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An asymmetric solar wind termination shock

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Voyager 2 crossed the solar wind termination shock at 83.7 AU in the southern hemisphere, ~10 AU closer to the Sun than found by Voyager 1 in the north[1–4]. This asymmetry could indicate an asymmetric pressure from an interstellar magnetic field[5,6], from transient-induced shock motion[7], or from the solar wind dynamic pressure. Here we report that the intensity of 4–5 MeV protons accelerated by the shock near Voyager 2 was three times that observed concurrently by Voyager 1, indicating differences in the shock at the two locations. (Companion papers report on the plasma[8], magnetic field[9], plasma-wave[10] and lower energy particle[11] observations at the shock.) Voyager 2 did not find the source of anomalous cosmic rays at the shock, suggesting that the source is elsewhere on the shock[12–14] or in the heliosheath[15–19]. The small intensity gradient of Galactic cosmic ray helium indicates that either the gradient is further out in the heliosheath[20] or the local interstellar Galactic cosmic ray intensity is lower than expected[21].

Low energy ions accelerated at the termination shock are observed upstream of the shock and in the heliosheath (Fig. 1). Voyager 2

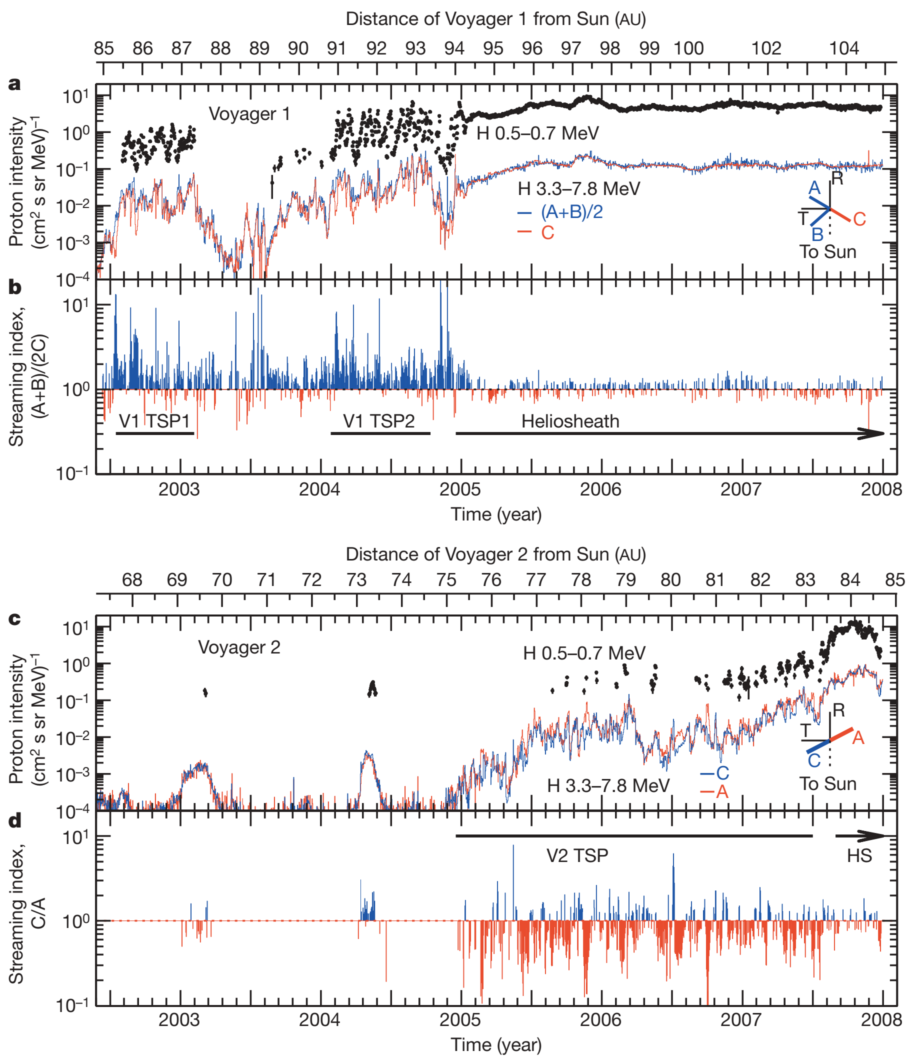

Figure 1 | Daily-averaged intensities and streaming of energetic termination shock particles that are accelerated at nearby regions of the shock. Voyager 1 and Voyager 2 crossed the shock and entered the heliosheath on 2004.96 (16 December 2004) at heliographic coordinates of (34.3°, 173°) and on 2007.66 (30 August 2007) at (−27.5°, 216°), respectively. Insets, telescope (A, B and C) viewing directions projected into the R–T plane, where −R is towards the Sun and T is azimuthal. Error bars on black filled circles, ±1s.d. **a**, The proton intensities (H) at 3.3–7.8 MeV observed by Voyager 1 particle telescopes (A+B)/2 (blue trace) and by C (red trace) are highly variable upstream of the shock owing to variations in the connectivity along the spiral field line[28,29]. The energetic ions are convected into the heliosheath, resulting in reduced variations. Similar properties are apparent in the intensity of 0.5–0.7 MeV protons observed by telescope A (black filled circles) and shown when the background correction was <60%. V1 TSP1 and V1 TSP2, two episodes of termination shock particles observed by Voyager 1. **b**, The streaming index (A+B)/(2C) for 3.3–7.8 MeV protons shows that upstream the ions at Voyager 1 were strongly beamed in the –T direction, with intensities in the oppositely directed detectors differing by up to a factor of 10. The intensities are more nearly isotropic in the heliosheath. Blue indicates that the average intensity in telescopes A and B exceeds that in C, indicating flow in the –T direction; red indicates the opposite. **c**, Same as **a** for Voyager 2 except that only telescopes A and C are used in determining the directional intensities of 3.3–7.8 MeV protons. **d**, Same as **b** for Voyager 2 except that only telescopes A and C are used. The upstream beaming was mainly in the +T direction, opposite to that observed by Voyager 1 and consistent with the predicted east–west shock asymmetry resulting from a local interstellar magnetic field[5,6,30]. Voyager 2 began observing upstream energetic ions at 75 AU from the Sun[1], 10 AU closer than did Voyager 1, leading to predictions that the shock would be closer in the southern hemisphere than in the north, but with significant differences in the predicted asymmetry[5–7]. HS, heliosheath.

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began observing upstream ions at 75 AU, leading to model predictions, differing in detail, that the shock would be found closer to the Sun by Voyager 2 than by Voyager 1 (refs 5–7). The observed shock location[8–11], low heliosheath plasma temperature[8], and high energetic ion pressure[11] will lead to improvements in the models.

There has been little variation in the intensity of termination shock particles (TSPs) observed by Voyager 1 in the heliosheath since mid-2005. However, the intensity of helium nuclei with an energy of 1–1.5 MeV per nucleon and 4–5 MeV protons at Voyager 2 just after it crossed the termination shock was three times larger than Voyager 1 observed concurrently (Fig. 2), suggesting that shock conditions affecting acceleration vary with time or shock region. Given the stability of the TSP intensity at Voyager 1, it will be important to determine the evolution of the spectrum at Voyager 2.

Among the surprises from the Voyager 1 termination shock crossing was that the intensity of anomalous cosmic rays (ACRs) did not peak at the shock as predicted[1]. Models have been proposed in which transients modify acceleration by the shock[22–24], the source of higher energy ACRs is the flank or tail region of the shock[12–14], or acceleration occurs as the particles diffuse outward in the heliosheath[15–19].

The Voyager 1 and Voyager 2 ACR proton and helium spectra just after the latter's shock crossing show distinct differences from those in late 2004 just after Voyager 1 crossed the shock (Fig. 2). The similarity of the changes at Voyager 1 in the heliosheath and Voyager 2 upstream (Figs 2 and 3) between the two spacecrafts' shock crossings suggests a common temporal change due to decreasing solar modulation. As a result, the Voyager 2 intensity of 12–22 MeV per nucleon He just after the shock was 8.4 ± 1.8 times the intensity at Voyager 1 just after its crossing. It was, however, a factor of 2.5 ± 0.4 smaller than the concurrent Voyager 1 intensity in the heliosheath, indicating that Voyager 2 did not observe the expected ACR source spectrum near the shock.

The ratio of the Voyager 1 and Voyager 2 intensities is a measure of the gradient between the spacecraft. The energy dependence of the proton and helium ratios (Fig. 2c, d) is essentially the same, but with the energy scales differing by a factor of four. Such scaling is expected from diffusive processes involving ions with velocity v, mean free path λ, and diffusion coefficient $\kappa = v\lambda/3$. If the dependence of λ on the ion momentum per charge is $\lambda \propto R^{\gamma}$, where the rigidity $R = Mv/(Qe)$, then two species with masses M of M_1 and M_2 and charges Q of Q_1 and Q_2 will have the same κ if their energies per nucleon are scaled as $E_1/E_2 = ((M_1/Q_1)/(M_2/Q_2))^{2\gamma/(\gamma+1)}$. For singly ionized ACRs, an energy scaling of 4 to 5 (ref. 25) indicates that $\lambda \approx R$ to $R^{1.4}$ for $0.2 < R < 1.5$ GV. Thus, the scaling in Fig. 2 probably reflects a diffusive spatial gradient in the heliosheath and a remote ACR source at the flank or tail region of the shock or further out in the heliosheath.

The ACR gradients in the heliosheath are also apparent in Fig. 3a. The absence of a gradient between Voyager 1 and Voyager 2 for 61–73 MeV per nucleon ACRs since mid-2005 indicates that the mean free path for ions with rigidities $R > 1.4$ GV is sufficiently large that the intensity is uniform in the nose region of the heliosheath and is probably the ACR source intensity. The constancy of the intensity indicates a steady, high energy ACR source since at least mid-2005.

Shorter diffusive mean free paths for lower rigidities result in intensity gradients for lower energy ACRs. The Voyager 2/Voyager 1 He intensity ratio of 0.4 ± 0.1 at 12–22 MeV per nucleon (Fig. 2d) corresponds to a radial gradient of 4.5% per AU in the heliosheath. The radial gradient would be smaller if some of the difference between Voyager 2 and Voyager 1 was due to longitudinal or latitudinal gradients (see, for example, ref. 13).

A gradient of 4.5% per AU is reasonably consistent with the intensity increase of 12–22 MeV per nucleon He at Voyager 1 between 97.0 and 102.4 AU (2005.8 and 2007.3; Fig. 3a), but not with the factor of 10 increase that occurred in the 10 months immediately following the shock crossing. This suggests that the latter increase was temporal, not spatial as has been assumed in fitting stochastic acceleration models to the Voyager 1 observations. Another suggestion to explain

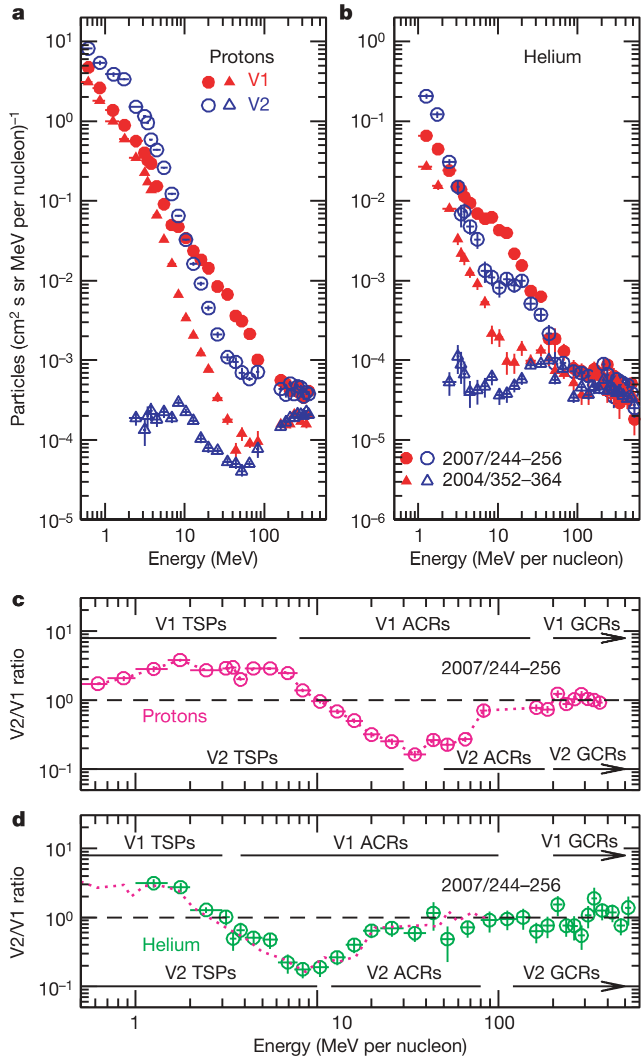

Figure 2 | Comparison of the energy spectra of protons and helium nuclei in the heliosheath near the times of the Voyager 1 and Voyager 2 shock crossings. During the 2004 period, Voyagers 1 and 2 were at 94.1 and 75.2 AU, respectively, and during the 2007 period, the former was at 103.8 AU and 34.3° N heliographic latitude and the latter was at 83.7 AU and 27.5° S. Error bars, ±1s.d. **a**, Proton spectra. Three components are apparent in 2007: TSPs convected from nearby shock regions (<6 MeV), anomalous cosmic rays (ACRs) that are modulated in the heliosheath (8–150 MeV), and Galactic cosmic rays (GCRs) (>200 MeV). The ACR and GCR intensities increased from 2004 to 2007 as solar modulation decreased with declining solar activity. In 2007, the Voyager 2 (V2) TSP intensity at 4–5 MeV was three times that at Voyager 1 (V1) and the spectrum from 0.5 to 3 MeV was $\sim E^{-1.1\pm0.1}$, harder than the Voyager 1 spectrum. The TSP spectra have breaks at ~3 MeV, with the Voyager 2 spectrum falling as $E^{-3.1\pm0.1}$ from 5–30 MeV. Triangles, spectra during period immediately following Voyager 1 shock crossing; circles, spectra during period immediately following Voyager 2 crossing. **b**, Helium spectra with time periods indicated (as year/days of year). Three helium components are apparent, although the energy intervals differ. In the 2004 period, the ACR component was observable down to ~10 MeV per nucleon. By the 2007 period, the intensity of 12–22 MeV per nucleon ACR He at Voyager 1 increased by a factor of 21 ± 4 as the spectrum approached the expected power law source spectrum. The intensity at Voyager 2 increased by a factor of 20 ± 3, suggesting a common change in solar modulation. Filled symbols, Voyager 1; open symbols, Voyager 2. **c**, Ratio of the proton intensities in **a** for 2007. The horizontal lines mark energies dominated by TSPs, ACRs and GCRs. The dotted line is drawn through the Voyager data points for reference. **d**, Ratio of the helium intensities in 2007. The dotted line is the proton intensity ratio from **c** shifted by a factor of 4 in energy per nucleon, showing that the proton and helium ratios are essentially the same. The dashed lines in **c** and **d** correspond to equal intensities at Voyager 1 and 2.

the Voyager 1 observations was the effect of a large transient on shock acceleration[22]. However, from the 12–22 MeV per nucleon He intensity profile at Voyager 2 in Fig. 3a, it does not appear that there was a large enough transient effect at the time of the Voyager 2 shock crossing to support that suggestion.

The heliosheath is expected to impede the diffusion of low energy Galactic cosmic rays (GCRs) into the heliosphere, resulting in a positive radial gradient. The estimated[21] local interstellar intensity of GCR He with 150–380 MeV per nucleon is twice the intensity observed by Voyager 1 at 104 AU (Fig. 3a), requiring a gradient of 2.2% per AU if it were uniform between Voyager 1 and a heliopause at 135 AU. However, the Voyager 1 and Voyager 2 intensities correspond to a radial gradient of $-0.2 \pm 0.2\%$ per AU, indicating there is either a larger gradient beyond 105 AU (ref. 20) or the local interstellar intensity is lower than current estimates.

The cosmic ray instrument also measures the intensity of electrons with energies from 2.5 to 160 MeV (Fig. 3b). Because of their low rigidities, GCR electrons with these energies are strongly modulated and their intensities should be larger in the outer heliosphere. They are also strongly affected by transients. However, the temporal effects associated with the two large transient magnetic field increases just upstream of the shock around 2007.42 and 2007.55 differed from those of merged interaction regions previously observed by Voyager 1 and Voyager 2 (ref. 26). These recent Voyager 2 transients did not produce concurrent transient intensity increases of 10 MeV electrons and 2–50 MeV H ions, nor was there an increase in the solar wind dynamic pressure[8], suggesting that they may be of a different character and possibly related to the nearby presence of the termination shock.

The Voyager 2 electron intensity at 2.5–5.2 MeV continued to increase after the shock crossing, reaching that concurrently observed by Voyager 1 at 104 AU. However, the Voyager 2 intensities at 6–14 MeV and at 26–45 MeV were less than at Voyager 1, indicating that the energy spectrum observed by the former spacecraft near the shock in the heliosheath is much steeper than observed concurrently by Voyager 1 much further from the shock. This suggests that other processes, such as re-acceleration at the shock[27], may be occurring.

With both Voyager 1 and Voyager 2 now in the heliosheath, it will be possible to determine the intensity gradients of ACRs and GCRs

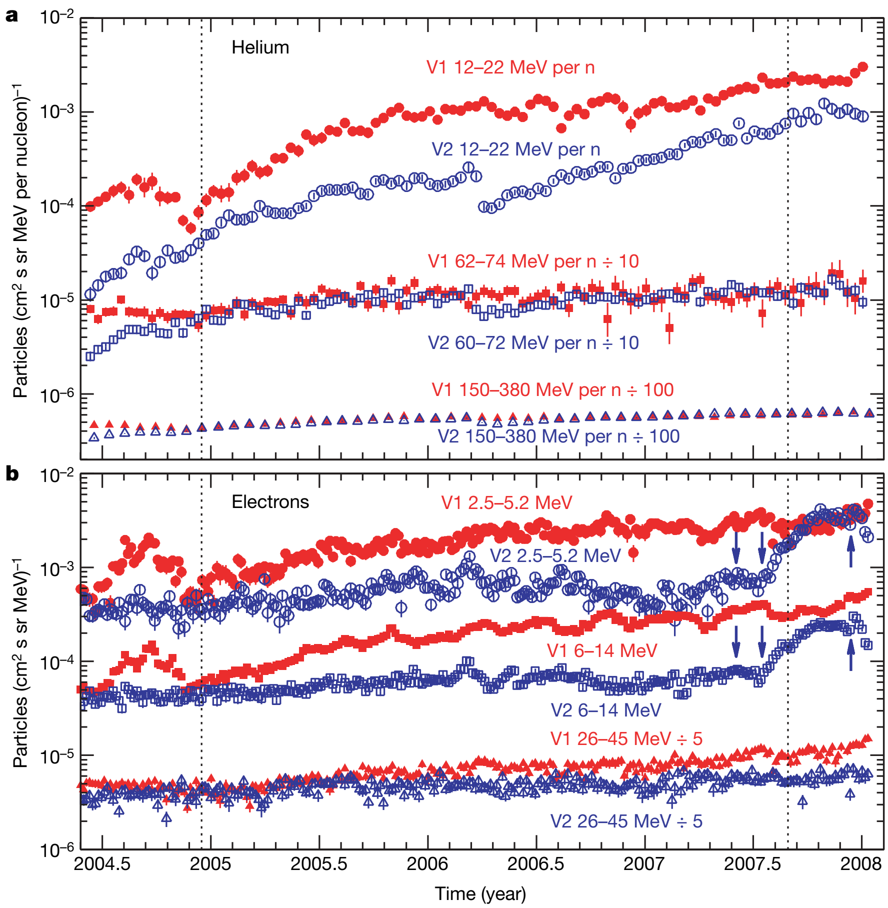

Figure 3 | Temporal changes in the intensities of helium nuclei and electrons. The vertical dotted lines mark times of the Voyager 1 shock crossing (2004.96) and the Voyager 2 crossing (2007.66), after which both spacecraft have been in the heliosheath. Error bars, ±1s.d. **a**, Intensities of helium nuclei in three energy bands. ACRs dominate in the two lowest energy bands plotted, and GCRs dominate in the highest energy band. The Voyager 1 and Voyager 2 intensities at ~61–73 MeV per nucleon are essentially the same, not only in 2008 when both are in the heliosheath, but for the past three years when Voyager 2 was upstream of the shock. In addition, the ~61–73 MeV per nucleon intensity has been nearly constant since mid-2005, indicating a steady ACR source at high energies and no observable gradient between the two spacecraft. There is an ACR gradient in the heliosheath at 12–22 MeV per nucleon as indicated by the difference in the intensities at Voyager 1 and Voyager 2. The nearly identical intensities of GCR helium nuclei with 150–380 MeV per nucleon indicate that the radial gradient in the heliosheath is $-0.2 \pm 0.2\%$ per AU between Voyager 2 at 84 AU and Voyager 1 at 104 AU. **b**, Intensities of electrons in three energy bands. Arrows indicate three transient events that affected the electron intensities. The intensities at Voyager 2 began increasing rapidly just upstream of the shock following the passage of two large transient magnetic field increases[9] around 2007.42 and 2007.55. About 50 days later, the Voyager 2 intensity equalled that at Voyager 1 at 2.5–5.2 MeV, but not at higher energies. However, there was a transient in the heliosheath[8] starting at 2007.95, with an associated transient intensity increase at energies up to 16 MeV, followed by a sharp decrease. This is similar to the passage of merged interaction regions previously observed in the supersonic solar wind.

during the next year, when there will be a minimum level of solar modulation, and to observe the evolution of the gradients as the level of modulation increases with the onset of the new cycle of solar activity.

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