhancements at ≤4 Mev/nuc for all species, with the exception of C. At higher energies, the hump associated with anomalous cosmic rays (ACR) is evident for O. By contrast, the panel on the left shows the spectra averaged over a similar time interval from the largest interplanetary shock event (ISE) observed by V1 in the outer heliosphere at ~46AU [6]. The slope is similar at the lower energies, but here C is also accelerated, and the ratio C/O is ~0.2, consistent with a solar particle source. In fact, overall abundance ratios for He/O and C/O were strikingly different during TS1 compared to the ISE as shown in Table 1, thus making it unlikely that the intensity increases in TS1 were accelerated from a seed population in the inner heliosphere, as had been suggested [2].

TABLE 1. Relative Abundances at 1 MeV/nuc.

Compositional Ratio	2002 (TS1)	1991 (ISE)
He/O	~17	~81
C/O	~0.02	~0.2

The dynamical nature of the increases during TS1 is shown in more detail in Figure 3 where the magnetic pressure $B^2/8\pi$ [3] is compared to particle pressure. The upper panel shows the perpendicular pressure estimated from sectors 1 and 5 [4] in the range measured by LECP transverse to the nominal magnetic field direction, while the lower panel shows the pressure as extrapolated to ~10 keV (since there is little indication from Figure 2 that that the spectra may be bending over at the lower energies). The transverse particle pressure generally exceeds the magnetic pressure except in cases where there is a relative minimum in the particles (e.g. 2002.67). In many instances particle pressure peaks are anti-correlated with magnetic pressure, suggesting filamentary spatial structures.

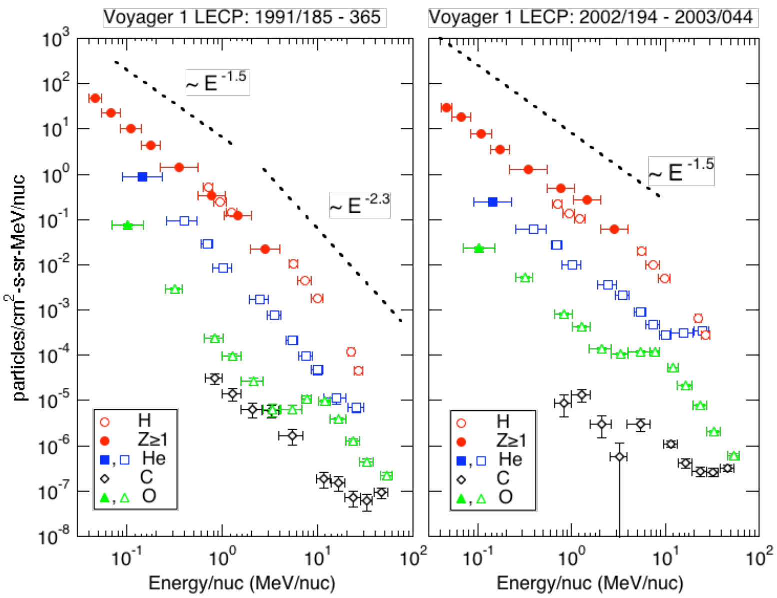

Figure 2. Comparison of composition spectra during TS1 (right panel), and for the 1991 interplanetary shock event (left panel). The C/O ratio was drastically different (~0.02 and ~0.2 at 1 MeV/nuc for TS1 and ISE, respectively) in the two periods, indicating the different sources for ISE (solar) and TS1 (ACR) particles.

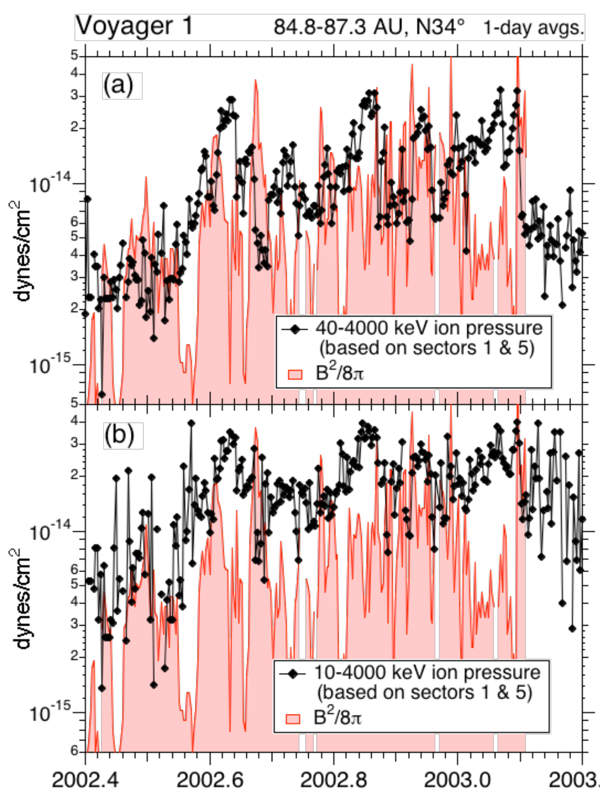

Figure 3. Computation of magnetic field [3] pressure compared to perpendicular particle pressure for two cases: (a) observed LECP energy range (upper panel) and (b) extrapolated spectra to 10 keV (lower panel).

ANISOTROPY ANALYSES

The azimuthally outward-directed anisotropy [1] has been shown to be generally field-aligned and frequently quite strong [7], leading to the general conclusion that V1 was located downstream from the termination shock during TS1. Time-averaged anisotropy distributions were used to infer that the solar wind velocity had decreased from ~300 km/s upstream to <50 km/s downstream of the shock [1]. Figure 4 shows the angular measurements (black line) from one of the several LECP channels, together with fits using a Galilean velocity transformation (non-linear Compton-Getting) for a field-aligned weak-scattering (non-diffusive) angular distribution with spectrum $dj/dE = KE^{-1.5}$ [1,8]. The two cases illustrated are for solar wind velocities of 400 km/s (blue trace) and 0 km/s (red trace). The small flow speed is clearly the best fit to the data from all 7 measured sector rates, and this persists over the full energy range (~40 keV to ≥1Mev) of the angular measurements [1].

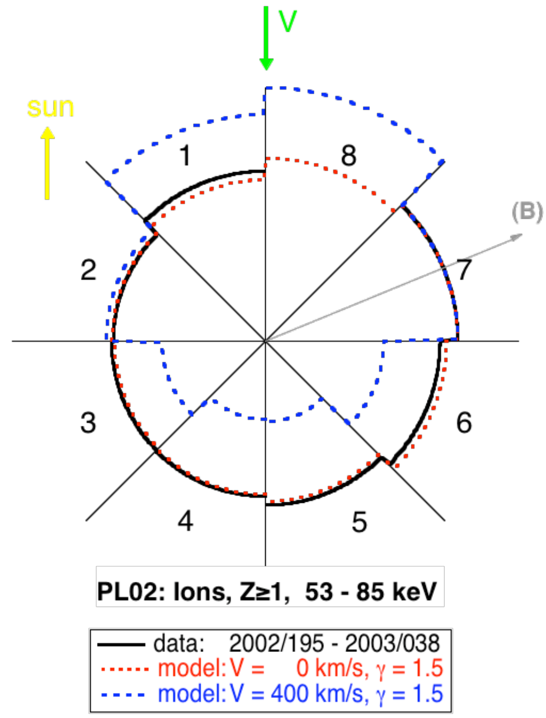

Figure 4. Angular distributions averaged over TS1 (black line) for 53-85 keV ions, typical of the full range of energies (40 keV to ~1 Mev). The model fits show Galilean velocity transformation to the spacecraft frame [8] for plasma flow speeds of 400 km/s (blue) and 0 km/sec (red).

On the other hand, interpreting the anisotropy measurements in terms of diffusion-convection theory, the radial flow is the difference between the contribution of an inward-directed diffusive flow driven by a positive radial gradient and the classical Compton-Getting anisotropy [8,9]. We examine this question by plotting the development of the radial anisotropy ξ_r during TS1 in Figure 5. Here ξ_r is on average consistent with zero (-0.024 ± 0.022), with only two notable exceptions of radial outflow (2002.61) and inflow (2002.68) at relative flux minima following onset of the event. Despite the strong intensity variations evident in Figure 5 on time scales as small as one day that are inconsistent with diffusive transport, a recent calculation [9] attempts to explain this result in terms of diffusive flow inward from the shock driven by a smooth upstream gradient, stating that such flow "…could account for the observations reported by Krimigis et al. if they were, in fact, upstream of the shock." (p. L147). This presumption, however, is completely inconsistent with the V1 anisotropy observations. The averaged field-aligned anisotropy (Figure 4) is azimuthally outward along the IMF [7], indicating unambiguously that the source of the particles is inside the radius of the spacecraft, so that V1 must be downstream of the shock. Although it has been argued that this outflow direction resulted from a local distortion in the shock geometry [10], just such a configuration would have had to recur one year later, because V1 is currently immersed in a second increase of energetic ions (TS2) whose behavior, in both intensities and anisotropies, is remarkably similar to the first episode (TS1) that we have discussed in this paper.

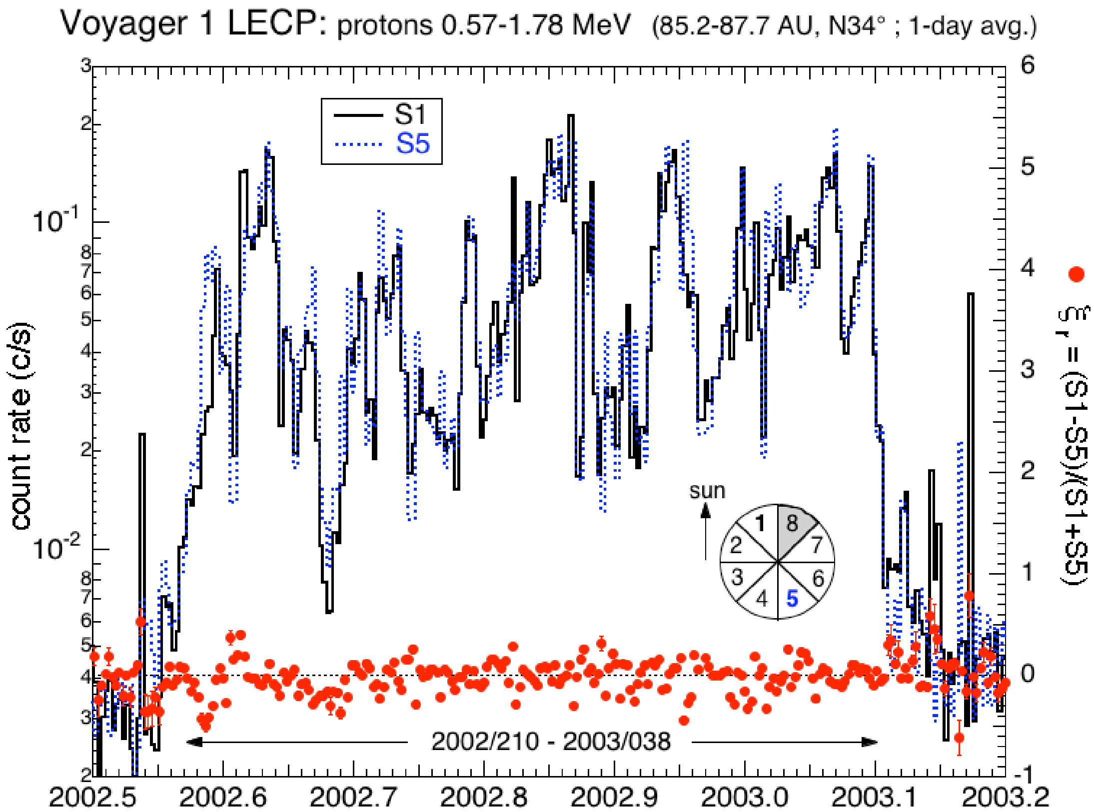

Figure 5. Observed radial anisotropies (Sector 1 *vs.* Sector 5) during TS1. The averaged anisotropy is statistically zero, indicating a very small (<50 km/s) flow speed.

SUMMARY AND CONCLUSIONS

Beginning in mid-2002 Voyager 1 observed remarkably large increases in energetic particle intensities, comparable to those previously seen at ~46 AU during the shock event of 1991. The intensity of all energies and species fluctuated coherently with time scales as small as one day, precluding the possibility of diffusive transport [1,8]. Most importantly, the frequent occurrence of beam-like field-aligned anisotropies [7] directed azimuthally away from the sun (in the sense of a Parker spiral) show that the particle source is downstream of the shock. This is contrary to recent calculations [9] that suggest that the zero-average radial anisotropy can be explained with V1 being in a diffusive regime upstream of the shock. The absence of a radial anisotropy is consistent with a very slow solar wind during TS1, an observation unique in the history of observations from both Voyagers [11].

Similarly, the unique composition signatures, whereby the C/O ratio of ~0.02 during TS1 is contrasted to a value of ~0.2 during the 1991 ISE, rules out source from a transient shock in the inner heliosphere [2], while the composition during TS1 is consistent with an ACR source. The high beta plasma present throughout this period and the general anti-correlation with the field pressure (Figure 3) has never been seen in the solar wind proper. All of the above lead to the conclusion that V1 was located beyond the TS during TS1. The spectral index history for the entire period (Figure 1) also suggests that the event currently in progress (TS2) is likely another crossing, with behavior very similar to TS1. During the intermediate period (TSU) Voyager 1 was upstream of the TS and observing upstream events. These observational facts are summarized in Table 2.

TABLE 2. Observational facts for modeling of energetic particles at the termination shock (TS)

Observation	**Comments and/or Implications**
Power-law spectrum to <40 keV	NOT unfolding at low energies as TS is approached or crossed
No velocity dispersion	Intensities at all energies (40 keV to >20 MeV) rise simultaneously (within counting statistics). Also, relativistic electron onset is similar to that of protons.
Highly (>200%) anisotropic, field-aligned distributions	Little evidence for diffusive equilibrium for >6 months.
Large, coherent, fluctuations	Time scales of hours to several days for all species.
Composition is ACR/PUI	Not consistent with convected solar wind/solar particle source.
Perp. particle pressure is $>B^2/8\pi$	For E>40 keV, and much more for >10 keV
GCRs at V1 not well correlated to V2 [1]	Why shouldn't GCR changes propagate radially outward after ~2002.5?

ACKNOWLEDGMENTS

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