In "Particle Acceleration and Transport in the Heliosphere and Beyond" - 7th Annual Astrophysics Conference, ed. by G. Li, Q. Hu, O. Verkhoglyadova, G. P. Zank, R. P. Lin, and J. Luhmann, American Inst. of Physics, Melville, NY, ISBN 978-0-7354-0566-0/08, pp. 335-342, 2008

Electrostatic Waves Observed At and Near the Solar Wind Termination Shock By Voyager 2

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Abstract. Upstream electron plasma oscillations and broadband bursts of electrostatic waves have been observed in the vicinity of the solar wind termination shock by the Voyager 2 plasma wave instrument. The upstream electron plasma oscillations were first detected on August 1, 2007, at a radial distance of 83.4 astronomical units (AU). These oscillations continued sporadically for about a month until, starting on August 31, three well-defined bursts of broadband electrostatic waves, similar to those observed at planetary bow shocks, were observed at a heliocentric radial distance of about 83.7 AU. Two of these broadband bursts corresponded to shock crossings identified in the magnetometer and plasma data, and one did not. During the crossings labeled TS-3 and TS-4 by the magnetometer and plasma teams, the broadband electrostatic bursts corresponded almost exactly with steep ramps in the magnetic field strength. By scaling the frequencies by the upstream electron plasma frequency and the spectral densities by the upstream plasma energy density, we have shown that the normalized spectrum is very similar to those observed at the bow shocks of outer planets. Plasma simulations based on the observed upstream parameters suggest that the broadband waves are driven by a beam-plasma instability caused by the reflection of solar wind ions in the magnetic field ramp.

Keywords: Electrostatic Waves, Termination Shock, Voyager 2
PACS: 52.35.Fp, 96.50.Ek, 95.55.-n

INTRODUCTION

Electrostatic plasma waves are known to play an important role in collisionless shocks and are produced by unstable non-thermal particle distributions that develop as the plasma flows through the shock transition layer [1]. As the waves grow to large amplitudes, the electric fields act to scatter the particles and drive the non-thermal particle distributions back toward thermal equilibrium. In addition, the electric fields accelerate some of the particles to high energies, forming extended high energy tails on the particle distributions, often with a power-law spectrum. Since the physics of the cosmic ray mediated termination shock has the potential of being markedly different than any other type of shock in the solar system, there has long been an interest in the wave-particle interactions that occur in the transition region of this shock. Although Voyager 1 was the first spacecraft to reach the solar wind termination shock [2], because of a gap in the ground receiving station coverage at the

CP1039, *Particle Acceleration and Transport in the Heliosphere and Beyond— 7th Annual Astrophysics Conference*
edited by G. Li, Q. Hu, O. Verkhoglyadova, G. P. Zank, R. P. Lin, and J. Luhmann
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time of the shock no measurements were obtained in the shock transition region [3]. Fortunately, during the more recent Voyager 2 crossing of the termination shock, very detailed measurements were obtained in the shock transition region [4,5,6,7], including measurements of the plasma wave electric fields [8]. In this paper we describe the plasma waves observed in the vicinity of the shock, and compare these observations with simultaneous magnetic field, plasma flow velocity, and plasma density measurements by the magnetometer (MAG) and plasma (PLS) instruments. For a description of the Voyager plasma wave instrument, see Scarf and Gurnett [9].

UPSTREAM ELECTRON PLASMA OSCILLATIONS

The first evidence in the plasma wave data that the spacecraft was near the termination shock occurred on August 1, 2007, when sporadic bursts of narrowband electron plasma oscillations were detected in the 311 Hz channel of the plasma wave instrument at a heliocentric radial distance of 83.4 AU, see Fig. 1. These oscillations, also known as Langmuir waves [10], are purely electrostatic waves that occur at a characteristic frequency of the plasma known as the electron plasma frequency. The electron plasma frequency [11] is given by $f_p = 8980\sqrt{n_e}$ Hz, where n_e is the electron density in cm^{-3}. The plasma frequency is in good agreement with the plasma density, 1.2×10^{-3} cm^{-3}, measured by the PLS instrument.

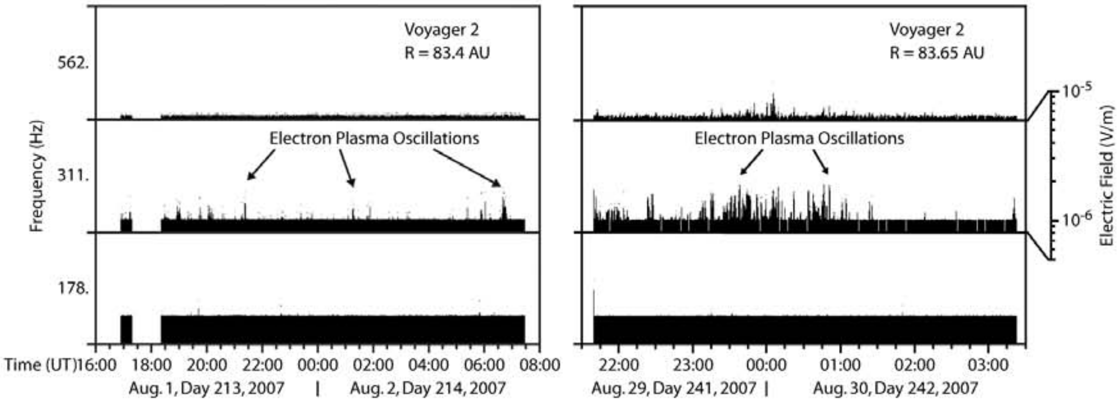

FIGURE 1. Electron plasma oscillations detected upstream of the termination shock in the 311 Hz channel. Panel (A) shows the first detection of these waves on August 1 and 2, 2007, and panel (B) shows somewhat stronger bursts of plasma oscillations on August 29 and 30, 2007, just before the termination shock crossing.

From observations near planetary bow shocks it is known that electron plasma oscillations are produced by an electron beam that escapes into the region upstream of the shock along interplanetary magnetic field lines. According to the well-known theory for beam-plasma instabilities [1] electron plasma oscillations are generated whenever the reduced electron velocity distribution, $F(v_\parallel)$, has a region of positive slope, i.e., $\partial F/\partial v_\parallel > 0$, that is sufficiently large to overcome the damping caused by thermal solar wind electrons. In the region upstream of the shock the positive slope condition is automatically satisfied by a geometric time-of-flight mechanism that dictates that only those electrons with velocities greater than a well-defined cutoff can reach the spacecraft [12,13]. The electron beam energy required to generate upstream

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electron plasma oscillations is typically in the range from a few keV to several tens of keV. Beams with such high energies usually originate from regions were the magnetic field is nearly tangent to the shock. Although we have looked for evidence of such beams in the plasma (PLS) and energetic particle (LECP) data, none was found. This is most likely due to the large gap, from about 6 to 35 keV, that exists in the energy coverage of the PLS and LECP instruments [14,15].

Although the onset of upstream electron plasma oscillations indicated that the spacecraft was in the vicinity of the shock, because so little is known about the propagation range of the electron beam responsible for the plasma oscillations, it was not possible to give a reliable distance to the shock, or to estimate when the shock crossing might occur. For Voyager 1 the onset of the upstream electron plasma oscillations occurred about 10 months before the spacecraft reached the termination shock [3]. Since Voyager 2 is moving outward from the Sun slightly slower than Voyager 1 (3.2 AU/yr versus 3.6 AU/yr), one could estimate that it would take about (3.6/3.2) x 10 months = 11.2 months for Voyager 2 to reach the shock. However, this simple estimate does not take into account the radial motion of termination shock, which varies considerably during the solar cycle due to variations in the solar wind pressure. For the Voyager 1 crossing of the termination shock, which occurred in 2004 during a period of high solar wind pressure shortly after solar maximum, there is good evidence that the shock had been moving outward from the Sun just upstream of the spacecraft for nearly two years [16], and that the crossing occurred as the shock started to move inward during the declining phase of the solar cycle. It was during the long extended period when the spacecraft was close to the shock that the electron plasma oscillations were observed. In contrast, the Voyager 2 crossing occurred near solar minimum when the shock was expected to be moving inward due to the declining solar wind pressure. The inward motion, combined with the outward motion of the spacecraft, was expected to significantly reduce the time that the spacecraft would spend in the region of upstream plasma oscillations. Based on these considerations, Kurth et al. [17] estimated that Voyager 2 would cross the termination shock within a few months after first detecting the upstream electron plasma oscillations, and possibly as soon as a few weeks. In fact, only about a month after the onset of the upstream plasma oscillations, five closely spaced crossings of the termination shock were detected by the particle and fields instruments [4,5,6,7,8] at a radial distance of only 83.7 AU, much closer than for the Voyager 1 termination shock crossing which occurred at 94.1 AU.

BROADBAND ELECTROSTATIC WAVES IN THE SHOCK TRANSITION REGION

The first indication in the plasma wave data that Voyager 2 had encountered the termination shock was the occurrence of a series of broadband electric field bursts on August 31 and September 1. These bursts occur in three groups and are labeled Events A, B and C in Fig. 2. Each group consists of a complex series of bursts of varying bandwidths that lasted up to several tens of minutes. However, within each group there was always one dominant very intense broadband burst that extended from the lowest frequency channel, 10 Hz, to at least 56 Hz (178 Hz in event B). These

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three broadband events are indicated by the vertical dashed lines in Fig. 2. Event A extends from about 17:47 to 17:55 Universal Time (UT) on August 31, event B extends from about 00:10 to 00:13 UT on September 1, and event C extends from about 02:43 to 02:47 UT on September 1 followed by two weaker narrower bandwidth bursts from about 03:03 to 03:06 UT and 03:20 to 03:24 UT. Although the Voyager plasma wave instrument has only an electric antenna and cannot distinguish purely electrostatic waves from electromagnetic waves, we can confidently claim that these waves are electrostatic, since they extend into a region, above the electron cyclotron frequency and below the electron plasma frequency, where no electromagnetic mode of propagation exists [1]. Broadband electrostatic bursts of this type are extremely rare in the solar wind and are almost always associated with shocks. No comparable broadband electrostatic bursts of this type have been observed in the Voyager 2 plasma wave data since the crossing of the bow shock at Neptune [18].

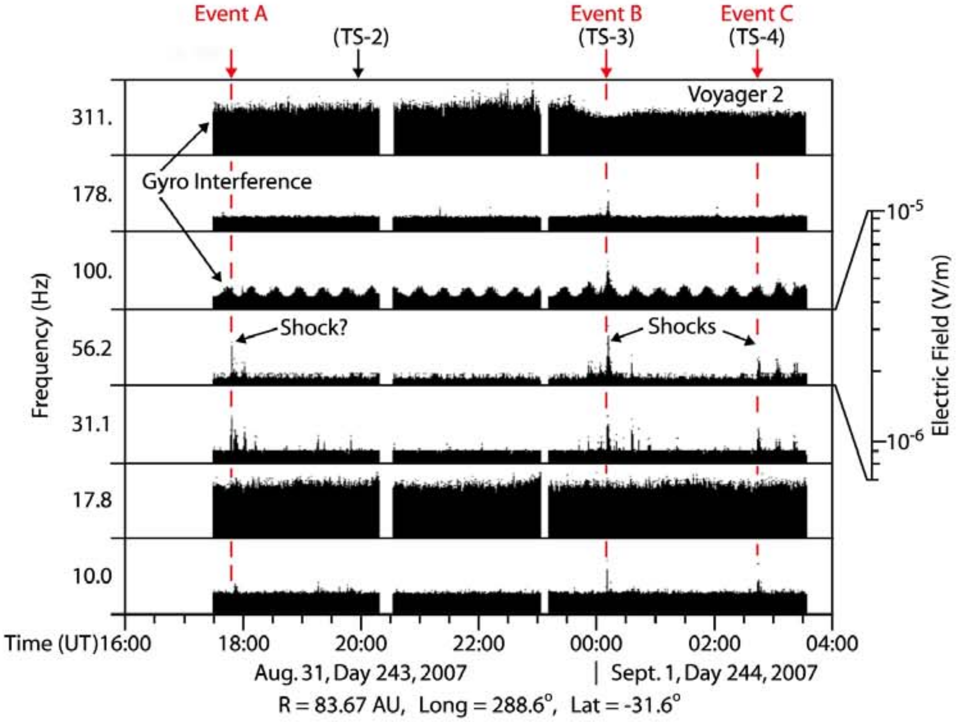

FIGURE 2. On August 31 and September 1, 2007, three well-defined broadband electrostatic bursts occurred (events A, B and C) of the type that are commonly associated with planetary bow shocks. Events B and C correspond to termination shock crossings labeled TS-3 and TS-4 by the MAG and PLS teams [7,6]. Event A was not identified as a shock, and no electrostatic waves were detected in association with the TS-2 crossing.

Comparisons with results from the magnetic field (MAG) and plasma (PLS) teams [6,7] show that events B and C correspond to the shock crossings that they labeled TS-3 and TS-4. Surprisingly, no electrostatic bursts occurred in association with the shock that the MAG and PLS teams identified as TS-2, which occurred at 20:10 UT on August 31. Burlaga et al. [7] have commented that this event appears to consist of two soliton-like pulses that are possibly in the process of reforming into a shock

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farther upstream. Waves have long been associated with energy dissipation in shocks, so if this event is in fact a soliton-like structure with no dissipation, then the absence of electrostatic waves may not be surprising. It is also interesting that the MAG and PLS teams did not identify a shock at the time of event A. However, there were substantial fluctuations in the magnetic field and plasma density around the time of this event, so although this event does not qualify as a shock according to the MAG and PLS criteria, the plasma wave data provide strong evidence of a non-thermal free energy source at this time with features similar those that occur at a shock. The MAG and PLS teams also identified two additional crossings of the termination shock, TS-1 on August 30, and TS-5 on September 1, both of which occurred in data gaps. Since these crossings occurred in data gaps in the ground receiving coverage no comparisons can be made.

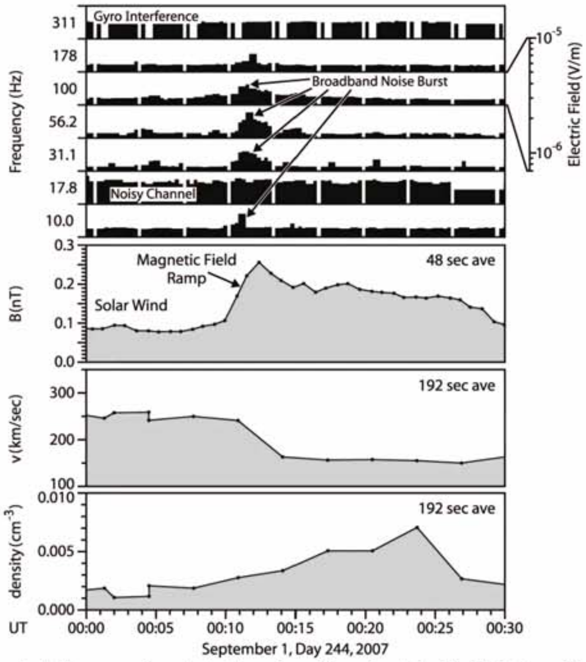

FIGURE 3. An expanded time scale plot showing the electric field intensities associated with the TS-3 shock crossing, and the relationship to the jumps in the magnetic field and the plasma flow velocity.

Of the two shock crossing for which we have simultaneous electric field, magnetic field, and plasma data, TS-3 is by far the most interesting. According to Burlaga et al. [7] this shock is a classic supercritical quasi-perpendicular shock with an Alfvén Mach number of about 8 and a compression ratio, B_2/B_1, of about 1.7. An expanded time-scale plot of the electric field strengths in the 10 Hz through 178 Hz channels, the magnetic field strength (B), the plasma flow velocity (v), and the plasma density (n) for this shock is shown in Fig. 3. As can be seen the broadband burst of electrostatic waves occurs almost exactly coincident with the ramp in the magnetic field and the abrupt decrease in the plasma flow velocity. A similar relationship between the broadband electric field strength and the ramp in the magnetic field is commonly observed at planetary bow shocks [19]. This relationship strongly suggests that the broadband electrostatic waves are closely related to the current responsible for the ramp in the magnetic field. One can also see that the

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frequency of the electrostatic waves increases systematically with increasing time as the spacecraft passes through the ramp in the magnetic field, starting first in the 10 Hz channel at about 00:11 UT, progressing upward 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 low frequencies and long wavelengths, is a characteristic feature of many electrostatic instabilities.

Since the broadband electrostatic waves associated with the TS-3 shock appears to be qualitatively similar to electrostatic waves observed at planetary bow shocks it is of interest to make a quantitatively comparison of the spectrums. Panel (A) of Fig.4 shows the absolute electric field spectral density of the TS-3 shock and comparable bow shock spectrums obtained by Voyagers 1 and 2 from Jupiter, Saturn, Uranus, and Neptune, as given by Moses et al. [20]. In absolute terms the electric field strengths at the termination shock are much weaker than at planetary bow shocks. However, because of the rapid $1/R^2$ decrease in the solar wind density with increasing distance from the Sun, one must take into account the fact that the solar wind energy density is much lower at the termination shock compared to the outer planets. Also, the characteristic frequencies of the waves are controlled by the electron plasma frequency, which is expected to decrease as 1/R with increasing distance from the Sun. To compensate for these effects panel (B) of Fig. 4 shows the electric field energy densities, $E^2/8\pi$, normalized by dividing by the plasma energy density, $8\pi nkT$, and the frequencies, f, normalized by dividing by the electron plasma frequency, f_p. When normalized in this way one can see that broadband electrostatic wave intensities at the termination shock are in fact very intense, more intense than most planetary bow shocks, and comparable to those observed at Neptune's bow shock.

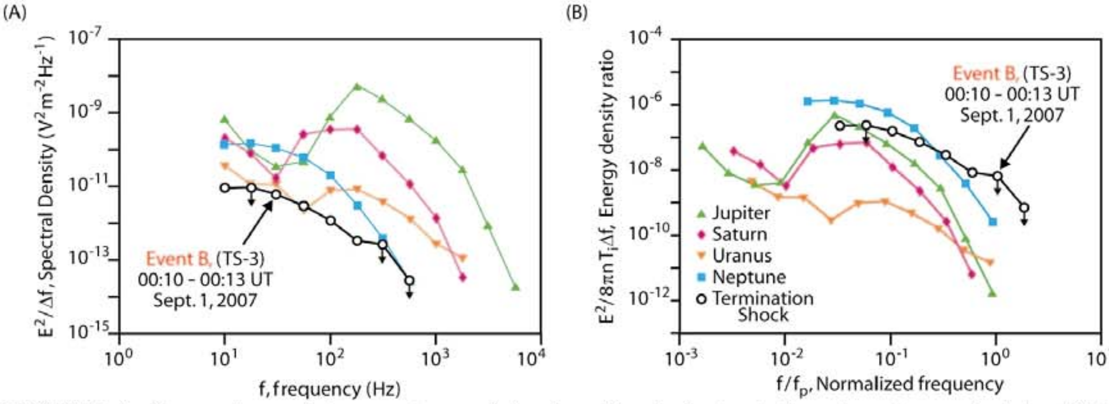

FIGURE 4. Comparison of the spectrum of the broadband electrostatic noise observed at the TS-3 shock with comparable bow shock spectrums at the outer planets. Panel (A) gives the electric field spectral densities, and Panel (B) gives the electric field energy density normalized by dividing by the plasma energy density, and the wave frequency normalized by dividing by the electron plasma frequency.

COMPARISON TO PLASMA SIMULATIONS

In order to help identify the origin of the broadband electrostatic waves observed at the termination shock we have performed a two and a half dimensional hybrid simulation in which ions are treated kinetically using the particles-in-cell (PIC)

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method and the electrons are treated as a massless fluid [21]. The simulation uses upstream parameters comparable to those observed at the TS-3 shock crossing. The results are shown in Fig. 5. Panel (A) shows the plasma number density, the ion temperature, the flow velocity, and the magnetic field as a function of distance X directed outward from the Sun in units of the ion skin depth, c/ω_{pi}. As one can see the plasma simulation does a good job in reproducing some key parameters of the shock, namely the jump in the magnetic field and the sharp drop in the flow velocity. However, the level of ion heating at the simulated shock is different from that observed by Richardson et al. [6], presumably due to absence of pick up ions in the simulation. Of more importance from our point of view are the 1-Dimensional reduced ion velocity distributions along the beam direction, which are shown in Panel (B). As can be seen in the vicinity of the magnetic field ramp the ion velocity distribution function develops a well-defined two-stream structure. This structure is the result of the partial reflection of the incoming solar wind ion beam by the magnetic field in the ramp region. Such two-stream velocity distributions are known to be highly unstable [1,22], and are a good candidate for generating the broadband electrostatic waves observed in the magnetic field ramp. In general, two types of instabilities are possible. One is due to nonresonant ion-ion interactions which saturates through trapping and results in ion dissipation. The other instability is due to electron-ion interactions (i.e., a current driven instability) where the Landau resonance with the electrons provides the free energy for wave growth. These two instabilities can operate simultaneously and lead to both ion and electron heating. The presence of pick up protons at the TS-3 shock could also result in additional instabilities and provide further amplification of the electrostatic waves. We plan to further investigate these various possibilities in the future using simulations that can take into account electron kinetic effects .

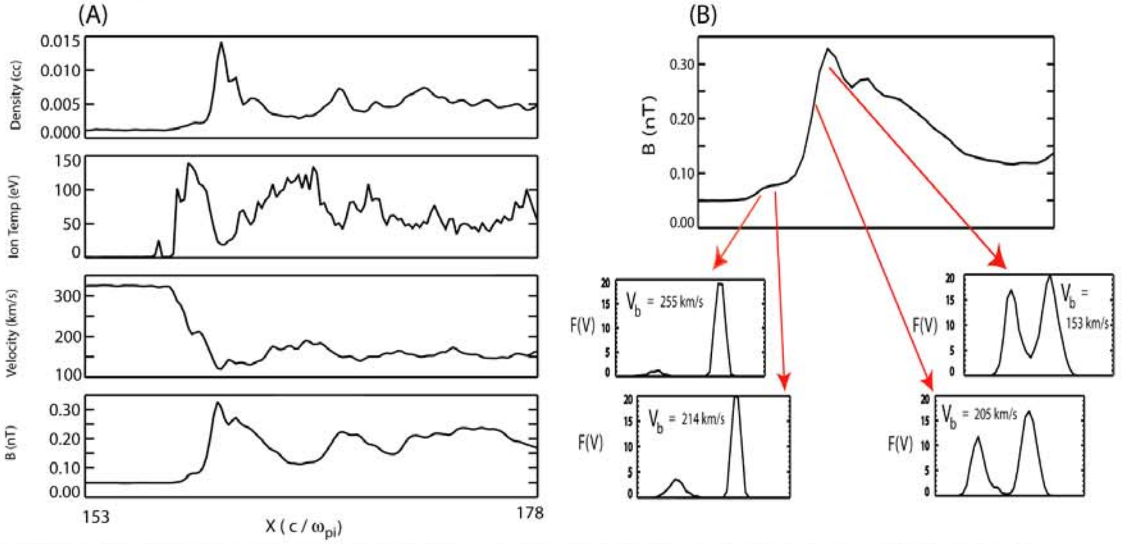

FIGURE 5. Panel (A) shows the results from a PIC plasma simulation, and panel (B) shows the resulting ion velocity distributions. A two-stream instability associated with these ion distributions is a likely candidate for the origin of the intense broadband electrostatic waves observed in the magnetic field ramp.

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Acknowledgements

The research at the University of Iowa was supported by NASA via contract 1279980 from the Jet Propulsion Laboratory (JPL). The research at Catholic University was supported by NASA Grant NNX07AW09G, and the research at the Massachusetts Institute of Technology was supported by NASA via contract 959203 from the Jet Propulsion Laboratory.

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