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Cluster 20th anniversary: results from the first 3D mission

A Review of Electrostatic Solitary Wave Research From the Cluster Mission

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Key Points:
- Twenty years of Cluster data have led to new insight into nonlinear electrostatic solitary waves and their role in geophysical processes
- First reports of electrostatic solitary waves propagating from one spacecraft to another over a few tens of milliseconds
- Significant advancement in knowledge of location and role of electrostatic solitary waves in magnetic reconnection region

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Abstract A review of the advancements in the knowledge of electrostatic solitary waves (ESWs) made with data obtained by the four satellite Cluster mission, after 20 years in orbit, is presented. ESWs are nonlinear solitary waves or structures observed in high time resolution waveform data. The ESW pulses are the wave data representation of electron or ion phase-space holes, or density/acoustic structures, and are observed throughout the Cluster orbit, particularly at boundary layers, in turbulent plasmas, and wherever there is mixing of plasmas, such as in the magnetotail with the onset of a super-substorm. Much of the research reviewed here involves ESWs involved in the magnetic reconnection processes of Earth, with their mapping across the separatrix region. One of the major advancements in ESW knowledge came from investigating propagation from one spacecraft to another, thus addressing the issue of lifetime and stability of these structures which cannot be adequately addressed with single spacecraft propagation studies. Knowing how stable the ESWs are can help determine their generation mechanism, which was also addressed in many of the papers discussed herein through observations and theory. The ESWs were found to be generated through a mix of instabilities and processes, namely two-stream, Buneman, bump-on-tail, electron-ion, beam-plasma, electron and ion acoustic instabilities, and out of turbulence.

1. Introduction

Electrostatic solitary waves (ESWs), sometimes referred to as electrostatic solitary structures (ESS), isolated electrostatic structures (IES), and solitary bipolar pulses, have been reported in space plasmas since 1982. These ESWs are observed in the electric field waveform data of satellites in the form of isolated sinusoids, that is, as unipolar pulses (one positive electric field peak, or one negative e-field peak), bipolar pulses (a one-cycle wave with one positive e-field peak followed by one negative peak, or vice versa) and tripolar pulses (a continuous wave consisting of two positive e-field peaks with an intervening negative peak, or vice versa). By their very nature as isolated pulses observed in waveform data, they are classified as nonlinear waves.

The waveform data of the S3-3 spacecraft, which was launched in 1976 into a near-polar orbit, revealed for the first time the presence of small amplitude unipolar pulses interpreted as double layers in Earth's auroral acceleration region and indicated the presence of electric fields parallel to the magnetic field (Temerin et al., 1982). There was a net potential jump across these structures. In contrast, the S3-3 data also showed the presence of solitary waves in the form of bipolar pulses parallel to the magnetic field, and these had no net potential change across them.

A few years later came the results from the Viking satellite (Bostrom et al., 1988), which made measurements in the magnetospheric plasma (satellite apogee 13,527 km, perigee 817 km, inclination 98.8°). Their data, similar to S3-3, revealed the presence of solitary waves (bipolar pulses) with no net potential drop across them and weak double layers (unipolar pulses) with a small net potential drop. The Viking results expanded on the S3-3 results by providing new information on the temporal and spatial scales of the solitary waves and weak double layers in addition to the direction of motion and velocity of those structures. The spatial scale of these structures was found to be ≅100 m and they had a negative potential (<~1 V) moving upward along magnetic field lines with a velocity characteristically equal to 5 to greater than 50 km/s (order of the ion acoustic velocity) and lifetimes of at least 10 ms when propagating from one probe to the other. They described the structures as resembling ion holes.

With the launch of the single spacecraft Geotail mission in the early 1990s, primarily to study the magnetotail, Matsumoto et al. (1994) were the first to name the bipolar pulses ESWs and the first to make the definitive association between the presence of an ESW and its FFT-derived spectrogram equivalent of the upper frequency part of Broadband Electrostatic Noise (BEN) (see their Figure 1). The first report of BEN was made by Scarf et al. (1974) at plasma sheet and neutral sheet crossings and by Gurnett et al. (1976) in the distant magnetotail. It was described as being bursty and impulsive, with frequency changing on extremely short time scales. The BEN emissions extended from the lowest frequencies around the lower hybrid frequency up to around the local electron plasma frequency and presented decreasing amplitude with increasing frequency (Gurnett & Frank, 1977). This is the expected signature of a waveform pulse when transformed using a Fast Fourier Transform. BEN had been reported in a few different regions in space, including along auroral field lines, and in the magnetosheath, and plasma boundary layers by the time Matsumoto et al. (1994) had made its association with ESWs.

The ESWs had a characteristic pulse width of 2–5 ms (Matsumoto et al., 1994). Assuming a velocity of 1,000 km/s (10,000 km/s), Matsumoto et al. (1994) determined the spatial size along the flow direction, L_ϕ, of 2–5 km (20–50 km), respectively. A generation mechanism for the ESWs was proposed by Matsumoto et al. (1994) and Omura et al. (1994). It consisted of a nonlinear model in which Bernstein-Greene-Kruskal (BGK) (Bernstein et al., 1957) type isolated potentials can reproduce the observed wave structure when starting with an electron two stream instability which produces phase space holes. Their other suggestions for generation involved electrons in the presence of a high speed ion flow and the Buneman instability.

Following Geotail, a considerable wealth of information about ESWs and their generation mechanism was obtained from the single spacecraft Polar and FAST missions launched in the mid-to-late 1990s. The Polar satellite carried an electric field instrument, EFI, with three axis orthogonal measurements for studying ESWs. With this instrument, Mozer et al. (1997) were able to directly measure the time domain electric field structures both perpendicular and parallel to the local magnetic field in the auroral acceleration region. Some of these structures/pulses were shown to be bipolar in the parallel electric field and had pulse widths ranging from ∼100 μs (undersampled at this time scale) to 2 ms. Cattell et al. (1999) also used Polar EFI data to reveal that ESWs observed at high altitudes (cusp and plasma sheet boundary) are positive potential structures. These structures were consistent with electron holes and had scale sizes of 10s of Debye length (λ_{DE}) propagating at velocities on the order of a few thousand km/s. Ergun et al. (1998), using FAST satellite electric and magnetic field instrument data, reported large-amplitude "fast solitary waves" observed in the mid-altitude auroral zone downward current region. The electromagnetic signature of these solitary waves appeared to be that of an anti-earthward propagating positive charge (electron hole). They proposed that "these nonlinear structures play a key role in supporting parallel electric fields in the downward current region of the auroral zone."

Tsurutani et al. (1998) surveyed the various types of waves that were observed in the Polar PWI waveform data at the polar cap boundary layer. They reported four different types of plasma waves, two of which were large amplitude bipolar and monopolar solitary "electrostatic" waves. They speculated that the bipolar pulses were possibly created along magnetic field lines at all local times in the field-aligned current region, with the monopolar pulses having evolved from the bipolar pulses. Tsurutani et al. (1998) reported the first findings of offset bipolar pulses, where there was a noticeable delay between the first positive (negative) pulse and the following negative (positive) pulse. They suggested these structures could be broadened electron holes. They also reported paired monopolar pulses, where the unipolar pulses alternate between one polarity and the opposite polarity with a short sustained zero-field between the pulses. They suggested these paired monopolar pulses could be electron holes split into two parts via interactions with density gradients.

The use of interferometry afforded by the Polar PWI instrument, which obtained time-domain waveforms using the EFI antenna, was fully employed by J. A. Franz et al. (1998) in order to gain insight into the speed and parallel size of the coherent electric field structures (ESWs) by observing their propagation from one antenna to another over distances around 50 m, the length of the measuring electric field antenna (see their Figure 3). J. A. Franz et al. (1998) reported that ESWs were observed at 2.02–8.5 Re in the high altitude polar magnetosphere. They had a typical estimated parallel scale size of 100–1,000 m and velocities of 1,000 km/s moving both up and down the magnetic field, sometimes simultaneously. J. R. Franz et al. (2000) followed up their earlier work to determine the perpendicular scale size of the ESWs. They showed that ESWs, which they interpreted as electron phase-space holes based on previously published studies, are nearly spherical for $\Omega e/\Omega p > 1$ (where Ωe is the electron cyclotron frequency and Ωp is the plasma frequency), and that they become more oblate with decreasing Ωe/Ωp, the perpendicular scale being larger than the parallel.

The launch of the four spacecraft Cluster mission in 2000 made it possible to advance the study of ESWs by obtaining the perspective from simultaneous measurements on multiple spacecraft, carrying out remote sensing of ESWs, and observing ESWs continuously over long periods of time and through short burst mode snapshots due to the specific instrumentation onboard. The review that follows contains the most significant results on ESWs obtained by Cluster in its thus far 20-year mission in orbit around Earth in which it encountered many different plasma regimes. Section 2 provides information on the Cluster mission and its orbit, as well as the key instruments involved in the ESW studies. This is followed by a review of the most significant results obtained on ESWs by Cluster in Section 3, including observational and theoretical/modeling studies. Section 4 presents a brief summary of the Cluster ESW results, as well as concluding remarks on the work that lies ahead.

2. Mission and Key Scientific Instruments

The four Cluster spacecraft were launched in July and August 2000 into a polar orbit with an apogee of about 19.6 Re and perigee of 4 Re with mission operations beginning on February 1, 2001. The spacecraft is spin stabilized at 15 RPM. The Cluster orbit allowed for the crossing of many of Earth's boundaries, obtaining measurements in the solar wind, magnetosheath, magnetotail, the plasma sheet, magnetopause, auroral zone, and inner magnetosphere. Due to Sun-Moon gravitational perturbations, throughout the mission's 20 years the apogee has been as great as 22 Re and the perigee as low as 200 km altitude on Cluster spacecraft 2, thus allowing access to regions not originally envisioned at launch, such as the auroral acceleration region. Inter spacecraft distances have varied throughout the mission from as low as 3 km to as great as 67,000 km in order to obtain measurements at various scales: fluid, ion and electron. Multiscale measurements across the spacecraft have also uniquely and successfully been made on Cluster throughout the mission due to the natural varying spacecraft configurations along the orbit and to mission-controlled spacecraft configurations, from perfect tetrahedrons to a string of pearls, based on proposed scientific objectives by the Cluster team and guest investigators.

The electric field antennas that are used to make all the measurements of the ESWs on Cluster are a part of the Electric Field and Wave experiment (Gustafsson et al., 1997). There are four spherical sensors per spacecraft, one near the end of each of four orthogonal booms that are fully deployed to 44 m in the spin plane. These probes are used to make all of the electric field measurements discussed in this review.

Two Cluster instruments specifically make electric field waveform measurements for directly detecting ESWs. These instruments are mounted on all four spacecraft. The first is the wide band data (WBD) instrument (Gurnett et al., 1997) which takes continuous and duty cycled time series data over frequencies from 70 Hz to 77 kHz with sampling rates of 27.4–219.5 kHz. This allows for the sampling of ESWs with time durations as low as a few 10s of μs (based on sampling rate) up to about 2 ms. The longer time constraint is a result of the ESW waveform becoming distorted when the time duration of the ESW pulse approaches or exceeds the resistive-capacitive time constant for each of three different WBD bandpass filters (see Swanner et al., 2006 for more details). WBD is mounted on all four of the spacecraft but makes measurements along one axis only in the spin plane. It uses the EFW electric field antennas to make measurements across two sensor probes lying on the same axis, a separation distance of 88 m. One advantage of WBD for measuring ESWs is that although it does not take data 100% of the orbit, it takes data up to a few continuous hours. This is very important when one is trying to observe the ESWs throughout a region, such as a separatrix region of magnetic reconnection, or across a boundary layer such as the bow shock.

The other instrument that makes valuable direct ESW measurements is the electric field and wave (EFW) experiment (Gustafsson et al., 1997). EFW makes probe voltage measurements in the spin plane using the EFW antennas in a standard burst mode (~450 samples/second) and an internal burst mode (9,000 or 4,500 samples/second) over a 10 s period. EFW typically makes measurements across the span between one antenna probe and the spacecraft (~44 m), allowing up to four possible measurements. The advantage of EFW for ESW measurements is that it can be used to carry out interferometry measurements as previously done on Polar and FAST in order to directly obtain the ESW velocity and scale size.

A third wave instrument, Whisper (Décréau et al., 1997), uses onboard processing to produce spectra of the wave electric field. This instrument can be used to infer the presence of ESWs when BEN is observed.

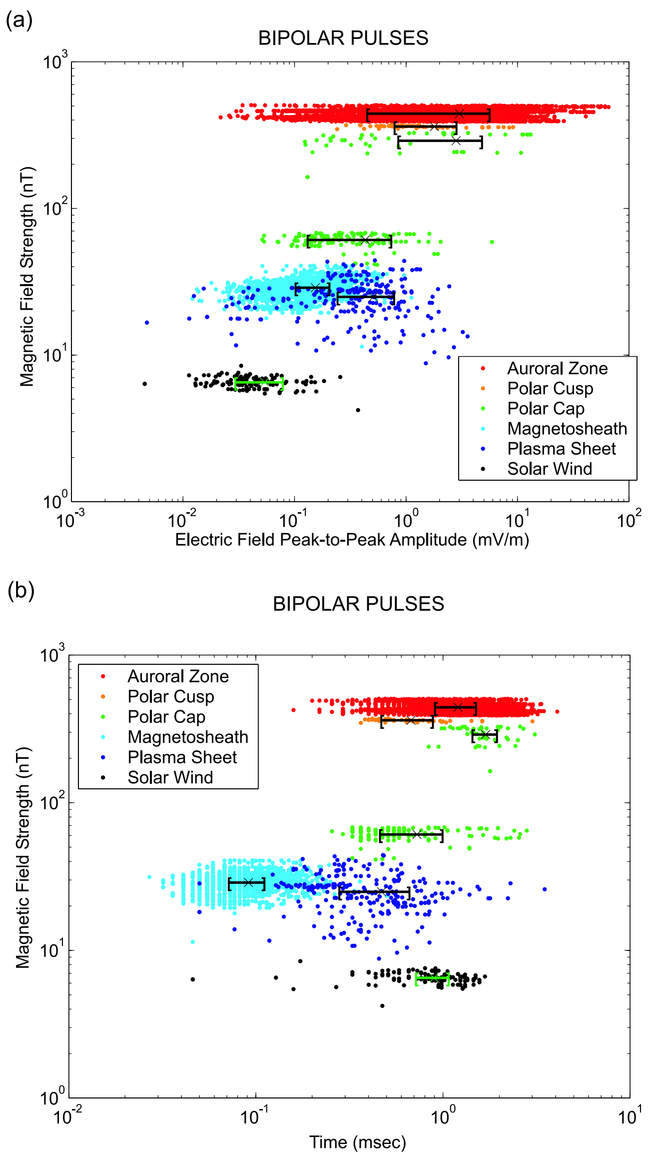

Figure 1. "Survey of the bipolar pulses observed by Cluster wide band data over a 2-year period. (a) Electric field amplitude versus magnetic field strength showing a trend of increasing electric field amplitude with increasing magnetic field strength. The over plotted bracketed lines with an imbedded "x" within each regional grouping represent the standard deviation and mean of that group, respectively. (b) Pulse duration versus magnetic field strength showing no trend between the two, but pointing out the obvious difference of the time durations of the magnetosheath pulses to pulses in all other regions. Bracketed lines with the imbedded "x" represent the standard deviation and mean of each regional group." Reprinted from Pickett, Chen, et al. (2004), Figure 3.

3. Review of Cluster ESW Results

3.1. Survey of ESW Observations and Properties

Up until the launch of the Cluster multi-spacecraft mission in 2000, ESWs had been observed by single spacecraft in the high altitude polar region (J. A. Franz et al., 1998), plasma sheet boundary layer (PSBL; Cattell et al., 1998; Matsumoto et al., 1994), magnetosheath (Kojima et al., 1997), the Earth's bow shock (Bale et al., 1998; Matsumoto et al., 1997), the solar wind (Mangeney et al., 1999), the high altitude cusp (Cattell et al., 1999), in the Southern hemisphere at 1 Re (Bounds et al., 1999), and in the auroral acceleration region (Ergun et al., 1998). They were also reported by Kurth et al. (2001) in and around the magnetosphere of Jupiter's moon Europa. Early in the Cluster mission, it was apparent that ESWs were being observed throughout much of the Cluster orbit. They were primarily observed in areas of turbulence or mixing of plasmas such as within boundary layers. The first obvious study for Cluster was thus to directly compare the ESWs observed in all the many distinctive regions of the magnetosphere that Cluster crossed in order to see how the ESW characteristics might vary by using the same instrumentation on up to four spacecraft.

A survey was carried out of WBD waveforms obtained throughout the Cluster orbit (Pickett, Chen, et al., 2004; Pickett et al., 2006). No other mission had thus far encountered as many such regions with instrumentation capable of taking so much data over long periods of time with such high time resolution. An automatic ESW detection algorithm had not yet been developed, so all waveforms were examined by eye. It would have been computationally and physically prohibitive to review every single waveform, so representative events from all of the regions where WBD observed ESWs were chosen. One of the goals of this survey was to provide a geophysical basis for the various time durations and amplitudes of the ESW pulses.

The results of this survey for bipolar pulses are presented in Figure 1 (reproduced from Figure 3 of Pickett, Chen, et al., 2004). The results for detected tripolar pulses were provided in Figure 4 of Pickett, Chen, et al. (2004) but not shown here, although the results were similar as for bipolar pulses. ESWs were observed and measured in various regions of Cluster's orbit, color coded by region as seen in Figure 1. The ESWs were shown to have time durations varying from about 20 μs (the shortest time resolution possible with WBD) up to about a few ms, while the amplitudes varied from about 0.04 mV/m up to about 80 mV/m (the largest possible amplitude with WBD). Because WBD uses an automatic gain function to keep the signal within its full measurement range while providing maximum resolution, some ESW waveforms were heavily clipped and were not considered in this survey, which was not intended to be a full statistical study. Impulsive waves, such as isolated ESWs, are more likely to be clipped because the WBD gain control takes at least 0.1 s to cycle between 5 dB gain steps. In Figure 1a, there is a rather clear trend that the pulse amplitude increases with increasing background magnetic field strength ranging from 5 to 500 nT. On the other hand, there is no observable trend in the time duration of the pulses based on the magnetic field strength (Figure 1b) with all regions showing similar time durations with the exception of the magnetosheath. The pulses observed in the magnetosheath were significantly shorter.

In order to understand these results, an examination of the properties of BGK solitary waves was carried out. Pickett, Chen, et al. (2004) stated that the "large spread in the electric field amplitudes for a fixed magnetic field strength is consistent with the key stability property of BGK solitary waves whose widths and potential amplitudes are constrained by inequalities." Thus Pickett, Chen, et al. (2004) concluded that for a given size of a BGK solitary structure, a large range of continuous electric field amplitudes (potential amplitude divided by size) are naturally allowed, as opposed to fluid solitons where there is only one allowed width for a certain amplitude which makes it unlikely there would be a large range of amplitudes for any one specific geomagnetic region. Based on the study by Chen et al. (2004), among others, Pickett, Chen, et al. (2004) stated that these inequalities (Equations 1 and 2 in Pickett, Chen, et al., 2004) have been shown "to hold at least in the regime where the cyclotron radius of the particles trapped in the solitary structure is much less than the size of the structure. This condition is based on the stability requirements of a BGK solitary wave when the lowest order effects of a finite magnetic field are considered." As further stated in Pickett, Chen, et al. (2004), "these conditions point to a trend that, for a much weaker magnetic field, either the potential amplitude would decrease or the size would increase, in order for the structures to be stable, and this results in smaller electric field amplitudes" as shown in Figure 1a. They also speculated that the reason for the significantly different time duration of the magnetosheath ESWs was that they were "spontaneously generated by turbulence in the absence of the two-stream instability" as suggested by Chen et al., 2003. In all the other regions Pickett, Chen, et al. (2004) suggested that the pulses were generated by the two-stream instability wherein the "time duration that a pulse is observed scales with the ratio of its size to its velocity" since "this ratio would be roughly constant with a certain spread" for this type of instability.

Ghosh et al. (2008) specifically examined the time durations and amplitudes of the ESWs observed in the cusp and magnetosheath, as discussed above and as reported by Pickett, Chen, et al. (2004); Pickett et al. (2008), through analytical modeling. They used a "Sagdeev pseudopotential technique to obtain the nonlinear evolution equation for the wave propagating obliquely with the ambient magnetic field." Their results showed "an extremely narrow and deep profile producing small-amplitude, narrow width, spiky solitary waves" which were identified as nonlinear positive amplitude electron acoustic solitary waves. Their results agreed well with the published Cluster ESW data of Pickett, Chen, et al. (2004); Pickett et al. (2008). However, they must be considered in the context of the width-amplitude relationship of fluid solitons as mentioned above as pointed out by Pickett, Chen, et al. (2004).

Olivier and Verheest (2020) referenced the tripolar structures reported in Pickett, Chen, et al. (2004); Pickett, Kahler, et al. (2004) in their investigation of "overtaking collisions between double layers and solitons." They carried out a "numerical simulation of the Gardner equation that governs small-amplitude double layers." Their results showed that the "double layer emerges unaffected after the collision," but "the soliton that emerges after the collision has the opposite polarity of the soliton prior to the collision." More importantly, it showed that transient tripolar electric field structures formed during the collision "have a finite lifespan, and will eventually decouple to form a soliton and a double layer."

3.2. Multi-Spacecraft Perspective—ESWs in the Magnetosheath

Our attention is now turned to the advantage of having multi-spacecraft measurements at distances of a few tens of km and greater separation. The objective of the studies discussed in this section was to obtain the larger picture through measurements taken in the same region (magnetosheath) by more than one spacecraft over several minutes to a few hours to see if ESW generation was consistent and constant across the region. One of the first surprising results in this regard came from the WBD instrument from data taken in the magnetosheath as shown in Figure 2 (reproduced from Pickett et al., 2005, Figure 1). Figure 2a is a spectrogram of the WBD data from two Cluster spacecraft as they crossed the bow shock in the magnetosheath around 03:19 UT on March 26, 2002. The separation of the spacecraft at this time was about 70 km. The WBD waveforms, a sample of which is shown in Figure 2b, were transformed by a Fast Fourier Transform to the frequency domain. Here the broadband electrostatic waves are the representation in frequency space of the bipolar and tripolar pulses measured in the time domain. It is surprising that the profiles of the broadband waves in frequency and amplitude across this 30-min period on both spacecraft in the magnetosheath are remarkably similar. As noted in Pickett et al. (2003) for a similar case, the ESWs are primarily "detected

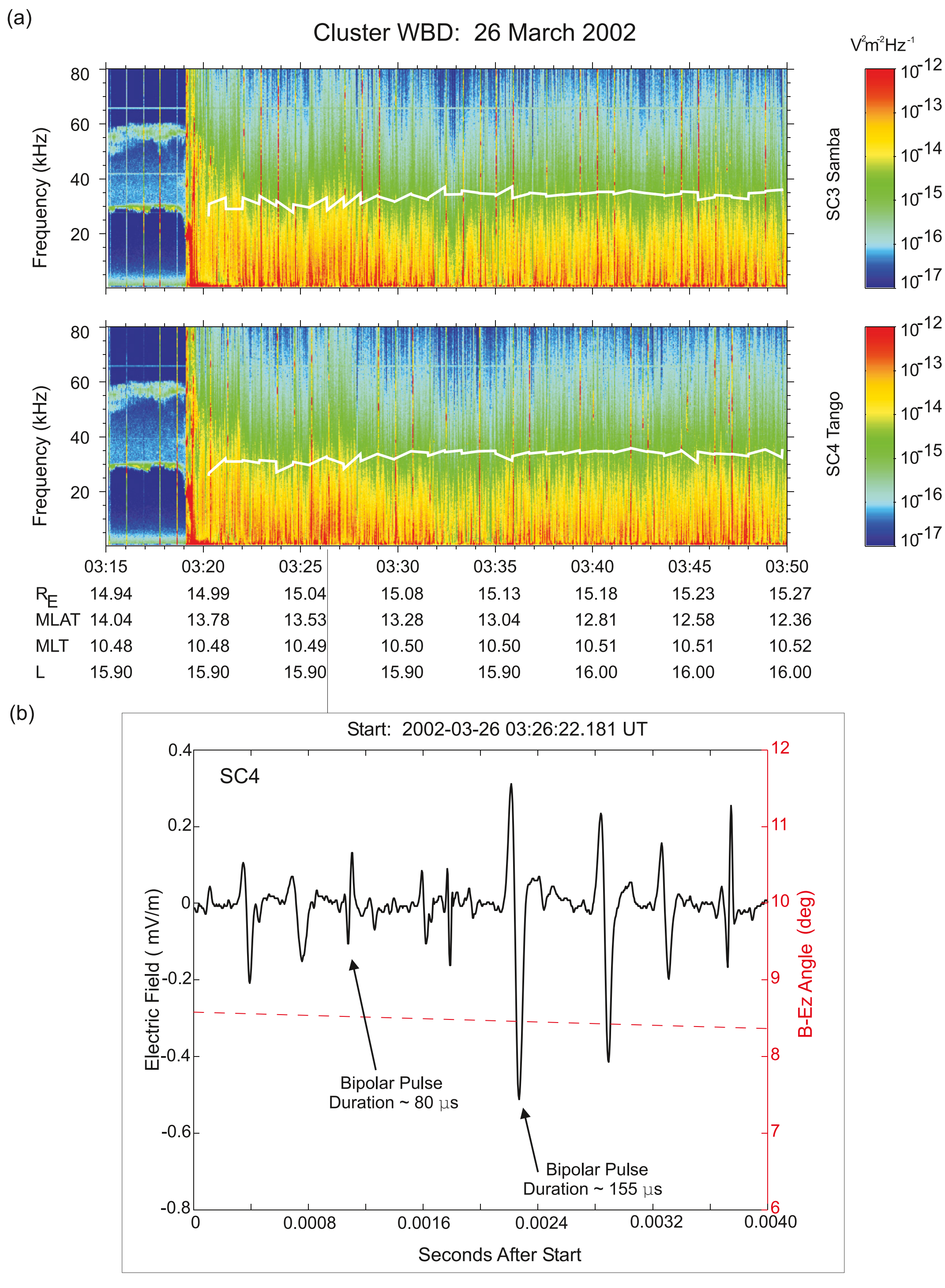

Figure 2. "(a) Wide band data spectrogram of plasma waves observed on March 26, 2002 as Cluster spacecraft 3 (top panel) and 4 (bottom panel) crossed into the magnetosheath at about 03:19 UT. Broadband waves up to and greater than the electron plasma frequency (white line) are observed in the magnetosheath on both spacecraft. (b) A 4 ms portion of the waveforms from which the spectrograms in panel (a) were produced. Note the short duration bipolar pulses seen throughout the 4 ms interval. These bipolar pulses are the primary reason for the broadbands seen in panel (a)." Reprinted from Pickett et al. (2005), Figure 1.

when then the local magnetic field is contained in the spin plane, indicating that they are propagated along the magnetic field."

Pickett et al. (2005) analyzed the characteristics of the ESWs obtained from several passes through the magnetosheath from the bow shock to the magnetopause where the locations of the bow shock and magnetopause boundaries for each pass are based on a model, as opposed to being determined by measurements. The ESW average time durations were extremely short at around 100 μs. Surprisingly, they found that "solitary waves are likely to be observed at any distance from the bow shock and that this distance has no dependence on the time durations and amplitudes of the solitary waves." They interpreted this to imply that the ESWs "are probably created locally in the magnetosheath at multiple locations." They also found that the two quantities of ESW time duration and amplitude showed "no dependence on either the ion velocity or the angle between the ion velocity and the local magnetic field direction." They thus concluded that the "generation mechanism is most likely not solely related to ion dynamics, if at all." One possibility suggested for their generation was the two stream instability, which is a type of electron beam instability, since this type of instability can lead to the generation of solitary waves. This suggestion was based on the fact that Cluster data showed "counterstreaming (~parallel and anti-parallel to the magnetic field electrons at or below about 100 eV)" present when most of the ESWs were observed. Other mechanisms suggested for the generation of the magnetosheath ESWs were the electron acoustic instability, as well as spontaneous generation out of turbulence, as mentioned in the Pickett, Chen, et al. (2004) study, and the lower-hybrid Buneman instability which can be initiated in the presence of an electron beam.

Lakhina et al. (2009) provided a mechanism for the generation of these ESWs in the magnetosheath, as reported by Pickett et al. (2005), "in terms of electron-acoustic solitons and double layers." Their model was based "on the multifluid equations and the Poisson equation, and uses the Sagdeev pseudo-potential technique" in investigating these solitary waves in a "multicomponent plasma consisting of background electrons, two counter-streaming electron beams, and ions." The width-amplitude relation issue for fluid solitons as pointed out by Pickett, Chen, et al. (2004) above was not addressed, although it was discussed in a later work (Lakhina et al., 2011); see the last paragraph of Section 3.5. Umeda et al. (2012) also investigated these magnetosheath ESWs and discussed the previous explanation provided by Lakhina et al. (2009). Umeda et al. (2012) examined "the excitation of electron acoustic waves and the formation of solitary structures ... by means of a one-dimensional electrostatic Vlasov simulation." They showed that "either electron acoustic solitary waves with negative potential or electron phase-space holes with positive potential are excited in four-component plasma." However, they needed to add a fifth component consisting of "a high-speed and small free energy source" in order to compare well to the time durations and amplitudes of the small and fast electron phase-space holes observed in the Cluster data.

3.3. Multi-Spacecraft Perspective—ESW Propagation and Stability

One of the major issues to be addressed by Cluster with regard to ESW was their propagation. Could they propagate over long distances, for example between Cluster spacecraft, and be stable over such large distances since up to now, evidence for propagation was limited to about 100 km distance? The first attempt to study the propagation of ESWs from one spacecraft to another was made by Pickett, Kahler, et al. (2004). Their motive in doing so was to understand something about their stability, and thus helping to distinguish their mode. All previous reports of ESW propagation up to this point dealt with single spacecraft by measuring the delay in propagation from one antenna probe to another, such as from two Langmuir or electric field probes with probe separations on the order of 100 m or less giving times for delay from one antenna to another of 50–100 μs. Pickett, Kahler, et al. (2004) used Cluster WBD waveform data obtained at 4.5–6.5 Re along auroral field lines, well above the auroral acceleration region, to study ESW propagation. Two cases of possible propagation of tripolar solitary waves from one spacecraft to another were reported. Tripolar pulses are thought to represent weak or hybrid double layers. Indeed, Pickett, Kahler, et al. (2004) found a measurable potential change across some of the tripolar pulses of up to 0.5 V. Using cross correlation of the tripolar waveforms across the two spacecraft for the case they presented in Figure 3 of Pickett, Kahler, et al. (2004) (also presented in Figure 5 of Pickett et al., 2006), a 0.8 cross correlation coefficient was found with a delay time of 0.020 s from one spacecraft to the other. This case was obtained while WBD was in a continuous data taking mode. The other case of cross correlation discussed in Pickett, Kahler, et al. (2004) had a cross

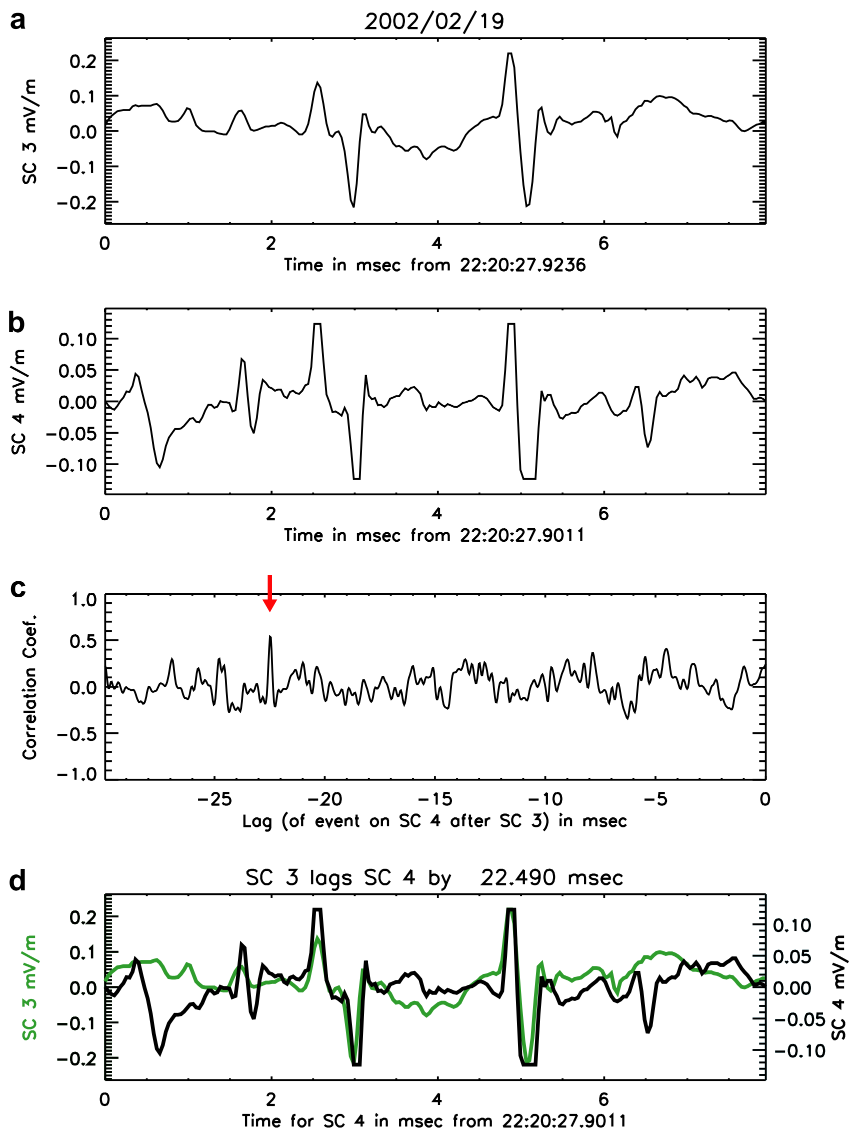

Figure 3. "Electrostatic solitary waves propagation from SC4 to SC3. (a) Waveform from SC3 showing an offset bipolar pulse followed by a usual bipolar pulse, (b) Waveform from SC4 showing the same primary bipolar pulses as in panel (a) plus several small amplitude pulses, (c) Results of cross correlating the SC3 waveform with that of SC4, showing the best correlation of 0.55 at a lag of 22.5 ms of SC3 from SC4, and (d) Overplot of SC4 and SC3 waveforms using the lag time of 22.5 ms providing confidence that the two major bipolar pulses observed on SC4 are the same ones observed on SC3 22.5 ms later." Reprinted from Pickett et al. (2008), Figure 5.

correlation coefficient of −0.25 and delay time of 0.027 s. It was taken in a duty-cycled mode, which leads to some uncertainty due to the intervening gaps. Of the two studied cases of cross correlations in Pickett, Kahler, et al. (2004), the ESWs were found to be propagating "at several hundred to a few thousand km/s." Further, they had a width of 50 km or greater perpendicular to the magnetic field and a width of approximately 2–5 km parallel. In determining these widths, it was assumed that the ESWs were propagating along the magnetic field as had been found in the previously published studies (cf., J. A. Franz et al., 1998). The spacecraft separation was a few 10s of km both along and perpendicular to the magnetic field, which was considered too great in this region to get a good correlation.

A striking example of ESW propagation was presented in Pickett et al. (2008). This case took place in the magnetosheath almost an hour prior to crossing the magnetopause and entering the cusp. Figure 3, reproduced from Pickett et al. (2008), shows the analysis from this event where a series of one offset bipolar pulse followed by an unusual bipolar pulse are correlated. The pulse time durations were about 600 μs. As can be seen in Figure 3c, the correlation coefficient was 0.55 with a lag of 22.5 ms, and when the waveforms are overplotted, there is exceedingly good agreement in time and amplitude for these two larger pulses. The angles of the antenna to the magnetic field were 45° and 20°, respectively for SC3 and SC4. The spacecraft were separated along **B** by about 30 km and perpendicular by around 40 km. The highly anticipated conclusion drawn from this, at least for the auroral zone, is that the ESWs can have lifetimes as long as 22.5 ms and that their stability spans over distances as large as 30 km. Based on the lag time and the separation distance, a velocity of 1,334 km/s was determined for these structures. Assuming propagation along the magnetic field, their cross magnetic field size was at least 40 km and parallel field size was 0.8 km, that is, pancake shaped. Pickett et al. (2008) concluded that their findings were consistent with those of J. R. Franz et al. (2000) in that "the electron holes observed by Polar are roughly spherical when the electron cyclotron frequency, Ω_e, is greater than the plasma frequency, ω_p, becoming more oblate ($L_\perp > L_{//}$) with decreasing Ω_e/ω_p."

Pickett et al. (2010) carried out another ESW propagation study from WBD data obtained on the magnetosheath side of the magnetopause. Table 1 of their study reported their findings of six cases of cross spacecraft "propagation of a series of noncyclical ESWs." All but one of these cases found the ESWs propagating toward the Earth with velocities on the order of 1,500–2,400 km/s. The sizes of these ESWs were found to be of the order of several tens of km perpendicular to the magnetic field and 1 km parallel to it. This study pointed out that the ESWs are stable over time spans much greater, in this case 16–38 ms, than their own characteristic ESW pulse duration times of a few 100s of μs.

Qureshi et al. (2010) used "an ion fluid model in a cylindrical symmetry by considering electrostatic condition" in order to investigate the offset bipolar electric field solitary (EFS) structure shown in Figure 3, that was reported by Pickett et al. (2008) to have propagated from one spacecraft to another. The model of Qureshi et al. (2010) showed that the offset bipolar EFS structures can develop from both ion-acoustic waves and ion cyclotron waves, and propagate along the magnetic field line in space plasmas in which the plasma properties satisfy certain specific conditions. Their results also showed that "the amplitude of the offset bipolar EFS structures does not monotonically vary with the wave velocity but first decreases and then increases with velocity."

This section is concluded by discussing a detailed investigation that used EFW measurements obtained in the PSBL. Norgren, Andre, Vaivads, and Khotyaintsev (2015) reported slow electrostatic solitary waves (SESWs) "embedded in a region with field-aligned electron flows and are interpreted as electron phase space holes." They did not "detect any magnetic signature of the holes. The electrostatic potential of the holes is of the order of $e\phi/k_BT_e \sim 10\%$, indicating that they can affect electron motion and further couple the electron and ion dynamics." Their multi-spacecraft measurements of the electron holes from 10 separate examples found them to have velocities in the ion reference frame of 150–600 km/s. Figure 4 of Norgren, Andre, Vaivads, and Khotyaintsev (2015) presented two of these examples correlated across two spacecraft showing the parallel and perpendicular electric fields, the electrostatic potential, and the parallel wave magnetic field. For the 10 examples, "the electron holes were stable over at least the interspacecraft separation distance parallel to the magnetic field, which is ∼30 km and corresponds to $\sim 120f^{-1}{}_{pe}$. Their parallel half widths are in the range of 2–4 λ_{De}, and they have a perpendicular extent of at least the spacecraft separation distance which is ∼20 km," which is approximately equal to or greater than $10\lambda_{De}$. "The shape of the electron holes seems to vary between oblate and spherical." Norgren, Andre, Vaivads, and Khotyaintsev (2015) noted that they also observed holes that were "not identifiable on both spacecraft, indicating that they either grow or decay too fast or are too small to be observed by both spacecraft…The low phase velocity and strength of the electrostatic potential indicate…effective coupling between ions and electrons." They speculated that the slow electron holes may have been generated by the Buneman instability.

Kakad et al. (2016) stated that these electron holes reported by Norgren, Andre, Vaivads, and Khotyaintsev (2015) could not be generated through the Buneman instability because the high bulk flow velocities required for it were not observed. Kakad et al. (2016) modeled these SESWs "on the basis of the nonlinear fluid theory and fluid simulation." Their "nonlinear fluid model shows the coexistence of slow and fast ion acoustic waves and the presence of electron acoustic waves in the PSBL region." Their fluid simulations also "showed the presence of an extra mode along with the waves supported by the nonlinear fluid theory. This extra mode is identified as the Buneman mode, which is generated by relative drifts of ions and elections (*sic*).” The detailed investigation of the SESWs revealed them to be slow ion acoustic solitary waves.

Norgren, Andre, Graham, et al. (2015) addressed the assertion of Kakad et al. (2016) that the Buneman instability could not generate these slow electron holes in a follow-up study. Multicomponent plasmas were the subject of this study using Cluster EFW data obtained at the magnetopause. Norgren, Andre, Graham, et al. (2015) stated that “Often slow ESWs are observed, suggesting generation by the Buneman instability. The instability criteria, however, are generally not satisfied.” They showed that “slow electron holes can be generated by a modified Buneman instability in plasma that includes a slow electron beam on top of a warm thermal electron background. This lowers the required current for marginal instability and allows for the generation of slow electron holes for a wide range of beam parameters that cover the expected plasma distributions in space, for example, in magnetic reconnection regions.” In order to produce faster electron holes, higher beam speeds are required and the electron-electron beam instability becomes dominant. Norgren, Andre, Graham, et al. (2015) state that the range of phase speeds for this model was consistent with a statistical set of observations at the magnetopause made by Cluster.

3.4. ESWs Associated With Magnetic Reconnection

Just as the first Cluster studies of ESWs associated with magnetic reconnection were starting to be carried out, Drake et al. (2003) published the first results of three-dimensional particle simulations of magnetic reconnection. These simulations revealed “the development of turbulence driven by intense electron beams that form near the magnetic x-line and separatrices. The turbulence collapses into localized three-dimensional nonlinear structures in which the electron density is depleted. The predicted structure of these electron holes compares favorably with satellite observations made at Earth's magnetopause.” The electron holes are some of the bipolar type ESWs which are being reported here. It was clear that on the observational front, Cluster had much to contribute with regard to ESWs and their role in magnetic reconnection if any because the orbit was favorable to passage through this region.

Early in the Cluster mission, Cattell et al. (2005) stated that “for the first time, large-amplitude (up to 50 mV/m) solitary waves, identified as electron holes, have been observed during waveform captures on two of the four Cluster satellites during several plasma sheet encounters that have been identified as the passage of a magnetotail reconnection *x* line.” These “electron holes were seen near the outer edge of the plasma sheet, within and on the edge of a density cavity.” EFW waveform captures were not obtained in the electron diffusion region itself. Cattell et al. (2005) were able to show, using these EFW waveforms captures and the electron data the one-to-one correlation between the solitary waves and the existence of narrow electron beams. Their observations provided measurements of the amplitude (up to 50 mV/m), scale size (>3 km), and velocity (~700−>2,500 km/s) of the positive potential solitary structures, the first such measurements at distances greater than the 9 Re orbit of Polar. Cattell et al. (2005) stated that the “velocities and scale sizes of the electron holes are consistent with the predictions of Drake et al. (2003).” In order to obtain good agreement between the simulations and data, the addition of a small (0.2 of the reversed field) ambient guide field was required. They proposed that “the traditional neglect of the guide field may not be justified.” Cattell et al. (2005) suggested that “the observed microphysics, including electron holes and large-amplitude waves, may play a role in dynamics of reconnection in the magnetosphere and, in particular, in the evolution of the electron distributions.”

Retino et al. (2006) also studied reconnection in the separatrix region (SR) using the Cluster data. They “observed solitary waves at the boundary between the SR and the reconnection jet and throughout most of the jet region, but not within the SR.” They did not exclude the possibility that they existed within the separatrix region because some observed pulses were discounted due to instrument limitations, that is, the possible pulse distortion introduced by WBD's filters for ESWs with time durations greater than 2 ms, as noted in Section 2. Deng et al. (2006) also reported on ESWs associated with reconnection using Cluster WBD data. Three of the four Cluster spacecraft detected the ESWs simultaneously at both sides of a neutral sheet. They suggested that “the nonlinear coherent structures may provide important dissipation in the electron diffusion region during reconnection.” They also noted that they observed ESWs associated with and without the guide field, in contrast to the earlier work of Drake et al. (2003) showing that ESWs can exist only with the magnetic guide field.

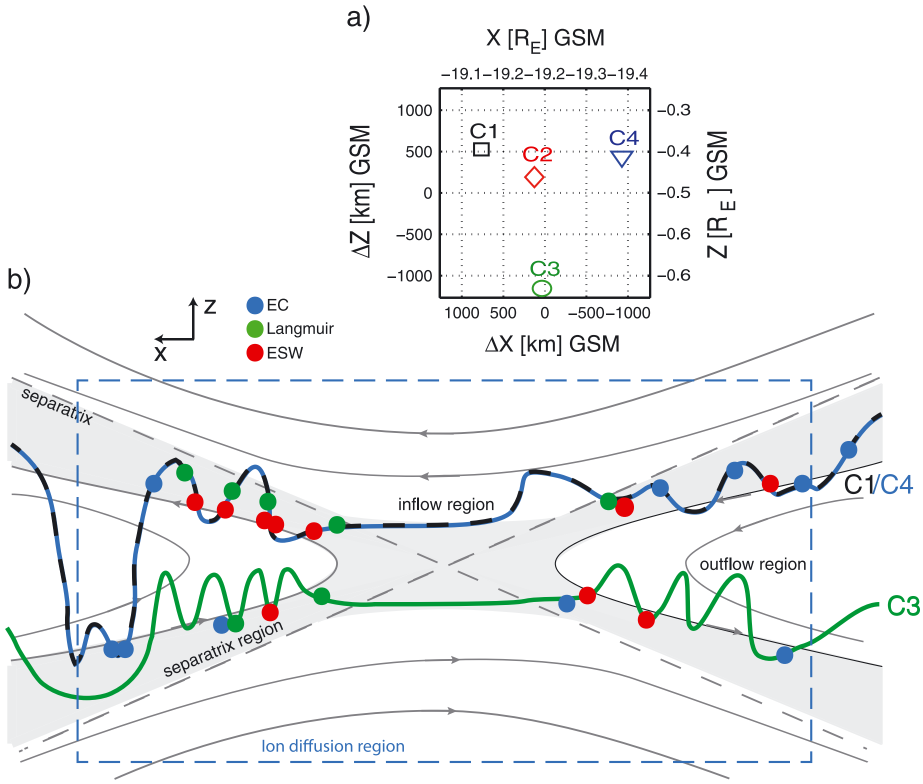

Figure 4. "Sketch of the event, with (a) The positions of the Cluster S/C and (b) The reconnection diffusion region (DR), with the approximate paths of C1, C3, and C4. Wave observations are indicated by the colored dots, and the different regions within the DR (blue box) are labeled." Reprinted from Viberg et al. (2013), Figure 3.

Khotyaintsev et al. (2010) presented "observations of electric field wave and solitary structures (electron holes) inside a magnetic flux rope close to a magnetic reconnection region." The largest amplitude structures were slow electron holes propagating with the ion sound velocity. They stated that the electron holes "are likely to be generated by the Buneman instability. This indicates the presence of dynamic current sheets with large current densities at subion or electron scales."

Magnetic reconnection studies of ESWs continued with the work of Li et al. (2010) in the vicinity of the magnetic null. They studied ESWs with data obtained by the WBD instrument in the magnetic reconnection region at the near-earth tail during a substorm on October 1, 2001, the same event studied by Cattell et al. (2005) when the current sheet was dramatically thinner. They use a "2-D reconnection model and study the characteristics of the ESWs near the X-line region and the magnetic null points." Their "result shows that ESWs can be generated in the diffusion region, and evolve along the magnetic field both in the outflow region and in the seperatrix (*sic*)." They also showed that as the "ESWs propagate outwards from the X-line along PSBL, the amplitude decreases."

A study by Viberg et al. (2013) used detailed "high-frequency (HF) plasma waves between the electron cyclotron and plasma frequencies within a reconnection diffusion region (DR) encountered by Cluster in the magnetotail." Using continuous electric field waveforms from the WBD instrument obtained on September 10, 2001, they identified "three waves types, all observed within the separatrix regions: Langmuir waves (LW), ESWs, and electron cyclotron (EC) waves." Figure 4, reproduced from Viberg et al. (2013), shows a mapping of where these waves were observed with regard to the reconnection x-line. They found "little or no activity in the inflow and outflow regions, and most of the wave activity is localized to the separatrix regions (SR)...In the outer part of the region (closest to the inflow), the LWs are observed...In the inner part of the SR, mostly ESWs are observed together with electron distributions showing counterstreaming electron populations" (low-energy flowing towards the X-line, high energy flowing away from the X-line). The electron cyclotron waves were reported for the first time in different parts of the separatrix region with the shortest timescales of the observed wave types. Viberg et al. (2013) noted that "studying these wave populations allowed for a precise mapping of kinetic boundaries in the reconnection region which helps to improve an understanding of the diffusion region electron dynamics."

Li et al. (2014) also studied the same event as Viberg et al. (2013). They noted that this is the first report of "such a large number of ESWs in a single magnetic reconnection event." The ESWs were observed, "around the magnetic null-pairs within the magnetic reconnection ion diffusion region." They performed "single-event-based statistical analysis of the characteristics of the ESWs around magnetic null-pairs." They speculated, "based on the statistical result," that "the two-stream instability originating from the magnetic null and traveling outward along the PSBL is the candidate mechanism of the large number of observed ESWs." In another ESW study, Li et al. (2015) provided evidence "of electron beam-associated symmetric bipolar" ESWs on the current sheet-side of the separatrix of the magnetic reconnection in the near-Earth magnetotail. The multi-spacecraft comparisons led to the conclusion that ESWs were "strongly associated with the cold electron beams of a few hundreds of EV (0.4–1 keV) antiparallel to the local magnetic field which is consistent with the bump-on tail instability." However, the electron beam is directed inward but the ESWs were traveling outward, suggesting it is not clear what the relationship is between the two.

Finally, Graham et al. (2015) have reported the observation of ESWs using the EFW data with distinct time scales at the magnetopause associated with asymmetric reconnection. Their results confirmed "an earlier suggestion by Cattell et al. (2002) that different types of ESWs can develop at the magnetopause." They observed these ESWs "near the separatrices of asymmetric reconnection where magnetospheric and magnetosheath electrons were observed. When the ESWs are observed, the magnetosheath electron population dominates, suggesting that magnetosheath electrons are responsible for the ESW generation." Graham et al. (2015) concluded "that the observations of ESWs with distinct speeds suggests that multiple instabilities are active in the magnetopause when magnetic reconnection is occurring." Graham et al. (2016) expanded their studies of ESWs and electrostatic waves which did not exhibit localized bipolar fields at the magnetopause, both on the magnetospheric side and magnetosheath side. The "speeds, length scales, and maximum potentials of the waves" were determined using cross-spectral analyses and compared with local plasma conditions. Again, a large range of phase speeds (~2 orders of magnitude) suggested multiple generation mechanisms, as found in their reconnection study. The observed waves were "consistent with those generated by the warm bistreaming instability, beam-plasma instability, and electron-ion instabilities, which account for the observed speeds and length scales." Such a large span of wave speeds suggested "that the waves can couple different electron populations and electrons with ions, heating the plasma and contributing to anomalous resistivity." In addition, the "ESW potentials are often sufficiently small that the ranges of trapped electron speeds do not overlap for ESWs with distinct speeds." This meant that "ESWs with distinct speeds can pass through each other without coalescence." This is the first time that this finding had been reported and it is quite significant with regard to the properties of ESWs.

3.5. Other Significant Discoveries

Several important Cluster studies were also carried out that contained significant results with regard to ESWs observed in magnetic structures, at the bow shock, in the polar cap and PSBL in connection with observed PC1 waves, and in relation to a super storm event. These studies are detailed below.

One of the early discoveries of ESWs with the Cluster spacecraft was their presence "within short large-amplitude magnetic structures upstream of the Earth's quasi-parallel bow shock" (Behlke et al., 2004). According to Behlke et al. (2004) these nonlinear electric field pulses (solitary waves) "often occur as bipolar pulses in the electric field data and move parallel to the background magnetic field at velocities of 400–1,200 km/s," They were identified as negative potential structures with parallel electric fields as high as up to 65 mV/m with parallel scale sizes of ~300–600 m approximately = λ_D. Because these are negative potential structures Behlke et al. (2004) suggested that these were ion depletion structures. The theories commonly used at the time to explain solitary waves did not adequately address their observations. However, Behlke et al. (2004) did suggest that BGK solitary waves might explain their observations "if ion phase space holes may exist in weakly magnetized plasmas and may move at the observed high velocities."

Qureshi et al. (2011) examined the bipolar solitary structures reported by Behlke et al. (2004) through an electrostatic ion fluid model. Qureshi et al. (2011) provided a physical explanation of the polarity of the structures, showing that "if initial electric field $E_0 > 0$, the polarity of the bipolar EFS structure will be positive/negative; and if $E_0 < 0$, the polarity of the bipolar EFS structure will be negative/positive. However, for a fixed polarity of the EFS, either positive/negative or negative/positive, if the satellite is located at the positive side of the EFS, the observed polarity should be positive/negative, if the satellite is located at the negative side of the EFS, the observed polarity should be negative/positive." Understanding the natural polarity of the electric field structures should provide insight into the physical processes that generate them.

Hobara et al. (2008) used the Cluster EFW data to investigate the electrostatic solitary structures in the foot region of Earth's quasi-perpendicular shock. They observed bipolar solitary waves indicative of ion depletion structures, for example, BGK ion holes. These solitary waves were "propagating downstream in the plasma rest frame … at a finite angle to the ambient magnetic field preferably with the solar wind ions." They have "highly oblate elliptical polarization in the direction of the wave propagation." This indicated that "the scale transverse to the wave propagation being much larger than the parallel scale size." The observed characteristics of the solitary waves are "in the range of theoretically allowed values for BGK ion solitary waves with $T_e/T_i \sim 1$" (see Figure 12 of Hobara et al., 2008). They suggested that "the properties of the potential structures of the observed solitary waves may also contribute to the plasma dynamics in the vicinity of the shock."

The first report of ESWs in connection with a super-substorm onset was made by Pickett et al. (2009) while the Cluster spacecraft were at 18–19 Re and moving northward to the lobes from the plasma sheet. These nonlinear ESWs were detected by the WBD instrument on three of the Cluster satellites approximately 5 min following the super-substorm onset of August 24, 2005. The ESWs was reported to be "somewhat more numerous, of shorter duration, and of larger amplitude than is usually encountered at this distance down the tail by Cluster." They also stated that the "electrons appeared to be heated early on and then develop field-aligned fluxes during the interval in which the most ESW are observed…During the same ESW interval, ions are streaming tailward up to several hundred km/s … with a significant constituent of O+, only slightly less than the dominant H+." This is precisely the kind of environment (boundary/current layer) where ESWs are usually observed.

For the first time, Pickett et al. (2010) showed an example where bursts of ESWs were "modulated at ~1–3 Hz, consistent with a Pc1 wave which was observed concurrently," on the earthward side of the magnetopause. They proposed "a Buneman type instability in which the $E_{//}$ component of the Pc1 wave provides a mechanism for accelerating electrons, resulting in the generation of the ESWs modulated at the Pc1 frequency."

The polar cap at 5–9 Re was the subject of a study by Teste et al. (2010) in which they found an "excellent correlation between ionospheric upgoing electron beams and broadband electrostatic emissions (0–6 kHz)" observed by the Cluster Whisper instrument. Although waveform data were not available to verify that the broadband emissions indicated the presence of ESWs, such is likely the case. They concluded that the observed "electron beams are likely to destabilize Langmuir waves and, by the non-linear evolution of the electron bump-on-tail instability, could be responsible for the appearance of electrostatic solitary waves above the polar cap."

The plasma sheet (PS) boundary layer was investigated by Teste and Parks (2009). They showed that "broadband (2–6 kHz) electrostatic emissions … are associated with cold counterstreaming electrons flowing at 5–12 × 10^3 km s^{-1} through hot Maxwellian plasma." They stated that these emissions contain Langmuir waves and contributions from the unresolved Debye scale solitary structures that are prominent in the PSBL, for example, Matsumoto et al. (1994) using Geotail data. Waveform measurements were not available to confirm the existence of ESWs. This work was the subject of a theoretical model by Lakhina et al. (2011) who used the particle and wave data provided in Teste and Parks (2009). The Lakhina et al. (2011) model "is based on the multifluid equations and the Poisson equation, and uses the Sagdeev pseudo-potential technique" to investigate the solitary waves. They proposed that this mechanism could lead to the "generation of ESWs … in terms of electron-acoustic solitons and double layers," the characteristics of which compare well to the ESWs discussed in the Cluster data by Pickett, Chen, et al. (2004); Pickett et al. (2009). They state that "such short electric field pulses" produced by their model, "when Fourier transformed, can appear as broadband electrostatic noise in the frequency range of ∼220 Hz–10 kHz," as observed by Teste and Parks (2009). Lakhina et al. (2011) also addressed the width-amplitude relationship for ESWs, stating that the "properties of the arbitrary amplitude of solitons predicted by the models based on the Sagdeev pseudo-potential techniques are different from the KdV type solitons; that is, depending upon the parametric range, their amplitudes can either increase or decrease with the increase of their width (Ghosh & Lakhina, 2004)."

3.6. Remote Sensing of ESWs

Single spacecraft have previously been used to infer the presence of ESWs, in the form of electron holes, in the auroral kilometric radiation (AKR) source region. Pottelette et al. (2001) used FAST spacecraft data to demonstrate that "a substantial part of the AKR emission," specifically the fine structure, "consists of a large number of elementary radiation events." They interpreted them "as traveling electron holes that may have resulted from the nonlinear evolution of electron acoustic waves and have the properties of Bernstein-Greene-Kruskal modes." In a later study, Pottelette and Treumann (2005) provided evidence "for electron holes in the upward current AKR source region," thus providing substantiation for their earlier claim (Pottelette et al., 2001) that AKR fine structure is produced by propagating electron holes. Pottelette and Pickett (2007) state that, based on previous numerical simulations, the electron holes modify the original horseshoe-distribution function, resulting from the electron-cyclotron maser mechanism that generates AKR. When the electron holes move deeper into the denser electron distribution, their amplitudes increase and they modify the original horseshoe-distribution function by imposing a steep perpendicular-velocity gradient on the electron-distribution function. This gradient increases steeply in both directions (parallel and perpendicular to the magnetic field). Pottelette and Pickett (2007) thus concluded "that the deformed electron holes produce steep, perpendicular gradients in the horseshoe velocity distribution at the hole boundaries and act as efficient radiation emitters." They further state that this "emission occurs at the edge of the electron holes where $\delta F_e/\delta v_\perp > 0$, while at the end where $\delta F_e/\delta v_\perp < 0$, the hole absorbs radiation" where Fe is the energetic electron distribution and v is the electron velocity. Absorption and emission occur at slightly different frequencies with very narrow bandwidths Δf/dt often as low as 10^{-4} to 10^{-3}.

Pottelette and Pickett (2007) and Pottelette et al. (2014) used high time resolution Cluster and FAST data to study fine frequency structures of different types in AKR. Pulsating AKR emissions modulated at frequencies around 2.8 Hz, which is typical for Pc1-pulsations, in a Cluster WBD spectrogram were prominent in Figures 5 and 9 respectively of their papers. According to Pottelette and Pickett (2007), the measurements were taken "during the recovery phase of a large storm in a 10,000–13,000 km altitude range given the observed frequency range of the radiation." They show that "the spectrum of AKR radiation reveals two different types of fine-frequency structures. The first one, known as striated AKR, is associated with moderate negative-slope frequency drifts and is recorded below a quasi-steady frequency f* ∼ 70 kHz at the low frequency edge of the spectrum" as shown in Figure 5 (reproduced from Pottelette et al., 2014). These were interpreted as the signature of ion holes (ion solitary waves) drifting through the auroral acceleration region (Mutel et al., 2006, see below). Pottelette et al. (2014) described these striations as having "a mean slope of −2.4 kHz s^{-1}, corresponding to a trigger speed of 210 km s^{-1}." This speed is consistent with the results of Bounds et al. (1999) of anti-earthward propagating ion holes using Polar data.

Pottelette and Pickett (2007) stated that the second type of fine structure observed in the Cluster spectrogram was "associated with an abrupt frequency expansion into higher frequencies above f_{ce}," as shown in Figure 5. According to Pottelette et al. (2014), the "upward frequency expansion (df/dt > 0) above f_{ce} ... can be interpreted as a result of a local acceleration by a pulsing DL located at a quasi-steady altitude of 12,000 km" (DL referring to a double layer). They note that there is "the presence of a well-defined series of closely spaced absorption and emissions bands (separated by several hundred Hertz, as described above) which may characterize AKR generation by EHs propagating earthward at high velocity."

Using Cluster data, Mutel et al. (2006) investigated a "particular type of AKR fine structure called striped or striated AKR (Menietti et al., 1996, 2000)," which they termed SAKR. Mutel et al. (2006) report that SAKR bursts were detected "in less than 1% of all WBD spectra observed when the spacecraft was above 30° magnetic latitude. (Note that below this latitude, there is often shadowing by the Earth's plasmasphere.)" An example of SAKR is shown in Figure 5 above at frequencies below 70 kHz. Mutel et al. (2006) showed a case

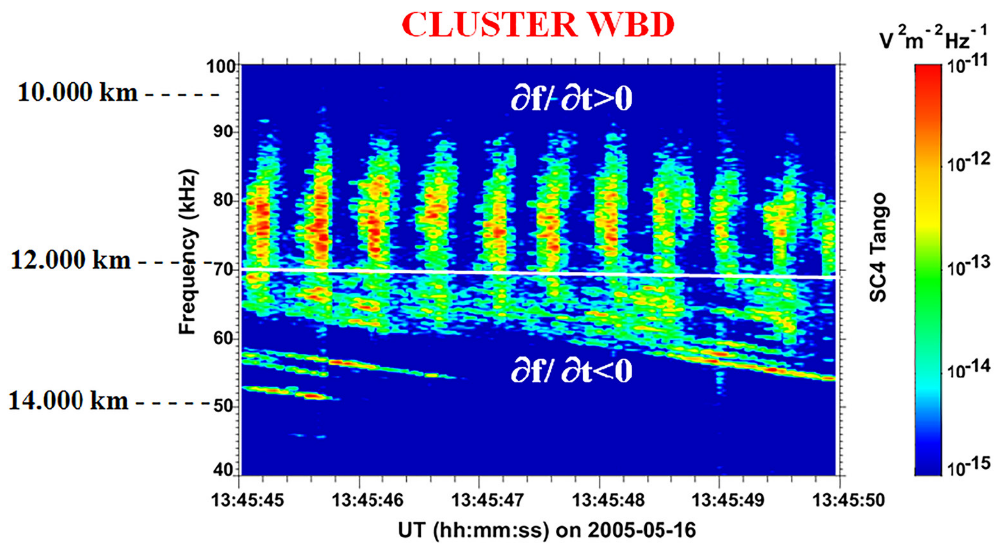

Figure 5. "Spectrogram covering a period of 5 s showing pulsed and striated auroral kilometric radiation observed by remote sensing on a Cluster satellite located in the nightside magnetosphere at 14.2 R_E and at an invariant latitude of 80°. The horizontal white line indicates the value of the local gyrofrequency, f_{ce} ~ 70 kHz at an altitude of ~12,000 km." Reprinted from Pottelette et al. (2014), Figure 9.

of negative sloped SAKR that correlated well on all four spacecraft in the frequency range 125.5–136 kHz. The spacecraft were separated by about 8,000 km and were located in the nightside magnetosphere at 11 Re, well away from the auroral acceleration region where the AKR is generated. Their analysis of the beaming characteristics of these types of SAKR bursts resulted in a determination that the "full width at half maximum angular size is $\theta = 5.0°$," which "is surprisingly small compared with most previously published observations of AKR beam size." They also stated that "the angular beaming observations, combined with measured flux density, allow a direct estimate of the average intrinsic power of individual SAKR bursts," the resulting power being ~1–10 W, "much smaller than the previous estimates of $P \sim 10^3$–10^4 W for a single "elementary radiator" (Pottelette et al., 2001)." Mutel et al. (2006) suggested that the SAKR bursts could be used as a remote tracer of ion holes.

From the analysis of the SAKR Mutel et al. (2006) listed several key findings with regard to propagation and stability of ion holes which include the following: (a) They can "propagate upward for more than 1,000 km, implying lifetimes of a few seconds," (b) the "ion holes propagate at a nearly constant speed during their entire lifetime," (c) "there is little evolution of the electric field intensity or spatial structure of ion holes over their lifetime," and (d) the ion holes "are more common at higher altitude, being more than 100 times as common at 10,000 km (f_{ce} ~ 90 kHz) than at 3,200 km (f_{ce} ~ 500 kHz) altitude."

4. Summary and Concluding Remarks

This review of the results of studies carried out on ESW using data from the first 20 years (2000–2020) of the Cluster mission proves that the mission was a resounding success in terms of advancing the knowledge of all aspects of nonlinear ESWs. The first reports of ESWs concentrated on detailing the time durations and amplitudes of ESWs which were discovered throughout much of the Cluster orbit, particularly at all boundary layers (plasmasheet, polar cap), at the bow shock and magnetopause, and in the magnetotail, magnetosheath, solar wind, and auroral zone using data from the WBD instrument. In addition, one study specifically examined the characteristics of ESWs observed at the onset of a super-substorm in the tail that occurred on August 24, 2005.

Many of these first studies used the advantage of the EFW instrument to provide correlations of ESWs propagating from one antenna probe to another on a single spacecraft, thus providing ESW propagation velocities, primarily along magnetic field lines. This naturally led to detecting ESWs observed propagating from one spacecraft to another when the spacecraft were sufficiently close (a few tens of km), allowing for estimates of the minimum lifetimes of these structures. For electron solitary waves these lifetimes were found to be on the order of 20 ms and for ion solitary waves around 1,000 ms (through remote sensing). The shape of the ESWs was found to be more spherical in the auroral acceleration region, while much more oblate or pancake-shaped in all other regions. The determined lifetimes, velocities, and sizes, both from a single spacecraft and a multi-spacecraft, were summarized in Table 1 of Pickett et al. (2008) for three regions (auroral field lines/plasmasheet at 5–8 Re, magnetosheath, and auroral acceleration region). In addition, Table 1 of Pickett et al. (2010) provided similar ESW characteristics for ESWs observed in the magnetopause boundary layer using multi-spacecraft propagation methods, as did Norgren, Andre, Vaivads, and Khotyaintsev (2015) for 10 ESW cases in the plasma sheet boundary layer. The lifetime aspect of the ESWs is important from the standpoint of stability as this knowledge can help determine the instability creating the ESWs.

Several instabilities were suggested, and in some cases shown through modeling, to generate the ESWs in various regions. These suggestions include the Buneman instability, the two-stream instability, modified two-stream stability, bump-on-tail instability, electron-ion instabilities, beam-plasma instabilities, the electron, and ion acoustic instabilities. Generation out of turbulence was in particular suggested for the magnetosheath where the time scales of the ESWs are so short. Many of the modeling efforts reproduced the basic characteristics of the ESWs observed in the Cluster data. It was also suggested that a few of these instabilities could be active at once in some particularly active regions, such as the magnetic reconnection region.

A wealth of information was gained from the Cluster data regarding the role of ESWs in magnetic reconnection. The ESWs were reported to be along the separatrix as the x-line passed over the spacecraft, but not in the inflow or outflow regions. Some were found to be large amplitude and associated with electron beams. Cluster magnetic reconnection studies of ESWs indeed paved the way for similar studies to be carried out on NASA's Magnetospheric Multiscale mission where the spacecrafts are closer in this region with controlled separations, and particle data are taken with higher resolution to better determine the instability leading to the creation of the ESWs.

Although the Cluster mission briefly visited the auroral acceleration region in parts of the years 2009–2013, no research was published on ESWs in this most active region where the first reports of ESWs were made (Temerin et al., 1982) and later by Ergun et al. (1998). An opportunity exists in 2023–2025 to obtain valuable cross spacecraft data on ESWs as the Cluster spacecraft begin the process of reentry. Also, a closer examination of the ESWs at the bow shock and in the magnetosheath needs to be made to better understand the processes which are taking place there. In particular, the magnetosheath ESWs are so plentiful and predicted from the bow shock to the magnetopause, but no clear picture of how they are generated has emerged. Does the turbulence present in the magnetosheath play a role in their development due to the extremely short time scales of the ESWs? Lastly, it is important to recognize that since ESWs are observed in so many regions of space, we must continue to build more sophisticated instruments and spacecraft that can deal with the high time resolutions and specific orientations of spacecraft that are needed to make the best measurements. In doing so we will better understand ESWs and fully appreciate their significance in the ongoing physical processes surrounding Earth and beyond.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All of the Cluster data contained within the reviewed study reside at ESA's Cluster Science Archive, URL www.cosmos.esa.int/web/csa/ and at NASA's Coordinated Data Analysis Web, URL cdaweb.gsfc.nasa.gov.

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