Electron Plasma Oscillations Upstream of the Solar Wind Termination Shock

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Electron plasma oscillations have been detected upstream of the solar wind termination shock by the plasma wave instrument on the Voyager 1 spacecraft. These waves were first observed on 11 February 2004, at a heliocentric radial distance of 91.0 astronomical units, and continued sporadically with a gradually increasing occurrence rate for nearly a year. The last event occurred on 15 December 2004, at 94.1 astronomical units, just before the spacecraft crossed the termination shock. Since then, no further electron plasma oscillations have been observed, consistent with the spacecraft having crossed the termination shock into the heliosheath.

Electron plasma oscillations, also known as Langmuir waves, are one of the oldest known and most widely studied of all plasma wave phenomena (*1*). For many years it has been known that electron plasma oscillations are generated ahead of planetary bow shocks by energetic electrons escaping into the solar wind upstream of the shock (*2–7*). This close relationship led Kurth and Gurnett (*8*) to predict that electron plasma oscillations would be present upstream of the solar wind termination shock. Here, we report the initial observations of these waves.

Electron plasma oscillations are electrostatic oscillations that occur at a characteristic frequency of the plasma known as the electron plasma frequency. The electron plasma frequency is given by $f_p = 8980\sqrt{n_e}$ Hz, where n_e is the electron density in cm^{-3} (*9*). Of the various mechanisms that can excite electron plasma oscillations, an electron beam is one of the most effective. According to the well-known theory of beam-plasma interactions (*10*), electron plasma oscillations are generated whenever the electron velocity distribution has a region of positive slope, $\partial f/\partial v_\parallel > 0$. If the region of positive slope occurs at velocities well above the electron thermal velocity, the resulting feature is called a beam. At planetary bow shocks electrons heated at the shock escape upstream into the solar wind along the solar wind magnetic field lines. Although the electron velocity distribution initially may not have a region of positive slope, time-of-flight considerations dictate that only those electrons with velocities greater than a well-defined cutoff velocity can reach a point in the upstream region (*11*). The existence of this velocity cutoff assures that the velocity distribution function has a region of positive slope, thereby establishing the necessary conditions for the growth of electron plasma oscillations (*12*). Because the solar wind magnetic field lines are in contact with a planetary bow shock only over a limited region, beams can only occur in a well-defined region upstream of the shock. This region is known as the electron foreshock. The upstream boundary of the electron foreshock is determined by magnetic field lines tangent to the nose of the shock.

Because the solar wind magnetic field lines are wound into an Archimedes spiral by the rotation of the Sun (*13*), electrons accelerated at the termination shock are expected to escape into the upstream region (Fig. 1). Although electrons can escape into the region upstream of the shock, this idealized configuration does not automatically lead to a region of positive slope in the distribution function of the escaping electrons. For a region of positive slope to develop, the geometry must be such that some of the magnetic field lines are tangent to the shock surface so that the time-of-flight mechanism can operate, similar to the mechanism that occurs at planetary bow shocks. Because the shock surface is unlikely to be smooth and irregularities are almost certainly present in the solar wind magnetic field direction, there are good reasons to believe that such tangent field regions will occur. The main uncertainty is how far beams with regions of positive slope, $\partial f/\partial v_\parallel > 0$, can propagate into the upstream region. Because of the complicated physics involved in beam-plasma interactions, it is very difficult to estimated this propagation distance. Kurth and Gurnett (*8*) suggest that it could range anywhere from a small fraction of an astronomical unit (AU) to several AU.

Previous observations (*3–6*) have demonstrated that the Voyager plasma wave instrument is easily capable of detecting electron plasma oscillations. The instrument uses an electric dipole antenna to detect the electric field of plasma waves and radio waves (*14*).

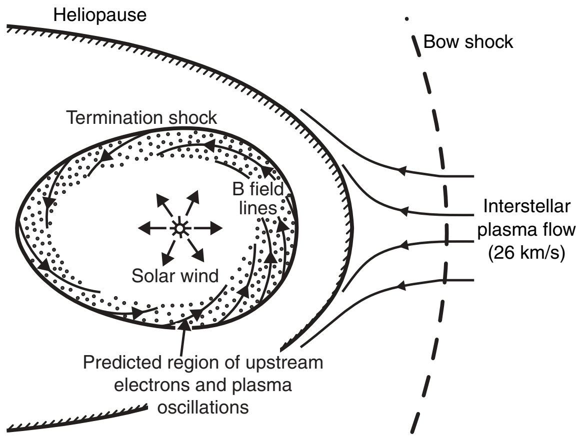

Fig. 1. An idealized conceptual drawing showing the key boundaries that are expected to occur in the outer heliosphere. On the basis of observations of planetary bow shocks, electrons accelerated at the termination shock are expected to form a beam, indicated by the shading, that streams inward along the solar wind magnetic field lines toward the Sun. This beam is expected to excite electrostatic oscillations, called electron plasma oscillations, via a process known as a beam-plasma instability (*8*). The radial thickness of the region where the electron plasma oscillations are expected to occur is greatly exaggerated in this drawing.

Table 1.

Date 2004	Day of year 2004	Radial distance (AU)	Frequency (Hz)	Maximum intensity (μV/m)
11–15 February	042–043	91.0	311	2.0
23–26 February	054–057	91.1	311	1.2
29 August–1 September	242–245	93.0	562	1.1
6–7 November	311–312	93.7	311	1.3
8 December	343	94.0	178	1.3
15 December	350	94.1	178–311	1.7

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Two types of data are obtained: low-rate electric field spectrum measurements in 16 logarithmically spaced frequency channels from 10 Hz to 56 kHz and high-rate waveform measurements from 50 Hz to 10 kHz. Because only about 1 min of waveform data is obtained per week, whereas the spectrum analyzer data are typically obtained for about 11 to 13 hours per day for Voyager 1 and 7 to 10 hours per day for Voyager 2, the search for electron plasma oscillations associated with the termination shock is best conducted with the use of low-rate spectrum analyzer data. These data provide one electric field spectrum every 16 s. To interpret the data, care must be taken to filter out various types of spacecraft-generated interference that are present, particularly in the lower frequency channels. Once the interference signals are filtered out, electron plasma oscillations can be easily identified by their bursty narrowband characteristics, usually consisting of an emission in a single channel at or near the electron plasma frequency. Occasionally when the electron plasma frequency is between two adjacent filter channels a response is observed in the two adjacent channels. To a good approximation, the electron plasma frequency in the solar wind is given by $f_p = 25{,}000/R$ Hz, where R is the heliocentric radial distance in AU. Variations of up to a factor of 2 can be expected from this average value.

In the outer region of the heliosphere, beyond about 10 AU, electron plasma oscillations are almost never observed, except near planetary flybys and occasionally in association with interplanetary shocks (*8*, *15*). The first evidence of electron plasma oscillations possibly associated with the termination shock occurred from 11 to 15 February 2004, when a series of sporadic narrowband emissions was detected in the 311 Hz channel of the Voyager 1 spectrum analyzer at a heliospheric radial distance of 91.0 AU. A plot of the electric field intensities observed during a portion of this event is shown in Fig. 2. The plasma oscillations are spiky and sporadic, as is often the case for such emissions. The frequency of these emissions is almost exactly the frequency expected for electron plasma oscillations at 91 AU, which, by using the formula given above, is 288 Hz. Subsequently, five more events were detected, all by Voyager 1 (Table 1). The last of these events (Fig. 3) occurred on 15 December 2004, at a heliocentric radial distance of 94.1 AU. This event occurred just before the crossing of the termination shock, as identified by the Voyager 1 magnetic field (*16*) and energetic particle (*17*, *18*) instruments. The termination shock crossing is believed to have occurred during a data gap that extended from about 21:05 universal time (UT) on 15 December 2004 to 01:54 UT on 17 December 2004.

Several arguments can be made that the electron plasma oscillations listed in Table 1 are associated with the solar wind termination shock. First, these events are all unusual. No clear examples of electron plasma oscillations comparable to those in Figs. 2 and 3 have been observed in the Voyager 1 data for many years; the last was in association with an interplanetary shock that occurred on 14 September 1991. Also, no comparable events have been detected by Voyager 2, which is closer to the Sun, now at about 77 AU. Second, the frequencies and electric field intensities, typically a few hundred Hz and a few microvolts per meter, are consistent with the predicted plasma frequencies and electric field intensities (*8*). Third, all of the events occurred within about 3 AU of the radial distance at which the termination shock was observed, i.e., from 91.0 to 94.1 AU, and the rate of oc-

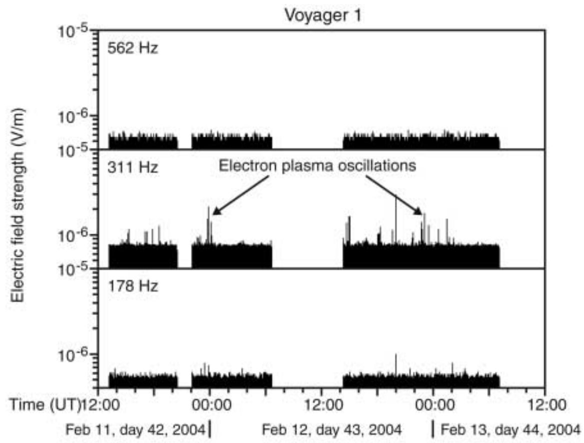

Fig. 2. The electric field intensity observed in the 178, 311, and 562 Hz channels of the Voyager 1 plasma wave instrument on 11 to 15 February 2004, at a radial distance from the Sun of 91.0 AU. The many short impulsive intensity spikes in the 311 Hz channel are plasma oscillations. After many years in which no clear electron plasma oscillation events were observed by Voyager 1 or 2, these are the first observations of plasma oscillations that could possibly be associated with the termination shock. From the equation $f_p = 8980\sqrt{n_e}$, it can be shown that a plasma oscillation frequency of 311 Hz corresponds to an electron density of $n_e = 1.2 \times 10^{-3}$ cm^{-3}. This density is consistent with the nominal electron densities expected in the solar wind at 91 AU.

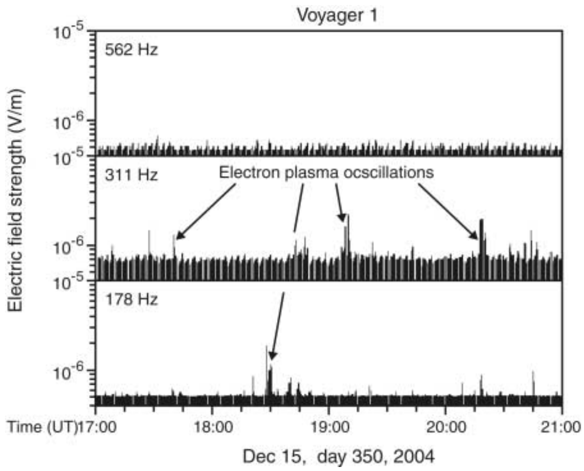

Fig. 3. The electric field intensity of electron plasma oscillations observed late in the day on 15 December 2004, just before crossing of the termination shock at 94.1 AU. This event is coincident with a highly anisotropic 0.35 to 1.5 MeV electron beam detected by the LECP instrument (*17*). The plasma oscillations observed during this event again occur in short bursts, with durations of a few minutes or less, very similar to the 11 to 15 February 2004 event (Fig. 2). Note that the plasma oscillation frequency shifts down to 178 Hz briefly at about 18:30 UT. This frequency shift indicates that the electron density decreased from about 1.2×10^{-3} cm^{-3} to about 3.9×10^{-4} for a short time around 18:30 UT.

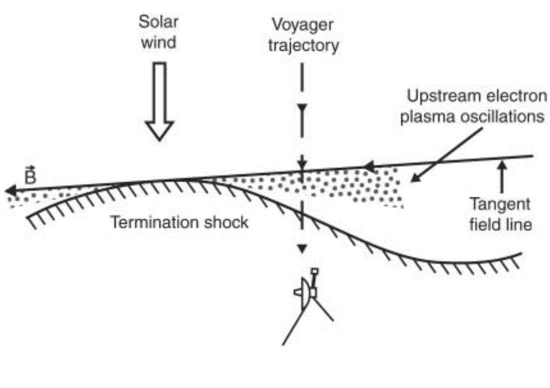

Fig. 4. The detection of a highly anisotropic electron beam by the LECP instrument just ahead of the termination shock that is coincident with the electron plasma oscillations observed on 15 December suggest that the spacecraft passed through a region (shown shaded) where the solar wind magnetic field is nearly tangent to the shock. From time-of-flight considerations it can be shown that very high beam velocities are to be expected in this region, thereby producing conditions favorable for generating electron plasma oscillations (*11*).

currence increased as the distance to the shock decreased. On the basis of these observations one could estimate that the radial thickness of the plasma oscillation region is about 3 AU. However, from Voyager 2 solar wind pressure measurements (*19*) it is known that the solar wind pressure at Voyager 1 was increasing during a substantial portion of the period when the plasma oscillations were being observed, from about mid-2001 to mid-2004. Therefore, it seems likely that the termination shock was moving outward from the Sun, possibly at the same rate as the spacecraft during the early part of this period, so the thickness of the region may be substantially less than 3 AU. Fourth, no further electron plasma oscillation events have been observed by Voyager 1 after 15 December 2004, consistent with a crossing of the termination shock on or about 16 December 2004.

The evidence that the electron plasma oscillations observed by Voyager 1 are associated with the termination shock is particularly compelling for the event that occurred on 15 December 2004. At the time of this plasma oscillation event, the low energy charged particle instrument (LECP) detected an intense highly anisotropic beam of 0.35 to 1.5 MeV electrons streaming away from the termination shock into the upstream region; see figure 2 in Decker *et al*. (*17*). This observation of an upstream electron beam coincident with the electron plasma oscillations provides strong evidence that the plasma oscillations are being driven by an energetic electron beam from the termination shock, exactly as predicted by Kurth and Gurnett (*8*). In analogy with planetary bow shocks, we suggest that just before passing through the termination region the spacecraft passed through a region where the magnetic field is nearly tangent to the surface of the shock, as illustrated in Fig. 4. The tangent field condition could be caused either by waviness of the shock boundary or by irregular variations in the magnetic field geometry. This interpretation is consistent with studies of the Earth's foreshock that show that the highest beam energies are produced near the tangent field line and that the most intense electron plasma oscillations are observed in this region (*11*). The sporadic bursty electric field intensity variations evident in Fig. 3 could be due to either time variations in the tangent field line configuration or nonlinear effects, both of which are known to occur at planetary bow shocks. We also note that the electron plasma oscillations occurred during a period when the LECP was observing large fluxes of anisotropic energetic (3.4 to 17.6 MeV) protons arriving from the shock. Although these protons are unlikely to be responsible for generating the plasma oscillations, they do provide further evidence that the spacecraft was in the region immediately upstream of the shock when the plasma oscillations were observed.

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20. We thank E. C. Stone, L. F. Burlaga, N. F. Ness, R. B. Decker, and S. M. Krimigis for discussions and L. J. Granroth for help in developing the computer algorithms necessary to identify and eliminate spacecraft interference from the plasma wave electric field data. The research at the University of Iowa was supported by NASA through contract 959193 with the Jet Propulsion Laboratory, Pasadena, CA.

14 July 2005; accepted 12 August 2005
10.1126/science.1117425

REPORT

Crossing the Termination Shock into the Heliosheath: Magnetic Fields

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Magnetic fields measured by Voyager 1 show that the spacecraft crossed or was crossed by the termination shock on about 16 December 2004 at 94.0 astronomical units. An estimate of the compression ratio of the magnetic field strength *B* (± standard error of the mean) across the shock is B_2/B_1 = 3.05 ± 0.04, but ratios in the range from 2 to 4 are admissible. The average *B* in the heliosheath from day 1 through day 110 of 2005 was 0.136 ± 0.035 nanoteslas, ~4.2 times that predicted by Parker's model for *B*. The magnetic field in the heliosheath from day 361 of 2004 through day 110 of 2005 was pointing away from the Sun along the Parker spiral. The probability distribution of hourly averages of *B* in the heliosheath is a Gaussian distribution. The cosmic ray intensity increased when *B* was relatively large in the heliosheath.

The existence of a shock at which a stellar wind makes a transition from a relatively cool supersonic flow to a hot subsonic flow was suggested by Weymann (*1*). In the solar wind, this shock is called the termination shock (TS), and the subsonic region between the TS and the boundary with the interstellar medium is called the heliosheath (*2*, *3*). A formula for the position of the TS in the solar wind was given by Parker (*4*). Observations of intense fluxes of energetic particles from 2002 to 2003 (which continued into 2004) suggested that Voyager 1 (V1), at ≈85 astronomical units (AU), was close to the TS (*5*). It was alleged that V1 actually crossed the TS into the heliosheath in mid-2002 (*6*), but this interpretation was not supported by the magnetic field observations (*7*, *8*). This Report and new observations described in this issue (*9–11*) indicate that V1 first crossed the TS on about 16 December 2004.

We discuss the V1 magnetic field observations from day 1 of 2004 (2004/001), through 2005/110. During this interval, V1 was at 34°N moving from 90.6 to 95.2 AU radially away from the Sun, and solar activity was decreasing. We believe that the TS was moving toward the Sun and V1 during this interval because the solar wind pressure and speed were decreasing (*12–18*). Predictions of the compression ratio B_2/B_1 across the TS (*19–21*) varied between ≈2 and ≈3.5. Whang *et al*. (*18*) calculated that this ratio would be ≈3.0 ± 0.2 if the TS were moving inward.

The magnetic field instrument on V1 (*22*) has two identical triaxial sensors mounted on a 13-m boom. The output of each magnetic field

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