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POLAR OBSERVATIONS OF SOLITARY WAVES AT HIGH AND LOW ALTITUDES AND COMPARISON TO THEORY

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ABSTRACT

Solitary waves with large electric fields (up to 100 mV/m) are often observed by Polar in the low altitude auroral zone and, at high altitudes(~ 4-8 R_E), during crossings of the plasma sheet boundary and cusp. Electron solitary waves are ubiquitous, and are observed for wide range of f_{ce}/f_{pe}. In contrast, to date, ion solitary waves have only been observed in the auroral zone at low altitudes in the region where f_{ce}/f_{pe}>>1. We describe some results of statistical studies of ion solitary waves at low altitudes and electron solitary waves at high altitudes. Ion solitary waves, observed in regions of upward field-aligned currents and ion beams, are negative potential structures and have velocities between O^+ and H^+ beam speeds, scale sizes of approximately $10\lambda_D$, and normalized amplitudes, $e\phi/kT_e$, of order 0.1 because the electron temperatures are large (plasma sheet values). In addition, the amplitude increases with both the velocity and the scale size which is inconsistent with the predictions of ion acoustic soliton theory. The observations are well modeled by the simulations of Crumley et al. (2000) which include only the plasma sheet electrons and the beam ions. Both observations and the simulations are consistent with an ion hole mode associated with the ion two stream instability. The high altitude electron solitary waves have velocities from ~1000km/s to >2500 km/s. Observed scale sizes are on the order of $1\text{-}10\lambda_D$ with $e\phi/kT_e$ up to O(1). For these solitary waves also, the amplitude increases with both the velocity and the scale size, consistent with electron hole modes as was observed at low altitudes. Even the very large amplitude solitary waves are stable based on the criterion developed by Muschietti et al.(1999).

INTRODUCTION

In the earth's magnetosphere, there are many regions where narrow boundaries and large gradients in particle properties and/or fields occur. Such regions often contain currents flowing along the earth's dipole field as well as other sources of free energy such as ion and/or electron beams. Wave growth often leads to very large amplitudes, and nonlinear electric field structures are often observed at these boundaries . One type of nonlinear structure which has received much study is solitary waves. Solitary waves, which were interpreted as negative potential pulses traveling up the magnetic field, were first observed in the auroral zone (Temerin et al., 1982, Bostrom et al., 1988). These solitary waves, which occur in association with ion beams propagating away from the ionosphere, have been associated with the ion acoustic mode and have been identified as ion holes. Later, lower amplitude solitary structures, interpreted as electron holes, were identified in the distant plasma sheet (Matsumoto et al., 1994).

Utilizing data from the FAST spacecraft, Ergun et al. (1998) identified a new type of solitary wave, associated with cold electron beams, which propagates upward at ~4500 km/s. These large amplitude waves have an electromagnetic signature and are interpreted as electron holes traveling with the beam. Both fast-moving electron solitary waves and slower ion solitary waves were identified in the low altitude Polar data by Mozer et al. (1997) and by Bounds et al. (2000). Bounds et al. (2000) also showed that the ion solitary waves were associated with upflowing ion beams and the electron solitary waves with electron beams. Preliminary results from Polar have also provided evidence for similar fast moving solitary waves at high altitudes (Cattell et al., 1998; 1999; Franz et al, 1998; 2000). Electron solitary waves have also been identified at the bow shock using Wind data (Bale et al.,1999). A summary of solitary wave properties and selected references on each type of solitary wave are given in Table 1.

Theoretical work on solitary waves initially focussed on ion acoustic solitons, which, for a simple system with one ion and one electron species, were shown to be compressive (positive potential) structures propagating slightly faster than the ion acoustic speed. Such solitons have not yet been observed; the observed ion solitons are rarefractive. Many more complex, multi-component systems have been studied, analytically, numerically and via simulations, providing information of propagation velocities, growth and stability, and structure (compressive or rarefractive) in various regions of parameter space. Similar studies made of electron acoustic solitary waves, indicate that, for most plasma models, the structures are negative potential and propagate above the electron acoustic speed. Positive potential structures occur only in a very restricted parameter space. The most common theoretical explanation for the fast moving solitary waves is an electron hole mode, such as analytic BGK modes (Muschietti et al., 1999) or evolution of a bump on tail instability or electron two stream instability (Omura et al., 1996; Mottez et al., 1997; Matsumoto et al., 1999; Goldman et al., 1999; and references therein).

In this paper, we present preliminary results of two statistical studies of electric field data from the Polar EFI instrument, one of ion solitary waves observed in southern hemisphere perigee passes (Dombeck et al., 2000), and the other of solitary waves observed during high altitude (~ 4-8 R_E) crossings of the plasma sheet boundary and cusp. As will be discussed below, the latter study is focused on electron modes, since, to date, no ion solitary waves have been definitively identified in the high altitude data. We also present results from new simulations of ion solitary waves (Crumley et al., 2000) for comparison to the observations. The first section describes the data sets and methodology , as well as briefly describing the simulations. An example of the low altitude solitary waves, the simulation results and a comparison of their solitary wave characteristics are in the next section. Several examples of high altitude solitary waves events and comparisons to theories are given in the fourth section. The final section discusses results, conclusions and future work.

DATA AND METHODOLOGY

Data Sets

The data for this study were obtained from the Polar satellite during both southern hemisphere perigee passes through the auroral zone and during crossings of the plasma sheet boundary and cusp injections at high altitudes (4-8 Re). The electric field and spacecraft potential measurements were made by the double probe electric field instrument on the Polar satellite (Harvey et al., 1995). This instrument, which saturates at 1 V/m, obtains 3d measurements of the electric field at 20 samples/second and, in addition, obtains bursts (waveform capture) of high time resolution data in many different modes. Electric field data sampled at 8000 samples/s are utilized herein. In addition to the electric field (potential difference between opposing probes), the delay time between signals at opposing probes were examined to estimate the propagation speed of electric field structures utilizing an automatic program (see Dombeck et al., 2000). Electric field data were rotated into a magnetic field-aligned coordinate system and the parallel component was examined for candidate solitary waves. Timing analysis was limited to events where one of the two spin plane boom pairs is nearly aligned along the magnetic field. In these cases, the signal from each single probe was splined to provide an identical time basis for all signals and spacecraft potential variations were removed using the perpendicular boom pair. The time delay between the observation of the solitary wave signal at opposing probes was determined using a cross correlation analysis. Coupled with the projected probe separation along the magnetic field, the time delay was used to estimate the propagation velocity of the solitary waves. The automatic program used to calculate velocity also determines the structure width, solitary wave amplitude, and includes plasma data to make statistical plots of normalized amplitudes and widths. Details of this procedure are described elsewhere (Dombeck et al., 2000).

DC magnetic field data were obtained from the fluxgate magnetometers (Russell et al., 1995). Plasma data from the Hydra instrument (Scudder et al., 1995) and ion composition data from TIMAS (Shelley et al., 1995) are also utilized. In addition to the statistical studies of solitary wave properties, the solitary wave velocities for specific low altitude events were compared to beam speeds obtained from O^+ and H^+ distributions. For selected electron SW events, comparisons were made to the plasma distributions and direction of field-aligned currents.

Comparisons between predicted relationships between the solitary wave amplitude and scale size (and/or velocity) are often used to determine whether the solitary waves are solitons or hole modes. For example, 1d soliton theory predicts that the amplitude is inversely proportional to the scale size, whereas a BGK hole has an amplitude which is proportional to the scale size. Care must taken in applying this test to real data. In the case of observed solitary waves, the structures are 3d, and the spacecraft will not usually cut through the center of the solitary wave (maximum amplitude). resulting relation is shown

Simulation Overview

The simulations are based on the 2D/3V electrostatic code of Marchenko and Hudson (1995). The input parameters are based on FAST observations in the region of upward field-aligned currents and ion beams. The most important difference between these simulations and previous ones is that no cold plasma is included, as observed on FAST (Strangeway et al., 1998; McFadden et al., 1999). Runs were made with only an H^+ beam and with both O^+ and H^+ beams. The initial beam speed and f_{ce}/f_{pe} were both varied. Details of the simulations and results have been presented by Crumley et al. (2000). Herein, we will compare the solitary wave velocities and amplitudes found in the simulations to those observed in the Polar data.

LOW ALTITUDE AURORAL ZONE ION SOLITARY WAVES

Example

An example of an event in the low altitude auroral zone, occurring on April 1, 1997 is shown in Figure 1 (from Dombeck et al., 2000). The top panel presents the electric field parallel to the background magnetic field for the entire burst. The next two panels show the velocity space distribution functions of H^+ (upper) and O^+ (lower). In the bottom panel, the amplitude of each solitary wave, identified by the automatic program, is plotted versus its velocity. Note that the left-hand scale gives the amplitude in mV/m and the right-hand scale is normalized by kT_e using the Hydra electron moments. Large amplitude 200mV/m peak-to-peak solitary waves can be seen. The bottom panel shows that the inferred velocities of the solitary waves range from ~100-400 km/s; between O^+ and H^+ beam speeds(marked on the plot). Due to the high electron temperature (plasma sheet electrons), $e\phi/kT_e$ is of order 0.1. The scale sizes (not shown) are on the order of 1-10λ_D. Additional examples and statistics can be found in Dombeck et al. (2000).

Comparison to Simulations

Figure 2a shows the results from the simulations of Crumley et al. (2000) on the relationship between the solitary wave velocity and ion beam speed. The average solitary wave speed and the simultaneous value of the O^+ and H^+ beam speeds are plotted versus the initial speed of the hydrogen beam (all normalized to the initial electron thermal speed, v_{te}). The solitary wave speeds obtained in the simulations lie in between the O^+ and H^+ beam speeds, in good agreement with the Polar data. Note that the ion acoustic speed is 0.1 v_{te} (due to the lower mass ratio used in the simulation). Although the solitary wave speed is on the order of an ion acoustic speed from the oxygen beam speed, the separation from the hydrogen beam speed is much less than the ion acoustic speed for low initial beam speeds and much greater for large initial beam speeds.

Figure 2b (Crumley et al., 2000) shows the dependence of the solitary wave amplitude (normalized to the electron thermal energy) on the initial beam speed. Note that the potentials are negative because ion solitary waves correspond to ion holes. The largest absolute values of the potential occur for the largest initial beam speeds. For the lower range of beam speeds (which are in the range of those observed by Polar for the events studied), $e\phi/kT_e$ is ~ 0.1, in agreement with the Polar observations.

HIGH ALTITUDE PLASMA SHEET BOUNDARY AND CUSP ELECTRON SOLITARY WAVES

Examples

An example of an event at the high altitude plasma sheet boundary on March 28, 1997 , at a radial distance of ~6.3 Re and 1:30 MLT, is shown in Figure 3. Very large amplitude solitary waves (up to 200 mV/m peak-to-peak) occurred at the edge of an intense downward current. A large-scale view of this plasma sheet boundary crossing is shown in Figure 2 of Cattell et al. (1999). The waveform burst occurred at a transition between downward and upward current. In the first distribution, there is a strong electron beam moving down the magnetic field peaked at ~10,000 km/s and a less intense, lower energy beam flowing up the field. In the second distribution, the beams have spread in the parallel direction resulting in a flat-top distribution similar to those observed by FAST at low altitudes. The packets of spiky parallel fields (with broad spectra) are solitary waves. The solitary wave velocity was ~1200->2500 km/s, comparable to, but slower than, the observed low energy upgoing electron beam.

Statistical information on the solitary waves identified by the automatic program during this burst are shown in Figure 4. Panel a plots the potential amplitude (the scale on the right is normalized to the electron temperature) versus width (the scale on the top is normalized to the Debye length). Solitary waves for which there was no measured delay ('infinite velocity') are indicated by an 'x.' For these events, only a lower bound on the potential and scale size could be determined. It can be seen that the amplitudes increase with width.

Figure 5 presents an example of a burst obtained in the high altitude cusp on April 7, 1997. The energy spectrograms of H^+ and He^+ from the TIMAS instrument are plotted in the top two panels, and the field-aligned component of the electric field in the burst is plotted in the third panel. The burst occurred near the beginning of the cusp injection.

Statistics and Comparison to Theory

For all the plasma sheet boundary crossings described above, as well as other cases which have been examined, the solitary waves are positive potential structures, travelling either parallel or anti-parallel to the magnetic field with velocities of 1000->2500 km/s. The solitary wave velocities are usually in the same direction as simultaneously observed electron beams or the direction of core electrons inferred from the field-aligned currents. The speed is much less than the electron beam, but is consistent with the core electrons. In addition to the bipolar parallel electric field, there are often unipolar perpendicular fields, indicating that the solitary waves are not one-dimensional, as has been observed at low altitudes by FAST (Ergun et al., 1998) and for the small amplitude high altitude events on Polar (Franz et al., 1999; 2000).

The parallel scale sizes are 10's of λ_D, and, for the largest amplitude structures, $e\Phi/kT_e \sim 1$. Note that there are also many smaller amplitude solitary waves observed in each burst with $e\Phi/kT_e < 1$. It should be noted that there were no signatures of the solitary waves observable in the AC magnetic field for most of the events. Only the very largest solitary waves have magnetic signatures.

CONCLUSIONS AND FUTURE WORK

Large amplitude (up to 100's of mV/m) solitary waves are commonly observed in the Polar electric field data at all altitudes (from ~1-8 Re). The solitary waves ** Electron solitary waves are ubiquitous, and are observed for wide range of f_{ce}/f_{pe}. In contrast, to date, ion solitary waves have only been observed in the auroral zone at low altitudes in the region where $f_{ce}/f_{pe} >> 1$. Cattell et al. (1999) suggested that this could be understood through examination of the simulations of Barnes et al. (1995) which showed that the plasma must be strongly magnetized for ion solitary waves to develop. The simulations of Crumley et al. (2000), however, have shown that ion solitary waves do develop even for $f_{ce}/f_{pe} \sim 1$. Thus, the lack of ion SW in other regions of the magnetosphere is still not understood. Further work, both observational and computational, is underway to examine this issue.

Ion solitary waves, observed in regions of upward field-aligned currents and ion beams, are negative potential structures and have velocities between O^+ and H^+ beam speeds. They have scale sizes of approximately $10\lambda_D$. Although wave amplitudes are frequently very large, the normalized amplitudes, $e\phi/kT_e$, is of order 0.1 because the electron temperatures are large (plasma sheet values). In addition, the amplitude increases with both the velocity and the scale size which is inconsistent with the predictions of 1d ion acoustic soliton theory. The observations are well modeled by the simulations of Crumley et al. (2000) which include only the plasma sheet electrons and the beam ions. Both observations and the simulations are consistent with an ion hole mode associated with the ion two stream instability.

Electron solitary waves are observed by Polar both in the auroral zone (Mozer et al., 1997; Bounds et al., 2000) and in the high altitude magnetosphere (Cattell et al., 1998 and 1999; Franz et al., 1998; 2000). Herein, we concentrated on high altitude observations at both the plasma sheet boundary and during cusp injections. Consistent with previous studies, the statistics showed that the velocities were from ~1000km/s to >2500 km/s. Observed scale sizes were on the order of 1-$10\lambda_D$, and $e\phi/kT_e$ were up to O(1). The amplitude increases with both the velocity and the scale size. This is consistent with electron hole modes. Cattell et al.(2000) presented additional arguments against the identification of the structures as electron acoustic solitons. Even the very large amplitude solitary waves were stable based on the criterion developed by Muschietti et al.(1999).

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