SHEDDING NEW LIGHT ON SOLITARY WAVES OBSERVED IN SPACE

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ABSTRACT

Electrostatic solitary waves are routinely observed by the Cluster Wideband (WBD) plasma wave receiver as the Cluster spacecraft cross boundary layers and regions of turbulence. These solitary waves are observed in the electric field waveform data as isolated pulses of various shapes, but primarily in the bipolar and tripolar forms. The amplitudes of the solitary waves appear to follow a somewhat general trend of increasing amplitude with increasing background magnetic field strength. Thus, the largest amplitude solitary waves are usually found closer to Earth as Cluster crosses magnetic field lines at about 4.5-6.5 R_E that map to the auroral acceleration region and the smallest amplitudes farthest from Earth in the plasmasheet, magnetosheath and solar wind at 18-19.5 R_E. Bow shock crossings are particularly interesting as there are significant differences in the number, amplitude and time duration of solitary wave pulses detected which probably indicate a dependence on the upstream environment and configuration of the interplanetary magnetic field. Continuing closer to earth into the magnetosheath we find that on the dayside, solitary waves are almost always present and the characteristics of them do not change appreciably from the bow shock to the magnetopause. This suggests that the solitary waves observed in the magnetosheath are being locally produced in the magnetosheath through one or more generation mechanisms. As we explore the properties of these solitary waves in the various regions, as well as the methods by which they could be produced, we hope to determine if and how these solitary waves are involved in more fundamental macroscale plasma processes.

1. INTRODUCTION

Broadband Electrostatic Noise (BEN) was first reported by Scarf et al. [1] and Gurnett et al. [2] using wave observations from the IMP 7 and IMP 8 spacecraft, respectively. BEN was characterized as being bursty and consisting of broadband spectral features usually extending from the lowest frequencies measured up to as high as the plasma frequency with the BEN intensity decreasing with increasing frequency. Subsequently, BEN was reported by investigators to be present in many regions of Earth, e.g., bow shock, magnetosheath, magnetopause boundary layer, cusp, plasmasheet boundary layer, along auroral field lines and in the auroral acceleration region. Most of these measurements were made by receivers which used onboard filtering techniques and relayed only the spectral information to the ground. Many theories were put forth to try to explain these broad spectral features, but none suggested they were simply the FFT-renderings of electrostatic solitary waves. During this same period of time, some observations of solitary waves and double layers were reported by Temerin et al. [3] using S3-3 waveform data. However, these data were not presented in spectral form and no link was made between the solitary waves and BEN.

Starting around 1985, some published theoretical works started to make a connection between solitary waves and BEN. Nishida et al. [4] pointed out that certain kinds of potential structures could explain the broad frequency spectra. A subsequent theoretical investigation by Dubouloz et al. [5] showed that electron acoustic solitons passing by a satellite would

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generate spectra that could explain the high frequency part of BEN, in agreement with experimental data from Viking. The first compelling observational breakthrough came in 1994 when Matsumoto et al. [6] made the link between the observed solitary waves and BEN for the distant magnetotail. Using Geotail Plasma Wave Instrument data, they showed that several modes were present in the ac electric field measurements of BEN, with one of the most surprising being the "Electrostatic Solitary Wave", or ESW. They described the ESW as being in the form of a bipolar pulse, i.e., a half sinusoid-like cycle followed by a similar half cycle having opposite sign. The ESWs had time durations on the order of 2-5 ms and peak-to-peak amplitudes of a few tenths mV/m. They concluded that most of the BEN in this region is not continuous broadband noise but is composed of a series of ESWs. A nonlinear BGK (Bernstein-Greene-Kruskal) [7] potential mode was proposed by Omura et al. [8] as the generation mechanism of the BEN based on computer simulations. This breakthrough came primarily through the use of a waveform receiver with high time resolution and having the waveform data available in digital form.

Most of the ESWs observed since then from other missions such as POLAR, FAST, WIND, and now CLUSTER have been interpreted as holes in electron or ion phase space, i.e., positive or negative potential structures, respectively, in agreement with the Geotail conclusions. For a review of some of these observations and subsequent theoretical investigations, see Franz et al. [9]. The potential structures move along magnetic field lines and generally are thought to be of the BGK type arising out of beam instabilities such as the two-stream instability. Some of the ESWs reported to be present in the auroral parallel acceleration region have been interpreted by Pottelette et al. [10] to be modulated electron acoustic solitons growing out of the electron acoustic instability.

In addition to the bipolar ESWs, there have also been reports of tripolar ESWs (three half sinusoids, two of one polarity and one of the opposite polarity). The tripolar ESWs were first reported by Mangeney et al. [11] from WIND observations and by Pickett et al. [12,13] for various regions around Earth using CLUSTER data. The tripolar structures are possibly weak double layers based on the small, but measurable potential change across the structures [11,12]. Tsurutani et al. [14] also reported observations from POLAR of paired monopolar (one half sinusoid) pulses of opposite polarity and offset bipolar pulses and concluded that these may be electron holes that are split and broadened, respectively.

Since the CLUSTER orbit traverses almost all regions of Earth where solitary waves are observed, this provided investigators using data from the Wideband (WBD) waveform receiver [15], due to its extensive amplitude range and high sampling rate, with an excellent opportunity to carry out surveys of the ESWs for comparison by region. The remainder of this paper is devoted to discussing the characteristics of the ESWs observed by WBD, presenting the ESW survey results, discussing the ESW propagation study, followed by an in-depth look at the ESWs observed in the magnetosheath, and concluding with an initial glimpse into the ESWs observed at the bow shock.

2. BEN AND ESWs EXAMPLE

Fig. 1a provides an example of the BEN observed in the spectrograms created by processing the WBD waveform data with a 1024-point Fast Fourier Transform (FFT). The plot contained in this figure is a time-frequency spectrogram with color indicating electric field power spectral density. This plot shows a quasi-perpendicular bow shock crossing at about 03:19 UT by both spacecraft 3 (upper panel) and spacecraft 4 (lower panel) on 26 March 2002, with data obtained upstream of the shock in the foreshock region prior to 03:19 and downstream in the magnetosheath after 03:19. The white line plotted in both panels is the plasma frequency obtained by the Whisper Sounder. The ephemeris data shown at the bottom of the plot, applicable to Spacecraft 4 only, gives radial distance from Earth in R_E, geomagnetic latitude in degrees, magnetic local time in hours and L-shell value.

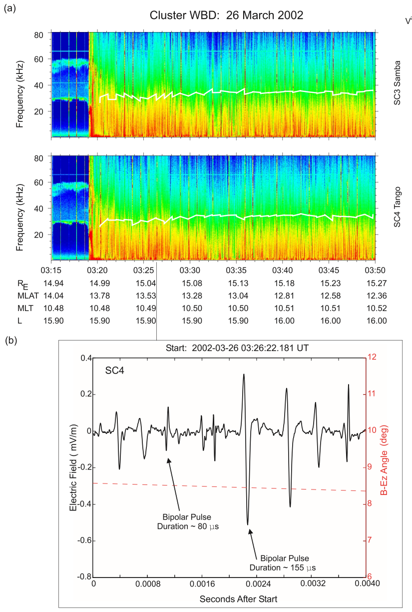

Fig.1. Example of (a) BEN observed in the magnetosheath after 03:19 UT and (b) 4 millisecond waveform showing a series of bipolar pulses which produces the broad spectrum. From Pickett et al. [17].

Fig. 1b shows one 4 ms sample of the waveform beginning at 03:26:22.181 UT used in constructing the spectrogram. Specifically pointed out in Fig. 1b are some very short time duration bipolar pulses. Nearly continuous bursts of these short time duration pulses, or ESWs, are the reason that the BEN observed in Fig. 1a extends to such high frequencies (~50 kHz), well above the local plasma frequency. Of significance is the fact that the BEN is not observed in the foreshock, but is observed at the bow shock and well downstream in the magnetosheath.

3. ESW SURVEY OF THE CLUSTER ORBIT

ESWs are observed in many of the regions explored with Cluster's orbit. We created an ESW detection algorithm for automatically detecting bipolar and tripolar pulses according to some criteria that set limits on the ratio of the field strength of one peak with regard to the other peak(s) and on the degree to which the field strengths are above the noise level of the instrument (see Pickett et al. [13] for a description of the criteria used). Some pulses can be missed with this algorithm but false positives will not be included. We then ran this detection algorithm on WBD data intervals obtained in the various regions in Cluster's orbit. This was meant to be a survey as opposed to a statistical study. As shown in Fig. 2, ESWs were almost always detected (white stars) near the bow shock, throughout the magnetosheath, at plasmasheet crossings at 17-19 R_E, and at all cusp and magnetopause boundary crossings. The red ellipses represent typical summer (right most) and winter (left most) orbits. ESWs are also almost always seen at 4.5 to 6.5 R_E as the orbit crosses field lines that map to the auroral region. They are only occasionally observed in the free solar wind as shown by the green stars in Fig. 2.

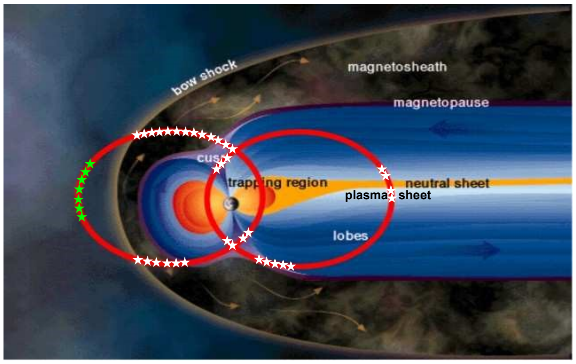

Fig. 2. Locations where ESWs are observed in representative summer (right ellipse) and winter (left ellipse) orbits. White stars represent regions where ESWs are almost always observed, green stars where they are sometimes observed.

One of the primary results of this survey [13] was that both the bipolar and tripolar ESWs show a general trend for their amplitudes to increase as the background dc magnetic field strength increases (see Fig. 3 for bipolar pulses). The ESWs used in this survey covered 4 orders of magnitude in amplitude over 2 orders of magnetic field strength. A similar trend was found for the tripolar pulses. One possible conclusion of these results is that the general trend is consistent with stability requirements of the BGK mode in finite magnetic fields as described in Chen et al. [16] although other possibilities are not ruled out. Another follow-on conclusion to be drawn from this trend is that the magnetic field strength in the solar wind is possibly too low, resulting in fewer ESW detections and that, if present, the ESWs are at or below the noise floor of the WBD receiver and not detectable. The same possibility exists for the usual lack of ESW detections in the foreshock.

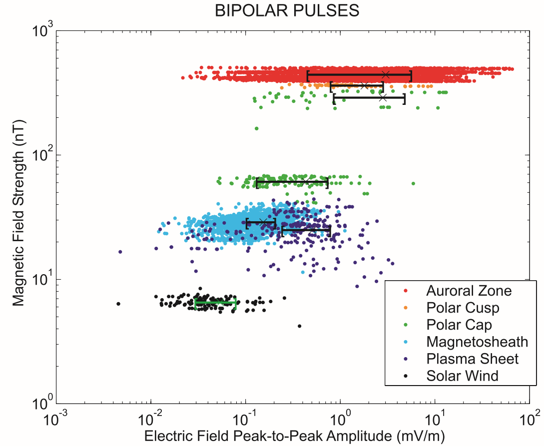

Fig. 3. Magnetic field strength vs. bipolar ESW amplitude color coded by region with bracketed lines representing standard deviation and asterisks the mean. From Pickett et al. [13]

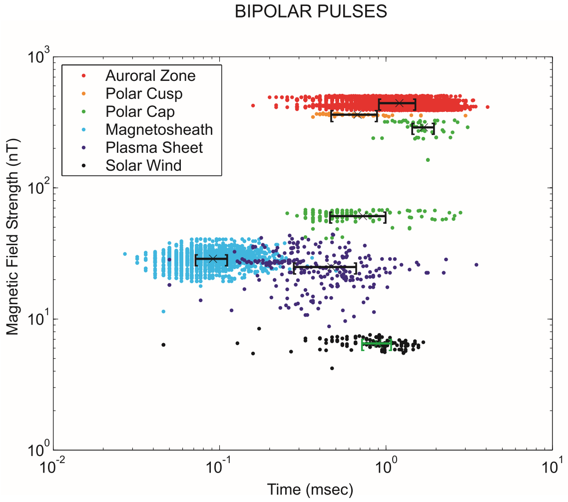

Fig. 4. Magnetic field strength vs. bipolar ESW time duration color coded by region. From Pickett et al. [13]

Another result of the ESW survey [13] was that there was no similar trend for ESW pulse time duration with increasing magnetic field strength (see Fig. 4 for the bipolar pulses). A similar result was found for the tripolar pulses. These results did point to the magnetosheath ESWs as having significantly shorter time durations than those of ESWs in all other regions included in the survey. The conclusion drawn from this is that the magnetosheath ESWs might be generated out of a different mechanism than for all of the other regions, although a difference in plasma parameters in the turbulent magnetosheath might also account for the shorter time duration ESWs.

4. ESW PROPAGATION STUDY

One of the primary questions that continues to be asked with regard to ESWs observed in space is how far they can propagate. Up until now, they have only been observed propagating from one antenna to another on any one spacecraft. Since the distance from one antenna to another on these single spacecraft is of the order of 100m or less, there was no way to infer from these measurements whether the ESWs are capable of propagating over distances as large as kms. Cluster's multispacecraft nature thus provided a natural laboratory for testing whether this is possible. Unfortunately, there are several complications in carrying out this study that make it very difficult to search the data for this purpose. First is the problem associated with the fact that solitary waves are almost never observed as one isolated ESW. ESWs usually come in a series of pulses, with some pulses regularly, but most irregularly, spaced in time. The possibility of isolating one bipolar pulse and being confident that this was the same one observed on another spacecraft is very low. Thus, it was determined that the search needed to be confined to a series of ESW pulses with similar amplitudes and time durations. Another complication is that the spacecraft are spinning. Unless the antennas on each spacecraft are oriented similarly with respect to the magnetic field, the ESW shapes (ratio of peak amplitudes for example) could look different from one spacecraft to the next. Here we assume that the ESWs propagate along the magnetic field based on results from single spacecraft studies. Finally, there is the complication that the two spacecraft need to lie along the same magnetic field line over distances not too large (tens of kms).

Pickett et. al. [12] determined that one of the best regions to look for such ESW propagation was along field lines that map to the auroral acceleration region at 4.5-6.5 R_E. Fig. 5 shows the best example found thus far from data obtained on 6 April 2002 at 10:23:06 UT. Panel A shows a 13 ms sample of waveforms from SC1 and panel B shows a similar length sample from SC3 slightly earlier than that of SC1. Both spacecraft show two tripolar pulses, with SC3 seeing an additional bipolar pulse that is not seen in SC1. The first tripolar pulse shown in SC1 (Panel 1) has its peaks clipped, not due to saturation but rather due to a lack of digital resolution which indicates that some gain needed to be taken out of the system by the automatic gain control. For this example, the antenna angles to the magnetic field were very similar, 154 and 163 degrees, respectively. Panel C shows the results of correlating the two waveform samples, coming up with a coefficient of 0.78 at about 10 lags of SC1 from SC3. Panel D shows the result of shifting the SC1 waveform forward by 10 lags. The result is that both of the tripolar pulses seen on both spacecraft nicely line up in form and time, providing confidence that these are the same ESWs observed on both spacecraft.

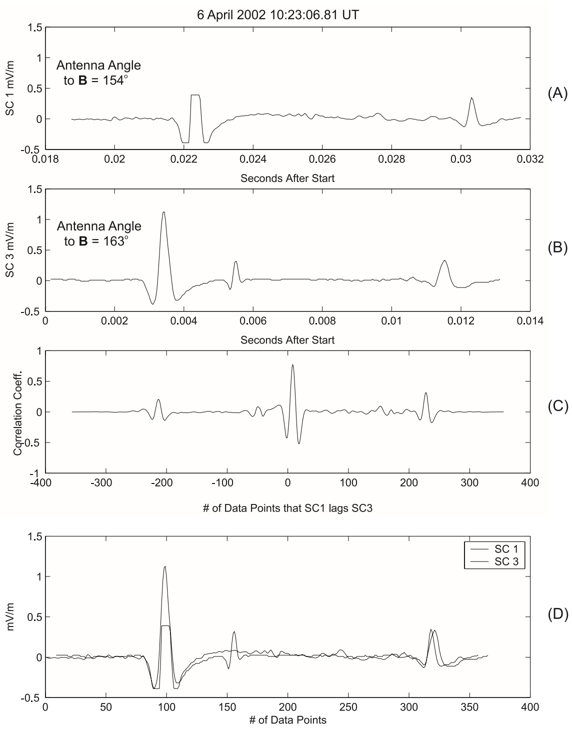

Fig. 5. Cross spacecraft correlation of tripolar ESW pulses showing propagation of two of the pulses from SC3 to SC1. From Pickett et al. [12].

Based on the 56 km separation along B for this case and 251 km across B, Pickett et al. [12] determined that these tripolar pulses had a propagation velocity of 2800 km/s away from Earth, with a parallel size of 4.5 km and a perpendicular size of at least 251 km. They concluded that the Cluster spacecraft are probably separated by too great a distance during most of the orbit or that the ESWs routinely grow, damp out or transfer their energy to particles or waves, thus making it unlikely that Cluster will observe many cases of ESW propagation. However, this was a preliminary study, paving the way for more detailed, systematic studies of ESW propagation.

5. MAGNETOSHEATH ESWs

Since the Cluster WBD instrument has extremely good time resolution, 5 microseconds in the 77 kHz bandwidth mode, this makes a very good match for studies of ESWs in the magnetosheath since the ESWs in this region are the shortest observed anywhere in Cluster's orbit. It was believed that the magnetosheath ESWs were probably generated at the bow shock and propagated from there throughout the magnetosheath. Thus, Pickett et al. [17] carried out various studies that would shed light on whether this was the case. They first took several magnetosheath cases and determined the characteristics of the ESWs (peak-to-peak amplitude and pulse time duration) as a function of distance from the bow shock downstream. Fig. 6 presents the results of that study. This figure shows that the characteristics of the ESWs do not change for either the bipolar or tripolar pulses as the spacecraft go deeper into the magnetosheath. This result suggests that there are probably several local sources of ESW generation in the magnetosheath as we would expect the ESW characteristics as the spacecraft get further downstream to change due to the turbulent nature of the magnetosheath. The characteristics of the ESWs were also studied as a function of ion velocity, with only a slight tendency for the ESW amplitudes to increase with ion velocity. The conclusion drawn from this is that probably electron dynamics are more involved in the generation of the magnetosheath ESWs than ion dynamics. The presence or absence of ESWs based on the type of bow shock (quasi-parallel or quasi-perpendicular) that might contribute to downstream conditions was examined. Pickett et al. [17] found no correlation between the type of bow shock and presence of ESWs, suggesting again that the magnetosheath ESWs are probably locally generated.

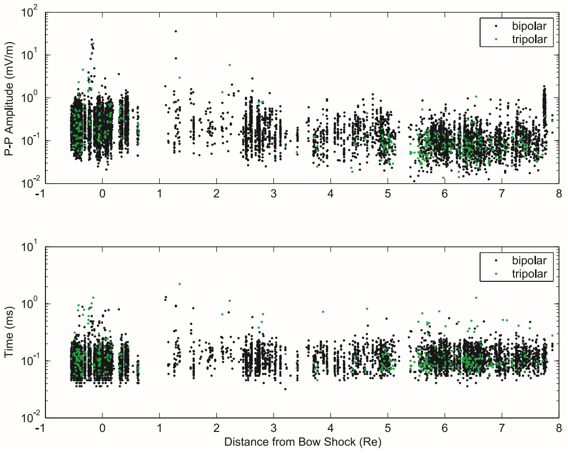

Fig. 6. Characteristics of ESWs as a function of distance from the bow shock. From Pickett et al. [17].

For almost all cases included in this study, Pickett et al. [17] found that counterstreaming electrons were present for most of them, suggesting the possibility that the ESWs were generated through a beam instability and would be BGK mode electron phase space holes. Another possible mechanism for the generation of ESWs could be the beam instabilities driven by low-frequency, wave-accelerated bistreaming electrons as described in Lakhina et al. [18,19]. We are currently exploring the possibility in a follow-on study that the ESWs are generated through the electron acoustic instability [20,21] since preliminary simulations show that negative potential electron acoustic solitons can be generated for the one case under study. Plasma parameters for that case were obtained through modeling of Cluster's electric antennas by Beghin et al. [22] during a special mutual impedance test involving the Whisper and WBD instruments.

6. BOW SHOCK ESWs

Finally, we have begun to look at the characteristics of the ESWs observed at the bow shock, specifically in the shock transition region. Bale et al. [23,24] have used WIND waveform observations of ESWs to conclude that the ESWs observed at Earth's bow shock are small scale unipolar convecting potential structures consistent with simulations of electron phase space holes or BGK trapped particle equilibria. Matsumoto et al. [25] have used Geotail waveform observations to characterize the four types of waveforms observed in the shock transition region, one of which is the bipolar pulse similar to the BEN observed in the tail, the remainder consisting of non-ESW types. The measurements from both of these missions are taken as snapshots so that continuous data are usually not being obtained across the entire bow shock transition region. WBD data, on the other hand, are obtained continuously through the crossing, with no duty cycling for the 9.5 kHz bandwidth mode and with duty cycling (10 milliseconds of data, 70 milliseconds of data gap) for the 77 kHz bandwidth mode. Pulse durations as short as 20 microseconds can be measured with the 77 kHz bandwidth mode and as short as 50 microseconds with the 9.5 kHz bandwidth mode. Thus, regardless of what mode WBD is in, we are able to characterize the ESWs across the entire transition region, aside from the limitation of the pulse time durations due to bandwidth considerations and pulse amplitudes that would fall below the WBD noise floor or greater than the upper amplitude cut-off as previously mentioned .

Fig. 7 is an example of a bow shock crossing made by SC1 on 13 May 2002. This figure shows the usual ESW peak-to-peak amplitude in the top panel and pulse time duration in the bottom panel vs. time, with the solid line giving the magnetic field strength according to the scale on the right vertical axis. A bipolar pulse detection is plotted as a black dot and tripolar pulse as a green asterisk with the characteristic scales shown on the left vertical axis. For this crossing, no ESWs are detected upstream or in the foot of the shock. Several ESWs are detected on the ramp, in the overshoot region and continuously downstream. The largest amplitude ESWs are detected on the ramp and in the overshoot, while the time durations of the pulses are generally around 0.4 ms or longer with the exception of a few downstream that are less than 0.1 ms. This was a quasi-perpendicular bow shock crossing, with $\theta_{BN} \sim 52$ degrees and upstream $\beta \sim 2.4$ and $M_A \sim 13.5$.

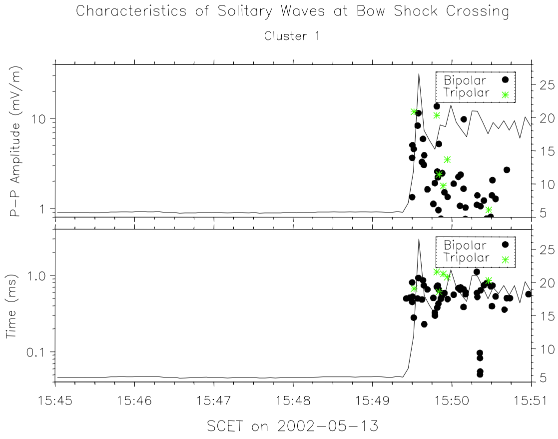

Fig. 7. Characteristics of ESWs for a quasi-perpendicular bow shock crossing. No ESWs are observed upstream or in the foot of the shock.

We have found that the presence or absence of ESWs, and the characteristics of them, in the shock transition region can vary quite greatly depending on upstream conditions and θ_{BN}. We are in the process of trying to determine what upstream factors mostly influence the ESWs, and what we can learn about the processes occurring at the bow shock based on this. As Bale et al. [23,24] have suggested, the ESWs may play a role in maintaining the finite resistivity in a plasma and in the thermalization or velocity-space mixing of electrons at collisionless shocks.

7. SUMMARY AND CONCLUSIONS

Electrostatic solitary waves (solitary structures) are routinely observed at many locations in Cluster's orbit, primarily regions of turbulent or mixing plasmas. The lower incidence of ESW detections in the turbulent solar wind and the lack of them in the foreshock may be related to the low magnetic field strength there. The bipolar and tripolar pulses associated with the ESWs have time durations that vary from ~20 microseconds to a few milliseconds and peak-to-peak amplitudes from about 0.01 (noise floor of the receiver) to 100 mV/m (upper amplitude cut-off). The shortest time duration ESWs are found in the magnetosheath. The ESWs follow a general trend of increasing amplitude with increasing background magnetic field strength, which is consistent with the ESWs possibly being BGK mode phase space holes. If BGK mode, this automatically implies trapping of electrons or ions for the bipolar ESWs and trapping of both species if tripolar ESWs [12]. Some ESWs in the auroral zone have been found to propagate over distances of 54 km along B. The characteristics of the ESWs found in the magnetosheath are consistent with local generation at various locations in the magnetosheath as opposed to generation at the bow shock or some other specific location. The proposed generation mechanisms for the magnetosheath ESWs are beam instabilities due to the presence of counter streaming electrons (BGK mode) and electron acoustic instability.

Although much has already been learned from Cluster and other satellite missions about ESWs, there are still many unanswered questions. For example, can we definitively determine the generation mechanism for the ESWs observed in various regions of Earth and if so, what are they? Do ESWs propagate over distances larger than a few tens of kms? What is the role of ESWs, if any, in ongoing plasma processes, both microscale and macrosale, in the regions in which ESWs are encountered. Cluster is poised to answer many of these questions in the years ahead through simulations that use Cluster data which have already been obtained with small to moderate spacecraft separations and with the large separations that have been in place since July 2005 and for the remainder of the mission.

8. ACKNOWLEDGMENTS

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9. REFERENCES

1. Scarf F. L., Frank L. A., Ackerson K. L., et al., Plasma Wave Turbulence at Distant Crossings of the Plasma Sheet Boundaries and the Neutral Sheet, *Geophysical Research Letters*, Vol. 1, 189-192, 1974.

2. Gurnett D. A., Frank L. A., and Lepping R.P., Plasma Waves in the Distant Magnetotail, *Journal of Geophysical Research*, Vol. 81, 6059-6071, 1976.

3. Temerin M., Cerny K., Lotko W., et al., Observations of Double Layers and Solitary Waves in the Auroral

Plasma, *Physical Review Letters*, Vol. 48, 1175-1179, 1982.

4. Nishida A., Hada T., Anderson K. A., et al., Broadband Electrostatic Noise in the Magnetotail: Its Relation to Plasma Sheet Dynamics, *Journal of Geophysical Research*, Vol. 90, 4453-4460, 1985.

5. Dubouloz N., Treumann R. A., Pottelette et al., Turbulence Generated by a Gas of Electron Acoustic Solitons, *Journal of Geophysical Research*, Vol. 98, 17415-17422, 1993.

6. Matsumoto H., Kojima H., Miyatake T., et al., Electrostatic Solitary Waves (ESW) in the Magnetotail: BEN Wave Forms Observed by GEOTAIL, *Geophysical Research Letters*, Vol. 21, 2915-2918, 1994.

7. Bernstein I.B., Greene J. M., and Kruskal M.D., Exact Nonlinear Plasma Oscillations. *Physical Review*, Vol. 108, 546-550, 1957.

8. Omura Y., Kojima H., and Matsumoto H., Computer Simulation of Electrostatic Solitary Waves: A Nonlinear Model of Broadband Electrostatic Noise, *Geophysical Research Letters*, Vol. 21, 2923-2926, 1994.

9. Franz J. R., Kintner P. M., Pickett J. S., et al., Properties of Small-Amplitude Electron Phase-Space Holes Observed by Polar, *Journal of Geophysical Research*, Vol. 110, doi:10.1029/2005JA011095, 2005.

10. Pottelette R., Ergun R. E., Treumann R. A., et al., Modulated Electron-Acoustic Waves in Auroral Density Cavities: FAST Observations, *Geophysical Research Letters*, Vol. 26, 2629-2632, 1999.

11. Mangeney A., Salem C., Lacombe C., et al., WIND Observations of Coherent Electrostatic Waves in the Solar Wind, *Annales Geophysicae*, Vol. 17, 307-320, 1999.

12. Pickett J. S., Kahler S. W., Chen L.-J., et al., Solitary Waves Observed in the Auroral Zone: the Cluster Multi-Spacecraft Perspective, *Nonlinear Processes in Geophysics*, Vol. 11, 183-196, 2004.

13. Pickett J. S., Chen, L.-J., Kahler, S. W., et al., Isolated Electrostatic Structures Observed Throughout the Cluster Orbit: Relationship to Magnetic Field Strength, *Annales Geophysica*e, Vol. 22, 2515-2523, 2004.

14. Tsurutani B. T., Arballo J. K., Lakhina G. S., et al., Plasma Waves in the Dayside Polar Cap Boundary Layer : Bipolar and Monopolar Electric Pulses and Whistler Mode Waves, *Geophysical Research Letters*, Vol. 25, 4117-4120, 1998.

15. Gurnett D.A., Huff R. L., and Kirchner D. L., The Wide-Band Plasma Wave Investigation, *Space Science Reviews*, Vol. 79, 195-208, 1997.

16. Chen L.-J., Thoule D. J., and Tang J.-M., Bernstein-Greene-Kruskal Solitary Waves in Three-Dimensional Magnetized Plasma, *Physical Review E*, Vol. 69, 055401(R), 2004.

17. Pickett J. S., Chen L.-J., Kahler S. W., et al., On the Generation of Solitary Waves Observed by Cluster in the Near-Earth Magnetosheath, *Nonlinear Processes in Geophysics*, Vol. 12, 181-193, 2005.

18. Lakhina G. S., Tsurutani B. T., and Pickett J. S., Association of Alfven Waves and Proton Cyclotron Waves with Electrostatic Bipolar Pulses: Magnetic Hole Events Observed by Polar, *Nonlinear Processes in Geophysics,* Vol. 11, 205-213, 2004.

19. Lakhina G. S., Tsurutani B. T., and Pickett J. S., Generation of Electric Solitary Structures (Electron Holes) by Nonlinear Low-Frequency Waves, *Physica Scripta*, Vol. T116, 79-82, 2005.

20. Singh S. V. and Lakhina G. S., Generation of Electron-Acoustic Waves in the Magnetosphere, *Planetary and Space Science*, Vol. 49, 107-114, 2001.

21. Singh S. V., Reddy R. V., and Lakhina G. S., Broadband Electrostatic Noise Due to Nonlinear Electron Acoustic Waves, *Advances in Space Research*, Vol. 28, 1643-1648, 2001.

22. Beghin C., Decreau P. M. E., Pickett J., et al., Modeling of CLUSTER'S Electric Antennas in Space: Application to Plasma Diagnostics, *Radio Science*, in press, 2005.

23. Bale S. D., Kellogg P. J., Larson D. E., et al., Bipolar Electrostatic Structures in the Shock Transition Region: Evidence of Electron Phase Space Holes, *Geophysical Research Letters*, Vol. 25, 2929-2932, 1998.

24. Bale S. D., Hull A., Larson D. E., et al., Electrostatic Turbulence and Debye-Scale Structures Associated with Electron Thermalization at Collisionless Shocks, *The Astrophysical Journal*, Vol. 575, L25-L28, 2002.

25. Matsumoto H., Kojima H., Kasaba Y., et al., Plasma Waves in the Upstream and Bow Shock Regions Observed by Geotail, *Advances in Space Researc*h, Vol. 20, 683-693, 1997.