Solitary structures associated with short large-amplitude magnetic structures (SLAMS) upstream of the Earth's quasi-parallel bow shock

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Received 19 January 2004; revised 14 May 2004; accepted 21 June 2004; published 25 August 2004.

[1] For the first time, solitary waves (SWs) have been observed within short large-amplitude magnetic structures (SLAMS) upstream of the Earth's quasi-parallel bow shock. The SWs often occur as bipolar pulses in the electric field data and move parallel to the background magnetic field at velocities of $v = 400-1200$ km/s. They have peak-to-peak amplitudes in the parallel electric field of up to $E'_{\|} = 65$ mV/m and parallel scale sizes of $L_{\|} \sim 10\ \lambda_D$. The bipolar solitary waves exhibit negative potential structures of $|\Phi_{\|}| = 0.4-2.2$ V, i.e., $e\Phi_{\|}/kT_e \sim 0.1$. None of the theories commonly used to describe SWs adequately address these negative potential structures moving at velocities above the ion thermal speed in a weakly magnetized plasma. *INDEX TERMS:* 7839 Space Plasma Physics: Nonlinear phenomena; 7851 Space Plasma Physics: Shock waves; 7871 Space Plasma Physics: Waves and instabilities. **Citation:** Behlke, R., M. André, S. D. Bale, J. S. Pickett, C. A. Cattell, E. A. Lucek, and A. Balogh (2004), Solitary structures associated with short large-amplitude magnetic structures (SLAMS) upstream of the Earth's quasi-parallel bow shock, *Geophys. Res. Lett.*, *31*, L16805, doi:10.1029/2004GL019524.

1. Introduction

[2] At the Earth's quasi-parallel bow shock, so-called short large-amplitude magnetic structures (SLAMS) are commonly observed [*Schwartz et al.*, 1992; *Lucek et al.*, 2002; *Behlke et al.*, 2003]. Observations combined with simulations [*Burgess*, 1989] led to the model of a cyclically reforming shock which is built up of a patchwork of SLAMS [*Schwartz and Burgess*, 1991]. The quasi-parallel shock could thus be described as an extended transition region characterized by the growth, deceleration and merging of SLAMS rather than a single shock surface.

[3] Solitary waves (SWs) travelling parallel to the background magnetic field have been reported from various parts of the magnetosphere. They are characterized by their bipolar electric field structure parallel to the magnetic field. SWs were first observed in the auroral acceleration region by S3-3 [*Temerin et al.*, 1982]. They are found at narrow boundaries, such as the plasma sheet boundary [*Cattell et al.*, 1998] and the quasi-perpendicular bow shock [*Bale et al.*, 2002] and in regions with strong currents, such as the auroral acceleration region [*Mozer et al.*, 1997]. Observations of SWs were also reported from the solar wind [*Mangeney et al.*, 1999], the magnetosheath [*Pickett et al.*, 2003], at high-altitude cusp injections [*Cattell et al.*, 2001] and the magnetopause [*Cattell et al.*, 2002]. In most cases, the structures were identified as electron SWs. They are observed at both high and low altitudes for a wide range of f_{ce}/f_{pe}. However, ion SWs have so far only been reported from strongly magnetized plasmas in the low altitude auroral region where $f_{ce}/f_{pe} \gg 1$ [*Boström et al.*, 1988; *Dombeck et al.*, 2001]. This letter presents the first observations, as known to the authors, of solitary structures within SLAMS.

[4] The data for this study were obtained by the Electric Field and Wave (EFW) experiment [*Gustafsson et al.*, 1997] onboard the four Cluster spacecraft [*Escoubet et al.*, 1997]. The EFW experiment consists of two pairs of spherical probes on wire booms in the spin plane of each satellite (approximately the ecliptic plane). The probe-to-spacecraft separation is 44 m. For the data presented here, the probe potential with respect to the spacecraft is sampled both at 9,000 samples per second (internal burst mode data rate, called IBM hereafter), as well as at 5 samples per second (normal mode data rate, called NM hereafter). This measurement is usually referred to as the negative of the spacecraft potential $-V_{sp}$ and gives an estimate of the plasma density [*Pedersen et al.*, 2001]. In addition, the electric field between two oppositely situated probes can be obtained. Using the two probe pairs, the electric field vector in the spin plane can be constructed. Furthermore, data from the fluxgate magnetometer (FGM) [see *Balogh et al.*, 2001] are used for the identification of SLAMS.

2. Observations

[5] An example of a quasi-parallel bow shock crossing observed by Cluster spacecraft 4 on February 3, 2002, at $\sim$(12, 3, $-$8) R_E (in GSE) is presented in Figure 1. The transition from the solar wind (UT 04:30–04:50) to a more turbulent region (from UT 04:50) with magnetic field and density pulsations can clearly be seen in Figures 1a–1b which display $-V_{sp}$ and the magnetic field magnitude B, respectively. In Figures 1c–1e, a shorter interval of 1 min reveals typical signatures of short large-amplitude magnetic structures (SLAMS). During this interval, two SLAMS are observed at UT 04:59:35 and 04:59:42. They are character-

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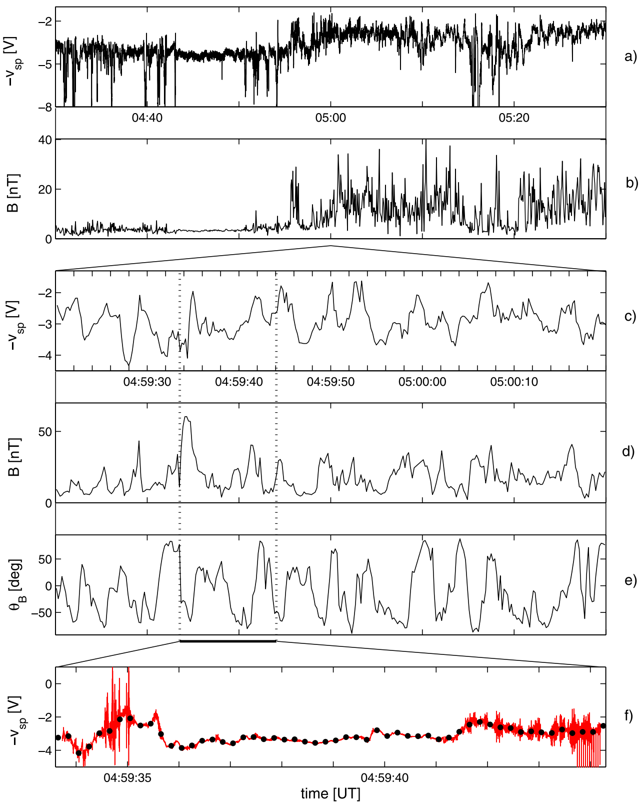

Figure 1. A quasi-parallel shock crossing observed by Cluster satellite 4 on February 3, 2002. Note the different time intervals for panels (a)–(b), (c)–(e) and (f), respectively. Panel (a) shows the negative spacecraft potential $-V_{sp}$. High $-V_{sp}$ corresponds to a high density (e.g., a $-V_{sp}$ of −8, −5, −2 V corresponds to about 6, 20, 100 particles cm^{-3}). Panel (b) displays the magnetic field magnitude B from FGM for the same period. Panels (c)–(e) show 1 min of data of the negative spacecraft potential $-V_{sp}$, the magnetic field magnitude B and the elevation angle of the magnetic field θ_B, respectively. Here, $\theta_B = 90°$ corresponds to a strictly northward field. Panel (f) displays 11.5 sec of $-V_{sp}$ data for probe 2. The red line gives the IBM data (9 kHz sampling rate) with NM data (5 Hz sampling rate) overlayed as black circles. The pattern of vertical lines in panel (f) at 04:59:44 is due to the active sounding of the WHISPER instrument.

ized by density enhancements [*Behlke et al.*, 2003], as seen in Figure 1c, as well as magnetic field enhancements [*Schwartz et al.*, 1992], as seen in Figure 1d. SLAMS are typically associated with rotations of the magnetic field, see Figure 1e which shows the magnetic field elevation θ_B. Although all four Cluster spacecraft were recording data during this period, we only present data for one spacecraft in this plot. Firstly, IBM data are only recorded for one satellite at a time. Secondly, the plot is restricted to one spacecraft for clarity reasons, since Figures 1c–1e are nearly identical for different spacecraft during this event at ~100 km separation between the satellites. For multi-spacecraft observations of SLAMS [see *Lucek et al.*, 2002; *Behlke et al.*, 2003]. A zoom-in of Figure 1c is shown in Figure 1f displaying an interval of 11.5 sec during which an internal burst was recorded. The black circles give the NM data whereas the red line shows the IBM data for probe 2.

[6] Note that some features of the SLAMS are only visible in the IBM data, e.g., short-duration, high-amplitude spikes. Details presented later clearly show that some of these spikes are SWs. In addition, high-frequency wave packets are observed (data not shown). During this quasi-parallel shock crossing, two more IBM data sets have been recorded on other spacecraft adding up to 33 sec of data.

[7] Figure 2 shows data from another spacecraft (SC 2) for the same event as displayed in Figure 1f. Two SLAMS are observed around 04:59:59–05:00:00 and 05:00:01–05:00:03. Data from both spacecraft 4 and 2 (Figures 1f and 2) show that electric field spikes (including SWs) are not confined to the SLAMS. However, the amplitude and occurrence frequency are strongly increased within the SLAMS. Outside of the SLAMS, the amplitudes are of the order of 0.1–0.5 V, whereas 3 V can be reached within the SLAMS.

[8] Figure 3 shows two short intervals of 100 ms with IBM data for spacecraft 4. $E_{\|}$ and $E_{\perp}$ are defined as the electric field components in the spin plane of the spacecraft parallel and perpendicular to the ambient magnetic field B, respectively, when B lies in the spin plane ($\theta_B \sim 0$). The SWs occur in groups (Figures 3a–3b) or as single structures (Figures 3c–3d). They have durations Δt less than or approximately 1 ms and peak-to-peak amplitudes in the parallel electric field $E'_{\|}$ of the order of or above 10 mV/m. Several spikes are embedded in a weaker irregular wave field.

[9] Solitary waves (SWs) are in general, as well as in SLAMS, characterized by a bipolar electric field pulse parallel to the background magnetic field. To determine the physical structure of a SW, its velocity vector must be determined. This can be done using the four probes as an interferometer. *Franz et al.* [1998] and *Dombeck et al.* [2001] presented the application of this technique on POLAR observations. As discussed by *Cattell et al.* [2003], this method returns scale sizes that are approximately four times larger than those obtained by a potential fit to a Gaussian. The first method is based on the gradient in the parallel electric field change, whereas the latter method uses the Gaussian half-width. Figure 4a shows a zoom-in of Figure 3c. It displays the well-resolved parallel electric field component of a SW. The interferometry analysis (data not shown) for this SW yields a velocity of $v \sim 400$ km/s. The potential depth as integrated over the

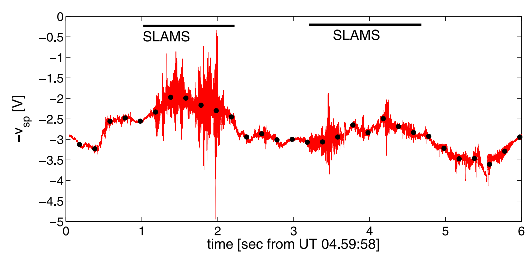

Figure 2. Observations by Cluster 2 on February 3, 2002. The same notation as in Figure 1f is used. Note that FGM data for this interval are presented in Figure 1d, B, and Figure 1e, θ_B, clearly showing an enhancement in and a rotation of B.

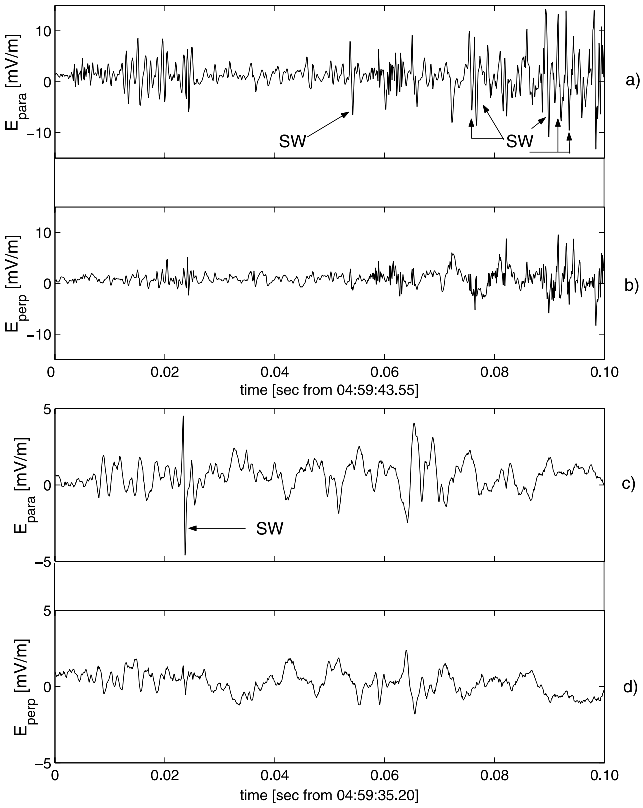

Figure 3. Observations by Cluster 4 on February 3, 2002. Panels (a)–(b) display $E_{\parallel}$ and $E_{\perp}$ (definition see text) with start at UT 04:59:35.9. Panels (c)–(d) give $E_{\parallel}$ and $E_{\perp}$ with start at UT 04:59:35.2. A few solitary structures are marked with arrows.

parallel component of the structure yields $\Phi_{\parallel} = -0.6$ V, as shown in Figure 4b. Note that there is no net potential drop over the structure. The duration of the pulse is $\Delta t \sim 0.75$ ms, which gives a parallel scale length $L_{\parallel} \sim 300$ m. Under typical conditions at SLAMS, the Debye length is $\lambda_D \sim 20$ m, thus $L_{\parallel} \sim 15\ \lambda_D$.

[10] The analysis of 10 other SWs yields parallel velocities of 400–1200 km/s, $L_{\parallel} \sim 300$–600 m and negative potentials of $|\Phi_{\parallel}| = 0.4$–2.2 V, i.e., $e\Phi_{\parallel}/kT_e \sim 0.1$. Note that the resolution of the magnetic field B used to calculated $E_{\perp}$ and $E_{\parallel}$ is about 0.04 s. Thus, changes of B on shorter time-scales might account for the large range of the estimated velocities.

3. Summary and Conclusions

[11] We have reported on the first observations of non-linear, electric field pulses (solitary waves, SWs) associated with short large-amplitude magnetic structures (SLAMS) upstream of the Earth's quasi-parallel bow shock. Our measurements show together with earlier observations (see references in Section 1) that SWs are ubiquitous in naturally occurring plasmas.

[12] The SWs move parallel to the background magnetic field with velocities of $v = 400$–1200 km/s and have peak-to-peak amplitudes in the parallel electric field of up to $E'_{\parallel} \sim 65$ mV/m. The parallel scale sizes are $L_{\parallel} \sim 300$–600 m $\sim 10\ \lambda_D$. The bipolar SWs exhibit negative potentials of $|\Phi_{\parallel}| = 0.4$–2.2 V, i.e., $e\Phi_{\parallel}/kT_e \sim 0.1$

[13] In our study, the solar wind speed is ~400 km/s in the unshocked region before ~UT 04:50, whereas it reduces to ~200 km/s in the shock-like region after ~UT 04:50. Detailed particle data are not included in this study and simultaneous particle distribution functions for individual SWs can not be obtained with the present instruments. Using typical parameters for this region, we find thermal (about 10 eV) proton and electron speeds of about 50 and 2000 km/s, respectively.

[14] An interesting question concerns the importance of SWs for the overall properties of SLAMS, including the importance for particle acceleration and for maintaining a larger scale parallel electric field. Most SWs have no obvious net potential drop. However, often a net potential of a few percent of $|\Phi_{\parallel}|$ can not be excluded since other fluctuations with lower amplitude and longer duration are also present in the plasma. Comparing with other regions of space we note that *McFadden et al.* [2003] argue that ion phase space holes in the auroral region are a consequence of the acceleration process rather than maintaining the parallel potential drop. However, reports [e.g., *Cattell et al.*, 2003] on electron SWs with $e\Phi_{\parallel}/kT_e \sim 1$ at the plasma sheet boundary suggest that these SWs might alter the electron distribution significantly. Again considering SWs in SLAMS, we can at this stage not conclude that the SWs are important for the main structure of the SLAMS.

[15] A further issue is the association between SWs of different shapes, durations and scales. Observations with the Wideband (WBD) plasma investigation [*Gurnett et al.*, 1997] onboard Cluster using one electric field component obtained at ~2.2 10^5 samples per second suggest another class of SWs within SLAMS (Pickett, private communication). These SWs have durations of the order of 10's of microseconds (not shown here). Assuming the same velocity as for the SWs we study, this implies a scale size of the order of one Debye length. Similar structures observed in the magnetosheath have been interpreted as electron phase space holes [*Pickett et al.*, 2003].

[16] The knowledge of the speed and potential of our SWs in SLAMS allows us to discuss their nature. Firstly, the negative potential nature of the SWs would suggest that these are ion depletion structures. Our average SW parallel

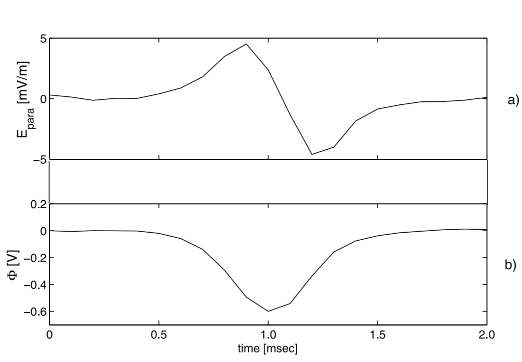

Figure 4. 2002-02-03, UT 04:59:35.22: Cluster observations (SC 4) of a solitary wave exhibiting the characteristic bipolar signature in the parallel electric field component (panel a). Panel (b) shows the potential over the structure with $\Phi_{\parallel} \approx -0.6$ V.

velocity is well above the typical ion thermal velocity, in contrast to the earlier observations of ion phase space holes in other regions [*Dombeck et al.*, 2001]. The solar wind convection can explain some of the SW motion, but the SW velocity is mainly field aligned and independent of the solar wind direction. Up to now, ion SWs in weakly magnetized plasmas ($f_{ce}/f_{pe} \ll 1$) have not been reported on in observations (see references in Section 1) or simulations [*Barnes et al.*, 1985]. However, *Turikov* [1984] showed theoretically for BGK electron holes that the SW speed is not constrained to the particle thermal velocity. Secondly, electron phase space holes can be excluded as a possible interpretation, since these structures always are positive potential structures and move with a speed comparable to the thermal electron speed. Both conditions disagree with our observations. Thirdly, theoretical work [e.g., *Mace and Hellberg*, 2001] show that for most plasma models, electron acoustic SWs are negative potential structures. They do not require the plasma to be strongly magnetized, but propagate at speeds above the electron acoustic speed [*Berthomier et al.*, 2000]. This speed is above the speed of the thermal electrons, i.e., above about 2000 km/s. Hence, electron acoustic SWs are not in agreement with the observed SWs. In summary, we find that none of the theories commonly used to describe SWs adequately explain our observations.

[17] Recent theoretical investigations indicate that BGK SWs may be more easily generated than previously believed [*Chen et al.*, 2004] and might explain our observations. Several features of the observed SWs are consistent with BGK ion holes. Ongoing theoretical work, e.g., on BGK solitary waves, need to show if ion phase space holes may exist in weakly magnetized plasmas and may move at the observed high velocities.

[18] Another example showing that present theories of SWs should be reconsidered and improved has recently been found at the quasi-perpendicular bow shock [*Bale et al.*, 2002]. Here electron holes have been observed convecting with the solar wind rather than moving with the much higher thermal electron speed.

[19] In conclusion, we have shown that SWs with a negative potential structure are common in SLAMS. An interesting challenge is that the theories commonly used to explain SWs do not adequately describe our observations.

[20] **Acknowledgments.** RB thanks Li-Jen Chen, A. Vaivads, A. Tjulin, A. I. Eriksson and S. C. Buchert for helpful discussions. JSP acknowledges support from NASA GSFC Grant NAS5-9974.

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