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LETTERS

Intense plasma waves at and near the solar wind termination shock

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Plasma waves are a characteristic feature of shocks in plasmas, and are produced by non-thermal particle distributions that develop in the shock transition layer. The electric fields of these waves have a key role in dissipating energy in the shock and driving the particle distributions back towards thermal equilibrium[1]. Here we report the detection of intense plasma-wave electric fields at the solar wind termination shock. The observations were obtained from the plasma-wave instrument on the Voyager 2 spacecraft[2]. The first evidence of the approach to the shock was the detection of upstream electron plasma oscillations on 1 August 2007 at a heliocentric radial distance of 83.4 AU (1 AU is the Earth–Sun distance). These narrowband oscillations continued intermittently for about a month until, starting on 31 August 2007 and ending on 1 September 2007, a series of intense bursts of broadband electrostatic waves signalled a series of crossings of the termination shock at a heliocentric radial distance of 83.7 AU. The spectrum of these waves is quantitatively similar to those observed at bow shocks upstream of Jupiter, Saturn, Uranus and Neptune.

The upstream plasma oscillations that provided the first indication that the spacecraft was approaching the termination shock were detected in the 311 Hz channel (Fig. 1) on 1 August 2007. These oscillations, known as Langmuir waves[3], are purely electrostatic oscillations that occur at a characteristic frequency known as the electron plasma frequency. The electron plasma frequency[4] is given by $f_p = 8{,}980\sqrt{n_e}$ Hz, where n_e is the local electron density in units of cm^{-3}. Although the electron plasma oscillations indicated that the spacecraft was close to the termination shock, because so little is known about the propagation of the electron beams responsible for these waves, it was difficult to estimate the distance to the shock or to determine how soon the shock crossing would occur.

For Voyager 1, comparable plasma oscillations were first detected about ten months before the spacecraft reached the termination shock[5]. Because Voyager 2 is moving away from the Sun slightly more slowly than Voyager 1 ($3.2\ \text{AU yr}^{-1}$ in comparison with $3.6\ \text{AU yr}^{-1}$), it might be expected to take slightly longer (perhaps $(3.6/3.2) \times 10 = 11.2$ months) to reach the shock. However, this simple estimate is complicated by the fact that the termination shock is not stationary. Its radial motion is controlled by the solar wind pressure, which varies considerably during the solar cycle. For the current phase of the solar cycle, which is near the solar minimum, the shock was expected to be moving inwards, owing to the low solar wind pressure. In contrast, for Voyager 1 the termination shock crossing occurred during the declining phase of the solar cycle, after a period of high solar wind pressure. Because of the higher solar wind pressure, it is believed that during this time the shock was moving outwards just beyond the spacecraft for a period of nearly two years[6,7]. It was during this relatively long period of close proximity to the shock that the upstream plasma oscillations were observed. Eventually, as the solar wind pressure began to decrease, the shock started to move inwards, leading to the shock crossing. On the basis of these considerations, we thought that the Voyager 2 crossing would occur much sooner than the Voyager 1 crossing, probably within several months and possibly within only a few weeks[8]. Nevertheless, it came as a surprise when, only 30 days after the first detection of the upstream

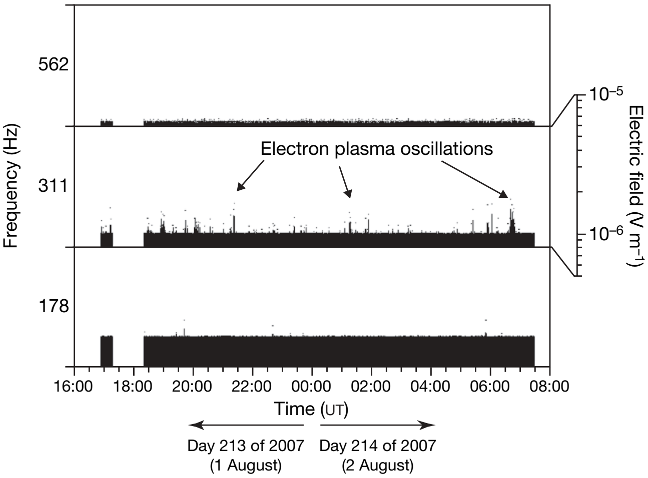

Figure 1 | The first detection of electron plasma oscillations by Voyager 2 upstream of the termination shock. Electric field intensities in the 178, 311 and 562 Hz channels of the plasma-wave instrument, at a heliocentric radial distance of 83.4 AU and heliographic longitudes and latitudes of respectively 288.6° and −31.6°. UT, universal time. The numerous impulsive intensity spikes in the 311 Hz channel are electron plasma oscillations. The frequency of these oscillations is consistent with the electron density ($n_e = 1.2 \times 10^{-3}\ \text{cm}^{-3}$) expected in the solar wind at this heliocentric radial distance, and agrees with the plasma density measured by the plasma instrument at this time[10]. The emissions are very similar to those observed by Voyager 1 upstream of the termination shock[5], and indicate that the spacecraft is close to the termination shock. On the basis of observations ahead of planetary bow shocks, upstream waves of this type are known to be produced by beams of electrons that escape upstream along magnetic field lines that intersect the shock. According to the well-known theory of beam–plasma interactions, the oscillations are excited when the reduced electron velocity distribution function[1], $F(v)$, has a region of positive slope, $dF/dv > 0$. This condition is always satisfied ahead of the shock, owing to a time-of-flight mechanism that dictates that only those electrons with velocities greater than a well-defined cutoff velocity can reach a point in the upstream region[19]. Typical beam energies required to generate the upstream electron plasma oscillations are in the range from a few keV to several tens of keV. Although we have looked in the Voyager 2 plasma[10] and energetic charged particle[11] data for evidence of the electron beam responsible for the electron plasma oscillations, no clear correlation was found. The absence of an identifiable beam is probably due to the gap from about 6 to 35 keV between the electron energy coverage of the plasma instrument and that of the energetic-charged-particle instrument[20,21].

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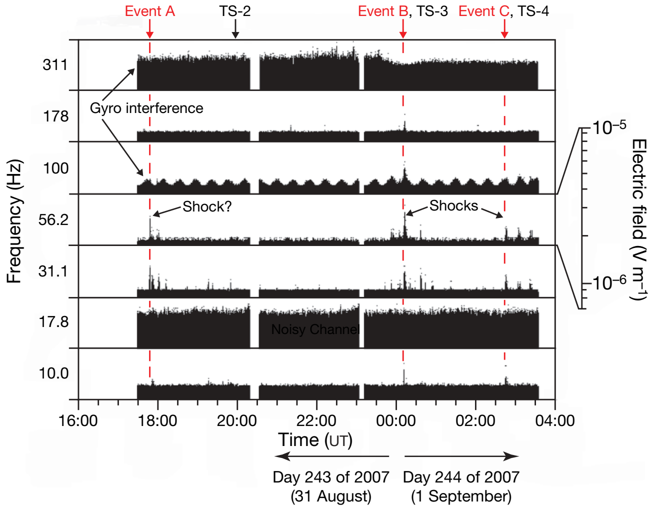

Figure 2 | Three bursts of broadband electrostatic noise of the type expected to occur at the termination shock. These bursts occurred during three time intervals: 17:50 to 18:15 UT on 31 August, and 00:11 to 00:13 UT and 02:45 to 03:35 UT on 1 September. The heliocentric radius is 83.67 AU, and the heliographic longitude and latitude are comparable to those in Fig. 1. The bursts (events A, B and C) and the shock crossings TS-2, TS-3 and TS-4, identified by the magnetometer and plasma teams[9,10], are indicated at the top of the plot. Events B and C correspond almost exactly to TS-3 and TS-4, respectively. Event A was not confirmed as a shock by the magnetometer and plasma teams, although there are variations in the magnetic field[9] around this time. No plasma waves were detected at TS-2.

plasma oscillations, a series of five closely spaced crossings of the termination shock were detected by the Voyager 2 particle and fields instruments[9–12] at a radial distance of only 83.7 AU, much closer than for the Voyager 1 termination shock crossing[6], which was at 94.1 AU. Because the Voyager 1 crossing occurred during a data gap[6], the Voyager 2 measurements provide the first direct observations of the structure of the termination shock.

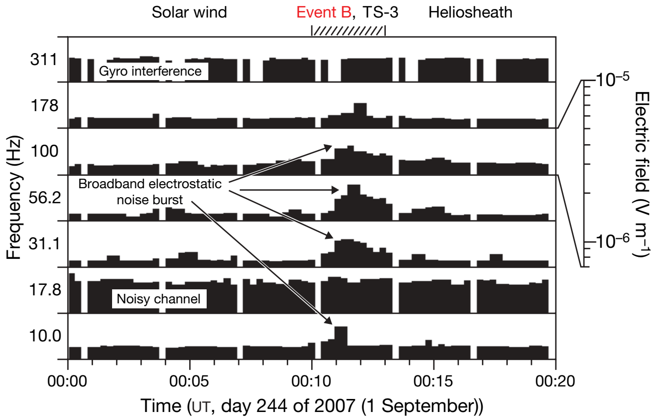

Figure 3 | A series of expanded timescale plots of the electric field intensities in the 10 to 311 Hz channels for event B. The heliocentric radius is 83.7 AU and the heliocentric longitude and latitude are comparable to those in Fig. 1. The broadband electrostatic noise burst that extends from 10 to 178 Hz between 00:11 and 00:13 UT corresponds almost exactly with the ramp in the magnetic field at TS-3 (ref. 9) and occurs just before an abrupt, well-defined peak in the plasma density[10]. The frequency of the electrostatic waves also is seen to increase systematically with increasing time as the spacecraft passes through the ramp, starting first in the 10 Hz channel at about 00:11 UT, progressing upwards through the 56.2 Hz channel about 30 seconds later, and finally reaching peak intensity in the 178 Hz channel at about 00:12 UT. This tendency, for the instability to start at long wavelengths (and low frequencies) and progress towards short wavelengths (and high frequencies), is characteristic of many electrostatic instabilities.

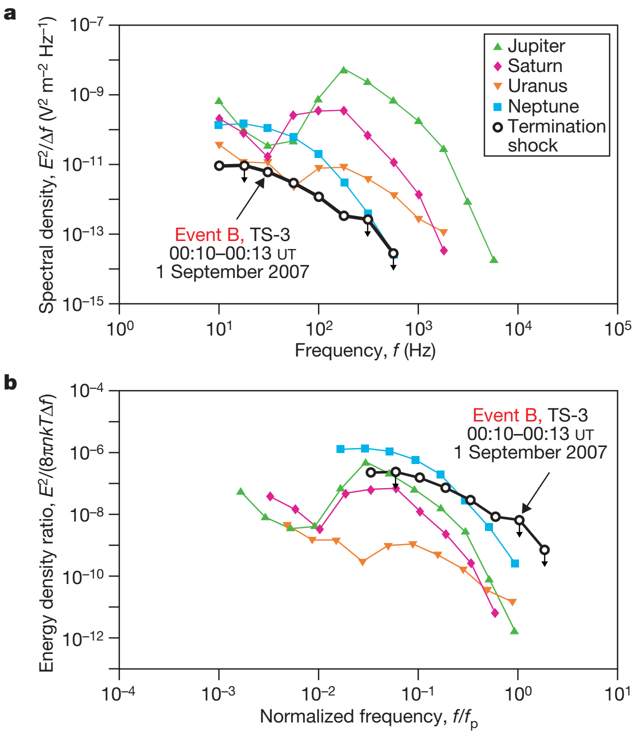

Figure 4 | Comparisons of the spectrum of the termination shock with spectra of planetary bow shocks. a, A comparison of the electric field spectrum at TS-3 with electric field spectra obtained by Voyager 1 and 2 at bow shocks upstream of Jupiter, Saturn, Uranus and Neptune[16]. The three downward arrows in the termination shock spectrum indicate upper limits, and Δf is the bandwidth used to convert the electric field amplitude, E, to spectral density. **b**, The same spectra normalized by dividing the electric field energy density, $E^2/8\pi$, by the plasma energy density, nkT, where n is the plasma density, k is Boltzmann's constant and T is the plasma temperature upstream of the shock, and by dividing the frequency, f, by the plasma frequency, f_p. The upstream parameters were taken to be $n = 1.2 \times 10^{-3}\ \mathrm{cm}^{-3}$, $T = 1.1 \times 10^4$ K and $f_p = 311$ Hz. This comparison shows that the normalized electric field intensities observed at the termination shock are in fact quite intense—more so than most of the planetary bow shock crossings, and comparably so to the bow shock crossing at Neptune.

The first indication in the Voyager 2 plasma-wave data of a possible crossing of the termination shock was the occurrence of three intense bursts of broadband electric field noise (labelled 'event A', 'event B' and 'event C' in Fig. 2) on 31 August and 1 September 2007. Events of this type are extremely rare and exhibit the intense broadband electrostatic wave spectrums that were expected at the termination shock[13]. Except for interplanetary shocks propagating outward from the Sun, which are generally less intense, no comparable broadband bursts have been observed in the Voyager 2 plasma-wave data since the crossing of Neptune's bow shock[14] on 24 August 1989. It is useful to compare these three events with measurements obtained from the particle and field instruments. Five successive in-and-out crossings of the termination shock, labelled TS-1 to TS-5, were identified by the magnetometer and plasma teams[9,10]. Of these, TS-1 and TS-5 occurred during data gaps, so no detailed comparisons can be made for these crossings. Of the remaining crossings, TS-3 and TS-4 occurred essentially simultaneously with events B and C (Fig. 2). Interestingly, no electric field bursts were observed during the shock crossing identified as TS-2. This shock crossing is unusual in that it consisted of two well-separated, soliton-like pulses[9] that are thought to be transient, non-dissipative structures that may be in the process of reforming into a shock farther upstream. For reasons that are not clearly understood, the characteristic signature of a shock was not present in the magnetometer and plasma data at the time of event A, the first broadband electrostatic burst.

TS-3 is especially clear and is worthy of further analysis. This shock, which represents a crossing from the solar wind into the heliosheath, is classified as a supercritical quasi-perpendicular shock[9,10]. High-resolution plots of the electric field intensities during this crossing (Fig. 3) show that the broadband burst of electric field noise (event B) starts at almost exactly the same time as the start of the steep ramp in the magnetic field, and ends at about the time that the magnetic field reaches peak intensity in the overshoot region[9]. A similar relationship also occurs at TS-4 (not shown). The close relationship between the electrostatic wave intensities and the magnetic field ramps observed at TS-3 and TS-4 implies that the electrostatic waves are closely related to the electrical currents that are responsible for the ramp in the magnetic field. Similar relationships between the broadband electrostatic wave intensity and the ramp in the magnetic field are commonly observed at planetary bow shocks[15,16].

Because the broadband electrostatic waves observed at the solar wind termination shock appear to be very similar to those observed at planetary bow shocks, it is interesting to compare the electric field spectrum observed at TS-3 with electric field spectra obtained by Voyagers 1 and 2 at bow shocks upstream of the magnetospheres of the outer planets[16]. This comparison (Fig. 4a) shows that the TS-3 spectrum has a shape that is very similar to those observed at planetary bow shocks, but with a distinct shift towards lower intensities and lower frequencies. This shift is a direct consequence of the $1/R^2$ decrease in the solar wind plasma density with increasing radial distance (R) from the Sun. If the electric field spectral densities are normalized by dividing by the solar wind energy density and the frequencies are normalized by dividing by the electron plasma frequency, then the TS-3 spectrum is found to be quite similar to the spectra observed at planetary bow shocks (Fig. 4b).

Although TS-3 has the classic electrostatic wave signature expected for a supercritical quasi-perpendicular shock, there are nevertheless large differences between successive crossings caused by fluctuations in the shock position. For example, TS-2 has no electrostatic wave signature at all, and event A, which has the classic electrostatic wave signature of a shock, was not identified as a shock by the magnetometer and plasma teams. Such complex variations are consistent with computer simulations of high-Mach-number supercritical shocks[17,18], which show that such shocks are highly unstable and continuously evolving.

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