Voyager 1 exited the solar wind at a distance of ∼85 AU from the Sun

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The outer limit of the Solar System is often considered to be at the distance from the Sun where the solar wind changes from supersonic to subsonic flow[1]. Theory predicts that a termination shock marks this boundary, with locations ranging[2] from a few to over 100 AU (1 AU ≈ 1.5 × 10^8 km, the distance from Earth to the Sun). 'Pick-up ions' that originate[3,4] as interstellar neutral atoms should be accelerated to tens of MeV at the termination shock, generating anomalous cosmic rays[5–7]. Here we report a large increase in the intensity of energetic particles in the outer heliosphere, as measured by an instrument on the Voyager 1 spacecraft. We argue that the spacecraft exited the supersonic solar wind and passed into the subsonic region (possibly beyond the termination shock) on about 1 August 2002 at a distance of ∼85 AU (heliolatitude ∼34° N), then re-entered the supersonic solar wind about 200 days later at ∼87 AU from the Sun. We show that the composition of the ions accelerated at the putative termination shock is that of anomalous cosmic rays and of interstellar pick-up ions.

The low-energy charged particle (LECP) instrument[8] on Voyagers 1 and 2 consists of a collection of solid-state detectors designed to perform measurements of ions (∼30 keV to tens of MeV) and electrons (∼28 keV to ∼10 MeV), including elemental composition over a range of energies (≥0.3 MeV per nucleon) and species (H, He, C, N, O, Ne, and so on). The double-ended detector telescope system is mounted on a stepping platform that rotates through 360° parallel to the R–T plane of the [R,T,N] coordinate system in eight sectors, with one sector shielded so as to provide background measurements. Each step occurs every 192 s.

In late 2000 (Fig. 1), a sustained increase of low-energy protons was measured at Voyager 1 with less intense but more structured activity measured at Voyager 2 (time-shifted for convection to the distance of Voyager 1 from the Sun ('radius') using the observed solar wind velocity at Voyager 2). Possible precursor enhancements in the 0.6 MeV protons occurred in late 2000 when Voyager 1 was located at ∼80 AU. Only two Voyager 1 increases (on decimal years 2001.2 and 2000.0) before the 2002.5 event are correlated with Voyager 2, while other Voyager 1 increases show higher intensities for this period, contrary to the conclusion of ref. 9. In mid-2002, however, there was a large, 100-fold increase at Voyager 1 with no obvious counterpart at Voyager 2. The Voyager 1 increase is the largest since the 1991 solar-flare-associated event when the spacecraft was located approximately half its present distance from the Sun[10]. From 2002.5 to 2003.1 little correlation is evident in either peak intensities or duration between Voyager 1 and the Voyager 2 time-shifted profiles. The possibility remains, however, that if significant solar/interplanetary activity occurred predominantly in northern heliographic latitudes (where Voyager 1 is located), it might have propagated asymmetrically and reached Voyager 1 without being first observed by Voyager 2 at southern heliolatitudes. Observations from instruments on the Advanced Composition Explorer (ACE) (at 1 AU) in the ecliptic plane and Ulysses (at ∼4 AU, ∼24–45° N) argue against such a possibility. Measured intensities between 1 and 4 AU are found to decrease in helioradius as $\sim R^{-2}$ while those from Ulysses to Voyager 1 decline as $\sim R^{-1}$, that is, the Voyager 1 intensities could not have been convected from the inner heliosphere without additional acceleration[11]. Finally, a Forbush decrease in galactic cosmic rays (GCR) typically associated with interplanetary events such as the one in 1991 (ref. 10) is not only absent in the last half of 2002, but replaced by a ∼20% increase (Fig. 1c). Note the coherence at Voyager 1 between the GCRs and the lower-energy particles in both the overall increase as well as the relative maxima.

The earliest possible onset in mid-2002 is on day 162 (11 June 2002) when Voyager 1 was located at ∼84.7 AU. Judging from typical reverse interplanetary shocks observed on Ulysses[12], however, these increases were probably precursors, whereas the exit from the solar wind most probably occurred near day 213 ± 5 days (1 August 2002). Importantly, spatial/temporal structures as short as 1–3 days exist, a highly unusual characteristic for either co-rotating inter-

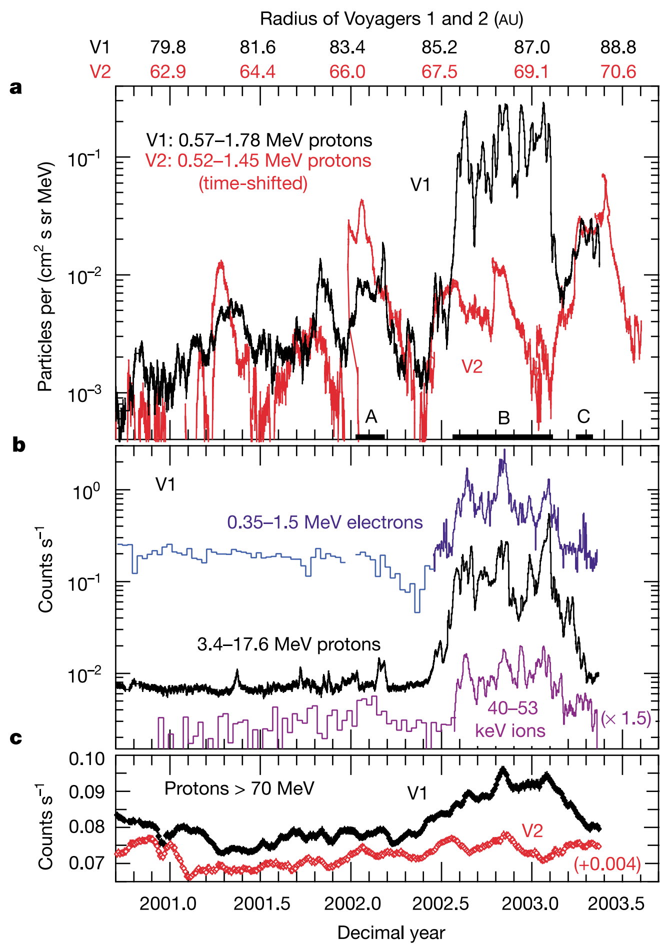

Figure 1 Intensity profiles at Voyager 1, Voyager 2 since late 2001. **a**, Profiles at Voyager 1 and Voyager 2 (time-shifted) using solar wind velocities measured at Voyager 2 (J. Richardson, personal communication). The Voyager 1 increase on 2002.5 is unique with no counterpart at Voyager 2. The three horizontal bars (A, B, C) denote periods where angular distributions were used to infer the solar wind velocity (Fig. 3). **b**, More-detailed profiles of daily averages for indicated energies and species. **c**, Intensity of >70 MeV GCRs at Voyager 1, together with equivalent channel (non-time-shifted) at Voyager 2.

action regions or global merged interaction regions[13]. Such short-term structures (Fig. 1a, b) are typically associated with shocks and are most probably either connection/disconnection of the interplanetary magnetic field with the shock fronts[14] or possibly filamentary structures within this region of the heliosphere. The acceleration of high-energy electrons over such a long period in the outer heliosphere (as evident by the intensity increases in Fig. 1b) is only consistent with previous observations at perpendicular shocks[15].

Anisotropy measurements for ~0.6 MeV protons are shown in Fig. 2. Protons arrive at the spacecraft predominantly from the azimuthal direction (sectors 7 and 6), between which the average Parker interplanetary magnetic field is expected to be located, and stream 'outward', implying a source inside the location of Voyager 1. The hemisphere in the opposite direction (sectors 1–4) displays a nearly isotropic distribution. This observation would be surprising if Voyager 1 was still inside the termination shock, since one would then expect a significantly higher intensity in sector 1 than sector 5 owing to convection from the solar direction by the solar wind. That prevalence of sector 1 rates has been observed by LECP for the past 25 years (ref. 16).

Figure 3 shows model fits (see Methods) and observed sector rates for the period of interest plus averaged rates during periods from before and after the mid-2000 event. Figure 3a shows fits to ~1 MeV protons before, during and after the 2002.5 increase, with solar wind velocities of ~300, ~0 and ~230 km s^{-1}, respectively. Figure 3b displays similar fits in five consecutive energy intervals. The 0 km s^{-1} model is in good agreement with the observations and the fitting error (Fig. 3c) suggests an upper limit of <50 km s^{-1}. It is also remarkable that the inferred direction of the interplanetary magnetic field is ~22° inward from the T-direction where the Parker spiral predicts a tangential field direction to within a degree at this distance in the solar wind. We conclude from this analysis that the plasma flow changed from supersonic (~300 ± 30 km s^{-1}) in early 2002 to subsonic (<50 km s^{-1}) for the period of high intensities and back to supersonic (~230 ± 25 km s^{-1}) following re-entry into the upstream solar wind, validating the premise that Voyager 1 had crossed a boundary for the first time in the July–August timeframe of 2002 and again in early 2003.

The Voyager 1 energy spectra (Fig. 4) demonstrate that the low-energy enhancement is relatively poor in carbon (C/O ≈ 0.02), as is the case for pick-up ions and anomalous cosmic rays (ACRs). The spectral shape is not the monotonically decreasing form for an unmodulated spectrum that was expected beyond the termination shock[6]. Instead, there appear to be two components—a power-law component at lower energies and a peaked spectrum at higher energies, observable at ~7 MeV per nucleon for O and indicated at the highest He energies shown. In this interpretation, the entire proton spectrum shown is locally accelerated at the termination shock, as are the He and O spectra below 10 MeV per nucleon and 2 MeV per nucleon, respectively. Above those energies the local He and O components are masked by an ACR component accelerated elsewhere. The spectral peaks thus result in the usual way, from energy-dependent transport from the remote acceleration sites to Voyager 1[17].

The salient features of the observations are as follows: (1) A gradual increase in ~1-MeV proton intensity in late 2000 culminated in a 100-fold step increase in mid-2002 lasting for over six months and ending within a few hours in early 2003. (2) The step increase was seen in energies ranging from ~40 keV to >70 MeV for protons and >0.35 MeV for electrons. (3) Large intensity fluctuations lasting from <1 to several days were present coherently in all energies and species throughout the period. (4) The composition of H, He, O and C are consistent with an ACR or pick-up ion source. (5) Outward-streaming anisotropies show that the particle source lies inside the Voyager 1 location. (6) Generalized Compton–Getting fits to the angular distributions show that the convection velocity changed from supersonic to subsonic and back to supersonic before, during, and after the increase, respectively.

The LECP data presented above demonstrate that Voyager 1 in July–August 2002 entered a new region in the outer heliosphere at a distance of ~85 AU, remained in it for about six months and re-entered the upstream solar wind at 87.4 AU. This conclusion is supported by the large, prolonged ion- and electron-intensity

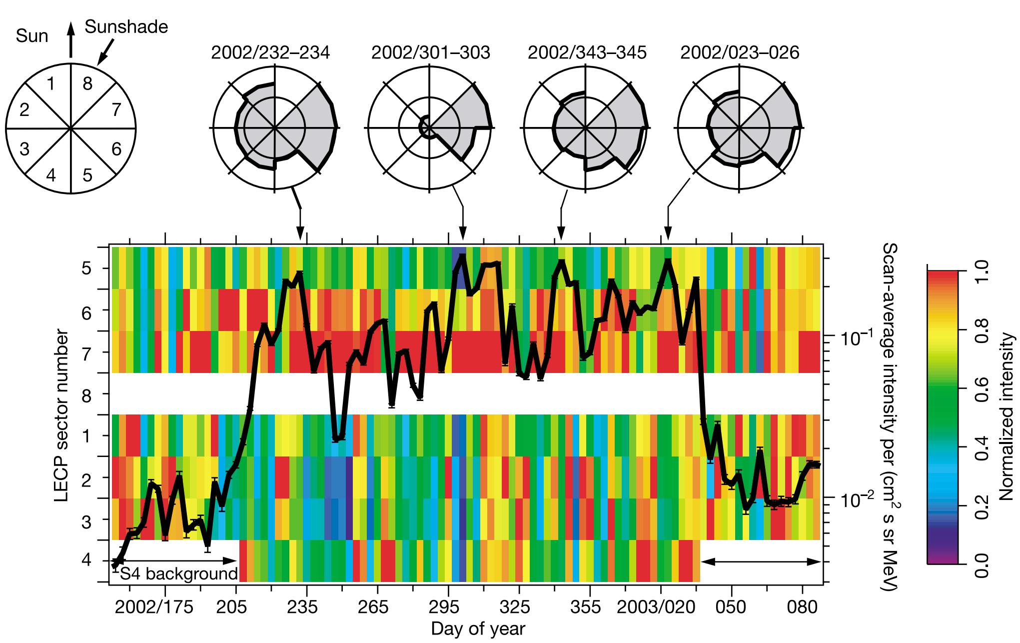

Figure 2 Data from Voyager 1 LECP for 0.57–1.78 MeV protons. Pie plots show three-day averaged normalized intensities of ~1-MeV protons for four selected flux peaks; the colour scale depicts arrival directions for all the data. The black trace shows the sector-averaged intensities. Sector 8 (see key to pie plots) contains a sunshade, so no foreground data are obtained in that direction.

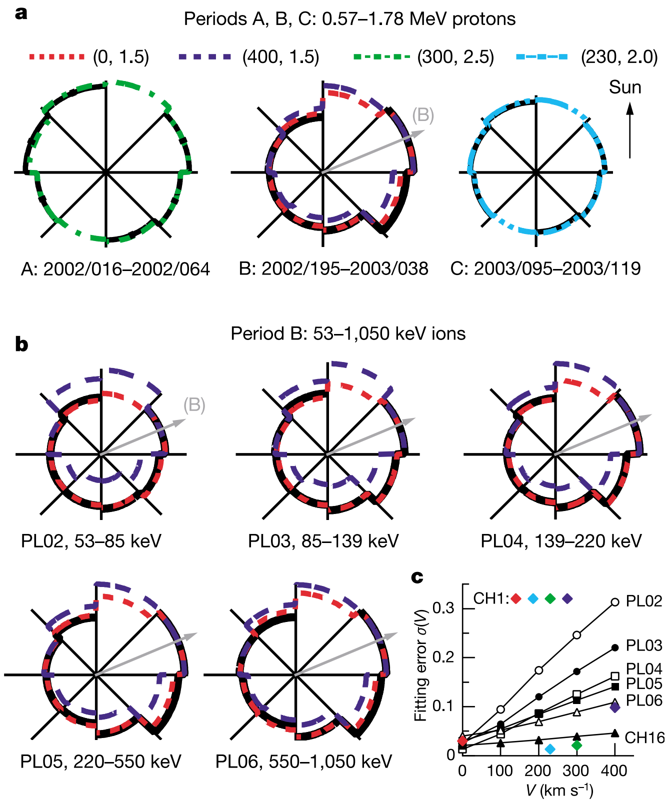

Figure 3 Anisotropy plots of time-averaged sector rates for periods A, B and C noted in Fig. 1 and solar wind velocity fits thereof. Solid black curves, data. Coloured dashed curves, models for ($\mathbf{V}$, γ) cases ($\mathbf{V}$ in km s^{-1}). **a**, Data fits for ~1-MeV protons for periods when Voyager 1 was upstream (left), in heliosheath (middle), and upstream again (right), with best fits of ~300 km s^{-1}, 0 km s^{-1}, and ~230 km s^{-1}, respectively. **b**, At lower energies (Voyager 1 in heliosheath), model-predicted rates best-fit data (statistical error is less than the line thickness) at 0 km s^{-1}. 'B' indicates the best-fit particle streaming direction. **c**, Model-fitting errors for each channel show the degeneration of fit as velocity increases.

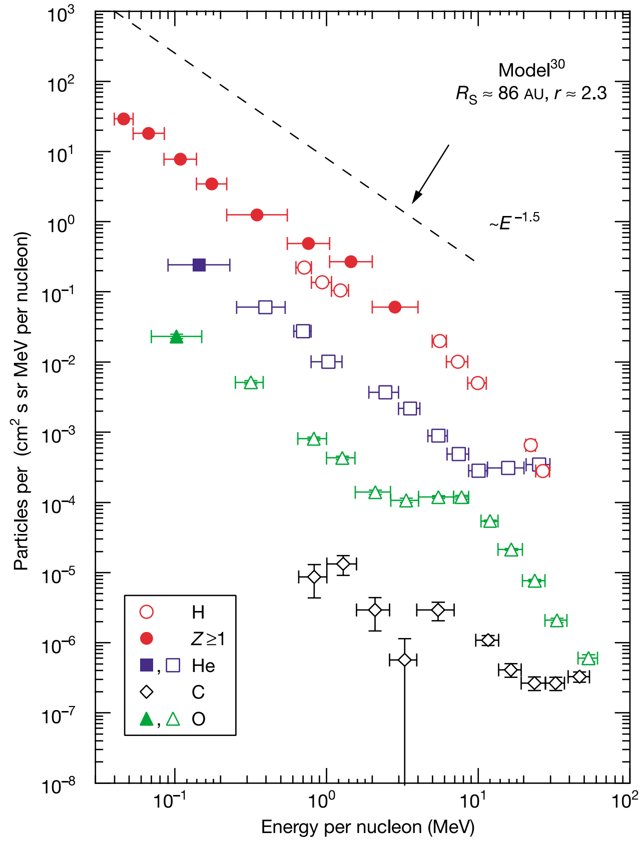

Figure 4 Composition spectra for the duration of Voyager 1's excursion into the heliosheath from LECP 2002/194 to 2003/044. At lower energies the spectrum is of the form $j = KE^{-\gamma}$, with $\gamma \approx 1.5$ for the three major species. There is no commensurate increase in the intensity of C (C/O ≈ 0.02 at ~1 MeV). The relative abundances at ≤2 MeV per nucleon are consistent with the ACR H, He and O measurements made by LECP during the peak of the most recent recovery period (~1995–1999) (ref. 17 and references therein), as well as pick-up ions[4]. The higher-energy component is of modulated ACRs observed by LECP before this event. Dashed line shows model predictions[30].

increases at Voyager 1 from 2002.5 to 2003.1 with no corresponding increases at Voyager 2, and the complete lack of a Forbush decrease in either ACR or GCR intensities, making an interplanetary disturbance a highly unlikely explanation. The ~20% GCR increase could be a manifestation of either additional acceleration at the termination shock at $E > 70$ MeV or a substantial gradient in GCR intensity between the heliosphere proper and the heliosheath, or both. The 'decreased modulation' scenario suggested[9] to explain the GCR increase cannot be valid, because such a change in modulation was not seen earlier by Voyager 2 (Fig. 1c), as is generally the case for convective delays. The anisotropies are directed outward, implying that Voyager 1 is beyond the termination shock and that the composition of H, He, C and O is consistent with both ACRs and pick-up ions, as would be expected near the termination shock.

Slowing of solar wind flow must be accompanied by changes in interplanetary magnetic field as required by the 'frozen-in' magnetic-field condition[1]. Only a small (~50–100%) magnetic field increase has been reported[18] in mid-2002. The observation that particles are streaming ~22° off the tangential direction (Fig. 3), presumably along the interplanetary magnetic field, suggests that the field is not in the Parker spiral direction as would be expected if Voyager 1 was still in the supersonic solar wind. The interplanetary magnetic field at this latitude (34°) may be more like the Fisk field[19], possibly deformed by FALTS (favoured acceleration locations at the termination shock[20]) being more radial than the Parker field, with its strength decreasing more like R^{-2}. Hence the ~0.044-nT magnetic field[20] may well be consistent with the observed decrease in the solar wind velocity.

The high fluxes of pick-up ions would change the nature of the termination shock from the conventional model, reducing the upstream Mach number, hence weakening the shock, and slowing down the solar wind[21–23] to 200–300 km s^{-1}, as suggested by our measurements. Such a strongly moderated shock has never been observed previously anywhere in the heliosphere. The closest analogues may be mass-loaded cometary shocks that produce copious quantities of accelerated ions and rarely show a definitive change in magnetic-field strength at crossing the bow shock[24,25]. The putative termination shock may well be a new variant that will test our understanding of the overall shock formation and acceleration processes. □

Methods

We extract the solar wind velocity ($\mathbf{V}$) by using the effect produced by the convection on the LECP intensity anisotropy. The Galilean transformation into the spacecraft frame is $f(\mathbf{v}) = f'(\mathbf{v} - \mathbf{V})$. The unidirectional differential intensity (which LECP measures) is $j(E, \mathbf{u}) = (v^2/m)f(\mathbf{v}) = (E/E')^2 j'(E', \mathbf{u}')$, where E is the energy and the particle velocity direction is $\mathbf{u} = \mathbf{v}/v$. It is usually assumed[26] that $j'(E', \mathbf{u}')$ is isotropic (independent of $\mathbf{u}'$) and that the transformation is linearized to $O(V/v)$. That approximation has been applied successfully[16] to the extraction of the solar wind velocity from the LECP anisotropy measurements on Voyager 1 and Voyager 2. However, the current Voyager 1 LECP measurements indicate significant field-aligned anisotropies strong enough to invalidate the use of the linearized transformation. Consequently, on the basis of gyrotropic weak-scattering theory[27], we assume an exponential distribution in pitch-cosine $j' = j_0(E')\exp[\alpha(v')\mu']$ that is convected with the solar wind[28]. We transform it (nonlinearly) into the spacecraft frame: $j(E,\mu) = j_0(E)C^{-(k+1)}\exp[\alpha(v)(\mu - V_{\parallel}/v)C^{(n-1)/2}]$, where $C = E'/E = 1\text{–}2\mathbf{V}\cdot\mathbf{v}/v^2 + V^2/v^2$, $V_{\parallel}$ is the component of the solar wind velocity along the magnetic field. We have also assumed that $V \ll v, j_0 \propto (E')^{-k}$ and $\alpha \propto (v')^n$. The measured spectral index is $k = 1.5$ and we find that $n \cong 0$ over the range of LECP energies. We allow for the weak coupling (backscatter) between hemispheres by setting $\alpha = \alpha_+$ for $\mu > V_{\parallel}/v$ and $\alpha = \alpha_-$ for $\mu < V_{\parallel}/v$. The LECP distributions consistently peak in sector 7, so we assign the direction of the magnetic field to its centre and normalize the intensities there (thus eliminating j_0). The normalized intensities in the remaining six sectors (sector 8 is blocked) for each LECP channel are then fitted by a least-squares minimization that varies the remaining parameters (α_+,α_-, and V). Thus we extract the solar wind velocity from the LECP angular distributions (see Fig. 3).

We could not explain our observations using diffusion–convection (strong-scattering) theory[29] under the assumption that Voyager 1 did not leave the normal solar wind and magnetic field, as suggested[9,18]. The equation describing the radial transport is $\xi_r = (3/v)(CV\text{–}\kappa_{rr}G_r)$, where ξ_r is the radial anisotropy coefficient, $C = 2(k+1)/3$ is the (linearized) Compton–Getting factor, $G_r = \partial \ln j/\partial r$ is the radial (logarithmic) gradient, and κ_{rr} is the relevant component of the diffusion tensor. The condition for diffusion–convection equilibrium with no radial streaming in the inertial frame is $\xi_r = 0$. This implies a positive radial gradient, $\kappa_{rr}G_r = CV > 0$, with a source of particles beyond Voyager 1 in order to nullify the solar wind convection. For an approximately diagonal diffusion tensor (appropriate to the outer heliosphere), the azimuthal anisotropy is $\xi_\phi = (3/v)(-\kappa_{\phi\phi}G_\phi)$. Because LECP observes a strong azimuthal anisotropy $\xi_\phi < 0$, this implies $G_\phi > 0$. If the average magnetic field is wound in a Parker sense, $G_\phi > 0$ corresponds to gradient of increasing intensity as one moves inward along the field. This parallel streaming then implies a source of particles inside the radius of Voyager, but this is inconsistent with the positive radial gradient $G_r > 0$ demanded by the radial transport equation.

We examined the quantitative implications of the diffusion–convection equation for long-term averages of the radial anisotropy $\langle\xi_r\rangle$ and its variance $\sigma_\xi^2 = \langle\delta\xi_r^2\rangle$. Diffusive balance implies that $\langle\xi_r\rangle = 0$, so that $\kappa_{rr}\langle G_r\rangle = CV$, under the assumption of no significant variation in either the solar wind velocity or the diffusion coefficient. The diffusion–convection equation also implies that $\sigma_\xi = \kappa_{rr}\sigma_G$, where $\sigma_G^2 = \langle\delta G_r^2\rangle$. Taking the ratio of the mean and root-mean-square equations, the diffusion coefficient cancels out and we find that $\sigma_G/\langle G_r\rangle = v\sigma_\xi/3CV$. We have estimated the mean $\langle\xi_r\rangle$ and the variance σ_ξ^2 of the radial anisotropy measured directly by LECP Channel 1 from the ratio of Sector 1 to Sector 5 (see Fig. 2). From $\xi_r = (S1\text{–}S5)/(S1 + S5) \cong (S1/S5 - 1)/2$, we find during period B that $\langle\xi_r\rangle \cong -0.015$ and $\sigma_\xi = 0.15$. Using the observed $k = 1.5$ we have $C = 5/3$. Using $350\,\mathrm{km\,s^{-1}}$ for the normal solar wind velocity and $14{,}000\,\mathrm{km\,s^{-1}}$ for the 1-MeV protons in channel 1, we conclude that $v\sigma_\xi/3CV = 1.2$. This value implies an abnormally disturbed region with $\sigma_G \approx \langle G_r\rangle$. We can estimate σ_G itself in the diffusion-convection context by assuming that the quasi-sinusoidal non-dispersive LECP intensity variations δj with period T were caused by spatial structures with instantaneous gradients (δG_r) being convected with velocity V over the spacecraft so that $V\delta G_r = \partial \ln j/\partial t$. There are about a dozen large ($\Delta \ln j > 1$) sinusoidal variations in LECP channel 1 over the 208 days during period B ($T \cong 16$ days). Therefore $V\sigma_G > 0.29\ \mathrm{day}^{-1}$, so for $V = 350\,\mathrm{km\,s^{-1}}$, we have the estimate $\sigma_G = 1.44\,\mathrm{AU}^{-1}$. Since we previously found that $\langle G_r\rangle \approx \sigma_G$, we obtain a time-averaged radial gradient $\langle G_r\rangle \approx 1\,\mathrm{AU}^{-1}$ that (along with its variation σ_G) is orders of magnitude bigger than gradients usually deduced for the outer heliosphere. We consider it unreasonable that such a configuration could endure there for half a year.

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Enhancements of energetic particles near the heliospheric termination shock

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The spacecraft Voyager 1 is at a distance greater than 85 AU from the Sun, in the vicinity of the termination shock that marks the abrupt slowing of the supersonic solar wind and the beginning of the extended and unexplored distant heliosphere[1,2]. This shock is expected to accelerate 'anomalous cosmic rays'[3], as well as to re-accelerate Galactic cosmic rays[5] and low-energy particles from the inner Solar System[4]. Here we report a significant increase in the numbers of energetic ions and electrons that persisted for seven months beginning in mid-2002. This increase differs from any previously observed in that there was a simultaneous increase in Galactic cosmic ray ions and electrons, anomalous