LETTERS

Magnetic fields at the solar wind termination shock

L. F. Burlaga[1], N. F. Ness[2], M. H. Acuña[1], R. P. Lepping[1], J. E. P. Connerney[1] & J. D. Richardson[3]

A transition between the supersonic solar wind and the subsonic heliosheath was observed by Voyager 1, but the expected termination shock was not seen owing to a gap in the telemetry[1–4]. Here we report observations of the magnetic field structure and dynamics of the termination shock, made by Voyager 2 on 31 August–1 September 2007 at a distance of 83.7 AU from the Sun (1 AU is the Earth–Sun distance). A single crossing of the shock was expected, with a boundary that was stable on a timescale of several days. But the data reveal a complex, rippled, quasi-perpendicular supercritical magnetohydrodynamic shock of moderate strength undergoing reformation on a scale of a few hours. The observed structure suggests the importance of ionized interstellar atoms ('pickup protons') at the shock.

This Letter discusses three termination shock crossings (TS-2, TS-3 and TS-4) that were observed directly by Voyager 2 (Fig. 1). At least two additional termination shock crossings (TS-1 and TS-5) occurred when there were gaps in the telemetry. The multiple crossings imply motions of the termination shock, possibly caused by its large-scale motion or ripples propagating along it[5–7]. The times between crossings are of the order of magnitude expected for ripples propagating on the shock.

Observations by the magnetic field experiment on Voyager 2 (ref. 8) show no significant change in the direction of the magnetic field **B** across any of the three termination shock crossings in Fig. 1, indicating that the shock was quasi-perpendicular at each encounter. This geometry is necessary to provide the return of reflected ions from the shock[9,10], which ultimately produce some of the heating behind a high Mach number (supercritical) shock.

The structure of TS-3 is shown in Fig. 2. The foot, ramp and overshoot of TS-3 (ref. 9) moved past Voyager 2 in ~23 min, ~1.5 min and ~17 min, respectively. There is an increase in the magnetic field strength B in the foot, where **B** is compressed as the solar wind slows down[11]. The foot contains gyrating protons that are reflected from the shock[9,12,13]. A further abrupt decrease in speed to its lowest value occurs at the ramp, owing to the electric potential associated with cross-field currents and gradients in B in the ramp[14,15]. Plasma waves were observed at the ramp of TS-3 (ref. 16). The ratio of the maximum B in the overshoot to B downstream of the shock is ~2.5, indicating that the ratio of the magnetosonic Mach number M_{ms} to the critical fast Mach number ($M_c \approx 2$) is ~5 (ref. 17), suggesting that $M_{ms} \approx 10$ for TS-3, consistent with a supercritical shock.

From the passage time of the ramp (1.5 min) and the estimated shock speed (68 ± 17 km s^{-1}; ref. 11), the thickness of the ramp is ~6,000 km. The ramp size is usually expressed in terms of the ion inertial length $c/\omega_{pi,u}$, where c is the speed of light and $\omega_{pi,u}$ is the plasma frequency of an ion upstream. For TS-3, $c/\omega_{pi,u} \approx 6{,}000$ km and the thickness of the ramp is ~1 $c/\omega_{pi,u}$.

The strength of TS-3, measured by the ratio of the B in the solar wind upstream of the shock (B_1) to that behind the shock (B_2) is $B_2/B_1 = 1.7 \pm 0.1$. The corresponding density ratio is $N_2/N_1 = 1.4 \pm 0.2 \approx B_2/B_1$, consistent with a shock strength of 1.6 ± 0.2. The moderate strength of TS-3 might have been produced by the pickup protons and other suprathermal ions that were present[18], as considered in models[9,19–21].

The magnetic field strength oscillated quasi-periodically within the ramp (Fig. 3). The ramp moved past Voyager 2 in ~90 s, and each oscillation passed the spacecraft in ~12.3 s on average. The shock speed gives a characteristic length of the fluctuations in the ramp, $\lambda \approx 1{,}000$ km $= 0.15\ c/\omega_{pi,u}$. An oscillating ramp containing substructures with a scale of $0.2\ c/\omega_{pi,u}$ was observed at 1 AU (ref. 22), where shocks are not influenced by pickup protons.

A few hours after crossing TS-3, Voyager 2 crossed the termination shock (TS-4) back into the solar wind. The re-entry into the solar wind might have been caused by a ripple propagating on the shock's

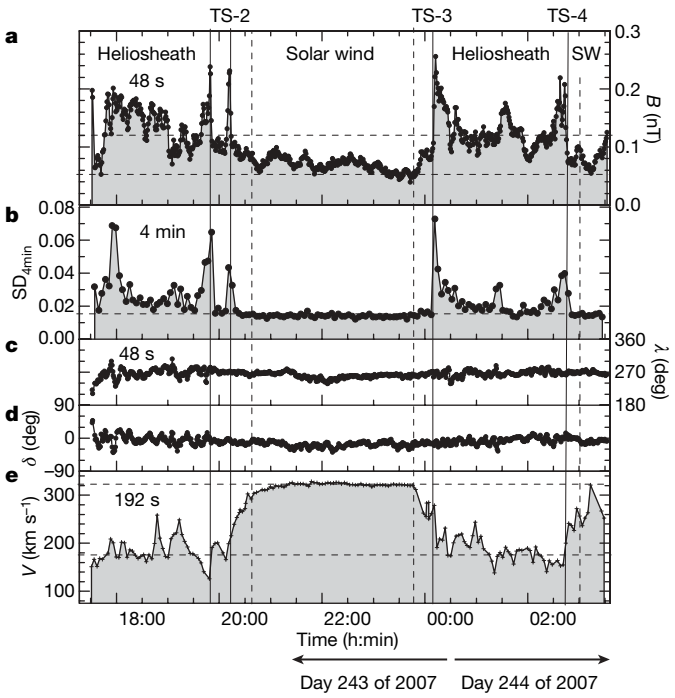

Figure 1 | Three crossings of the termination shock, illustrating reformation and the variability of its structure. The figure shows 48-s averages of magnetic field strength B (**a**) and the standard deviation of B for 4-minute intervals (**b**), azimuthal angle λ (**c**) and elevation angle δ (**d**), and the 192-s average of solar wind speed V (**e**) as a function of time measured in days from the beginning of 2007. (Here the directions λ and δ of **B** are in heliographic coordinates.) The time between the first and second of the observed termination shock crossings (TS-2 and TS-3, respectively) is ~3.7 h, and that between the second and third of the observed crossings (TS-3 and TS-4, respectively) is ~2.8 h. The Larmor frequency of a proton with the solar wind speed 300 km s^{-1} gyrating in the magnetic field upstream of the termination shock is $\Omega_{L,u}{}^{-1} \approx 17$ min. The two enhancements in B at TS-2 were separated in time by $\sim\Omega_{L,u}{}^{-1}$. The uncertainty in B is ±0.03 nT.

[1]NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771, USA. [2]The Catholic University of America, Washington DC 20064, USA. [3]Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA.

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surface[5,23]. The structure of TS-4 (Fig. 1) is different from that of TS-3. In the foot region, $B(t)$ (where t is time) appears as a narrow peak, and the overshoot is smaller than that of TS-3. Such a peak evolves from the foot as a result of bunching of reflected solar wind ions where they are turned back towards the shock[6,12]. The amplitude of the overshoot decreases while the step-like foot evolves to a peak. These changes were observed from TS-3 to TS-4 (Fig. 1). The structure of the termination shock evolved significantly within 2.7 h. The small peak in B at the front of TS-4 is expected to evolve to a new ramp on this timescale, as part of the shock reformation process[10,12,24,25].

Reformation of the local structure of a supercritical quasi-perpendicular shock was predicted by both hybrid and full particle simulations[10,13,25] for a shock with large M_{ms} and/or a low β, where β is the ratio of thermal pressure to magnetic pressure. Recall that we estimated that $M_{ms} \approx 10$ for TS-3. Neglecting pickup protons, $\beta = 0.04$ in the solar wind upstream of TS-3, so that β might be small even if the pickup protons contribute significantly to it. Reformation is a patchy cyclic shock reformation process with a characteristic time of the order of the downstream gyroperiod[25].

Further evidence for local reformation of the termination shock is provided by the qualitative transformation of the shock structure during the ~3.9-h interval between TS-2 and TS-3 (Fig. 1). At the front of TS-2, the bulk speed V increased continuously, rather than in a step-like form. Instead of a simple ramp-overshoot structure in B, there were two narrow enhancements in B resembling solitons, in each of which there was a change in B comparable to that in the ramp of TS-3. A shock structure at 1 AU resembling that of TS-2 was reported in fig. 5 of ref. 26.

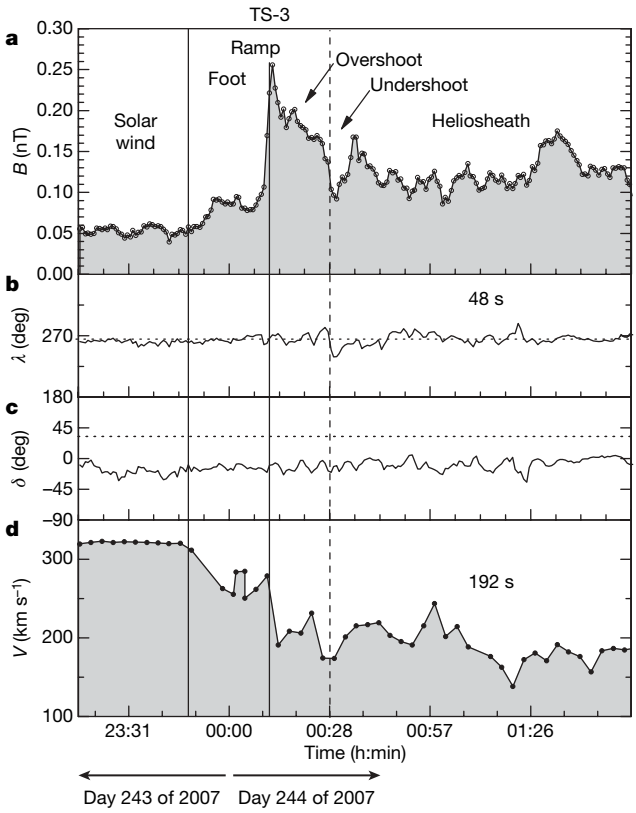

Figure 2 | TS-3 is a supercritical quasi-perpendicular shock. The 48-s averages of the magnetic field strength B (**a**) and its directions λ (**b**) and δ (**c**) are shown here together with the 192-s average of the solar wind speed V (**d**) across TS-3. The magnetic field strength profile shows the classical features of a supercritical quasi-perpendicular shock: a 'foot', 'ramp', 'overshoot', 'undershoot' and smaller oscillations, in that order.

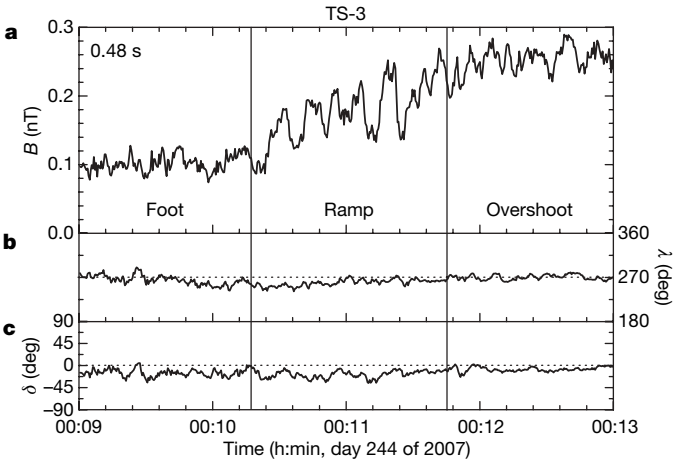

Figure 3 | The internal structure of the ramp of TS-3. The structure is based on observations of the magnetic field strength B (**a**) and its directions λ (**b**) and δ (**c**) at 0.48-s intervals. The magnetometer on Voyager 2 sampled the vector magnetic fields in the termination shock at a rate of 2.08 samples s^{-1}, and the spacecraft was able to transmit all of this information, making it possible to determine the complex internal structure of the ramp shown here.

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