Electrostatic solitary structures observed at Saturn

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[1] We report observations of electric field solitary structures, measured by the Cassini Radio and Plasma Wave Science (RPWS) instrument in the vicinity of Saturn's magnetosphere with ambient magnetic fields that range from ~0.1 nT to 8000 nT. The peak-to-peak electric field amplitudes of the observed solitary structures range from a few μV/m to 10 mV/m and show a slight trend toward larger amplitude electric field pulses being associated with larger ambient magnetic fields. The time durations of the pulses range from a few hundred μs to a few 10's of milliseconds. The solitary waves appear in plasma boundary regions or in regions with abrupt changes in the magnetic field. The solitary waves tend to be observed when the dipole antenna is aligned with the magnetic field. **Citation:** Williams, J. D., L.-J. Chen, W. S. Kurth, D. A. Gurnett, and M. K. Dougherty (2006), Electrostatic solitary structures observed at Saturn, *Geophys. Res. Lett.*, *33*, L06103, doi:10.1029/2005GL024532.

1. Introduction

[2] Electrostatic solitary waves have been observed in many plasma regions around the planet Earth; including the auroral region [*Temerin et al.*, 1982; *Ergun et al.*, 1998; *Franz et al.*, 1998], the magnetotail [*Matsumoto et al.*, 1994], the magnetosheath [*Pickett et al.*, 2004], the magnetopause [*Cattell et al.*, 2002] and the bow shock [*Bale et al.*, 1998]. Aside from the near Earth environment *Kurth et al.* [2001] have found solitary structures in the wake of Jupiter's moon Europa, which is, to our knowledge, the only report of electrostatic solitary structures seen around any planet aside from Earth. In this paper, we present the first observations of electrostatic solitary structures seen in the planetary environment of Saturn.

[3] Near-Earth observations in the auroral region [*Temerin et al.*, 1982], the magnetotail [*Kojima et al.*, 1997] and the solar wind [*Mangeney et al.*, 1999] have shown that electrostatic solitary waves tend to be polarized such that the electric field points in the direction of the ambient magnetic field. The range of peak-to-peak electric field amplitudes for electrostatic solitary waves seen in the near-Earth environment is 10's of μV/m in the plasma sheet [*Pickett et al.*, 2004] to 100's of mV/m in the auroral region [*Ergun et al.*, 1998]. The range of pulse time durations for near-Earth solitary waves is 10's of microseconds in the magnetosheath [*Pickett et al.*, 2004] to hundreds of microseconds in the auroral region [*Ergun et al.*, 1998] to tens of milliseconds in the plasma sheet boundary layer [*Kojima et al.*, 1997]. Cassini observations at Saturn show that solitary structure are most often seen when the electric field antenna is aligned with the ambient magnetic field and that pulse amplitudes and time durations fall within the ranges seen in the near-Earth plasmas.

[4] The data are from the Radio and Plasma Wave Science (RPWS) instrument [*Gurnett et al.*, 2004] and the Dual Technique Magnetometer (MAG) [*Dougherty et al.*, 2004] on the Cassini spacecraft. Waveform data from two separate receivers on RPWS are used, the wideband receiver (WBR), which uses a 9.26 m dipole antenna to measure one component of the electric field and the waveform receiver (WFR), which also uses the same dipole and a 5.0 m monopole antenna to simultaneously measure two electric field components and the full vector magnetic field. In practice only data from the dipole antenna were used. In each receiver the electric field measurement is determined by dividing a differential voltage measurement by the effective antenna length. The WBR receiver has a spectral range of 0.06–10.5 kHz with a resolution of 13.6 Hz and a sample rate of 27,777 samples per second. Likewise, WFR has a spectral range of 0.003–2.5 kHz, a resolution of 3.5 Hz and a sample rate of 7143 samples per second. The WBR mode, had a 3% duty cycle over the course of the observations while the WFR had a 0.5% duty cycle. The WBR mode does not provide concurrent magnetic field measurements so we are unable to determine if the electric field disturbances are electrostatic. Measurements from WFR however, show that the solitary structures are electrostatic and so by extension we assume that the solitary waves from WBR are also electrostatic. The RPWS instrument is designed to detect wave phenomena in the frequency range of 1 Hz to 16 MHz, hence it is sensitive to solitary structures whose inverse period falls within this range. While the instrument is not optimised for 'DC' and does not measure all three components of the electric field, the observations in Figure 1 demonstrate its ability to detect the presence of and measure the amplitude of electrostatic solitary structures. The instrument normally does not make measurements in an 'interferometry' mode which would enable the direct determination of the velocity of electrostatic structures as they move past the spacecraft. Due to these limitations we are unable to estimate the structure scale size or whether or not we see electron or ion solitary waves. We are also unable to give a true measure of the polarization of the waves.

2. Observations

[5] We present examples of the two types of solitary waves in Figure 1. Event starting times are given in the upper right corner in each plot. Actual times are obtained by adding milliseconds onto the event starting time. Figure 1a shows a grouping of bipolar pulses, all of which start with a downward deflection. Bipolar pulses which are grouped like

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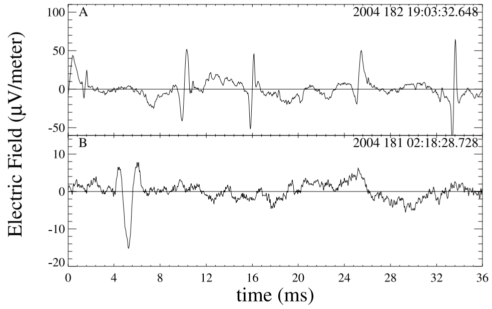

Figure 1. Solitary structures observed during the first days of Cassini's arrival at Saturn: (a) example of several bipolar events and (b) tripolar event.

this tend to have the same starting deflections, either upward or downward. These pulses are thought to be caused by either electron or ion holes. *Ergun et al.* [1998] have observed a group of bipolar pulses separated in time by the period of the lower hybrid wave. The pulses we observed are roughly separated by 1/2 of the lower hybrid period. Figure 1b shows an example of a tripolar pulse; which are rarely seen in groups. These waves are thought to be caused by weak double layers first observed by *Temerin et al.* [1982]. As coherent structures these tripolar pulses require the presence of trapped electrons as well as ions. Both types of pulses were included in the survey but since there were no differences between the bipolar and tripolar pulses in terms of amplitude and duration no distinction between them was made in the subsequent analysis.

[6] The detection algorithm for solitary pulses involves ensuring that the pulses are isolated and significantly above the ambient background electric field. For example, the bipolar deflection seen at the beginning of the data frame in Figure 1a is discarded because it is too close to the start of the interval and we are unable to determine if it is sufficiently isolated. The plasma environment around Saturn is dusty and dust impacts on the spacecraft cause both the WBR and the WFR receivers to respond with a monopolar pulse characterized by a sharp rise time followed by a slowly falling return to background. Aside from ensuring that the pulses are isolated and significant, care was taken to be certain that any pulses that were found were not due to dust impacts. This was accomplished by discarding all monopolar signals as well as manually examining all other pulses and discarding those which did not conform to the above criteria.

[7] To obtain an overview of when the solitary pulses occur with respect to different environments in near-Saturn space, Figure 2 shows solitary pulse events overplotted on the ambient magnetic field observed by the MAG instrument. This particular time is the first Cassini encounter with Saturn's magnetosphere. The magnetic field trace shows seven separate bow shock crossings between 27 June, 2004 (day 179) and 29 June, 2004 (day 181). The top plot shows the electric field peak-to-peak amplitude for all of the events in this period. The bottom plot shows the pulse time duration for the same events. The short vertical bars across the top plot indicate the time periods when either the WBR or WFR receiver was sampling. Note that the majority of the events occurred just as the bow shock passed over the spacecraft, and only 2 events were seen while Cassini was in the solar wind. The maximum peak-to-peak electric field was approximately 1.2 mV/m and was observed coincident with the fifth shock crossing where the magnetic field was ~1 nT.

[8] On 1 July, 2004 (day 183) the Cassini spacecraft was inserted into its Saturn orbit and made its closest approach to the planet (r = 1.34 R_S, R_S = 60268 km). Figure 3a

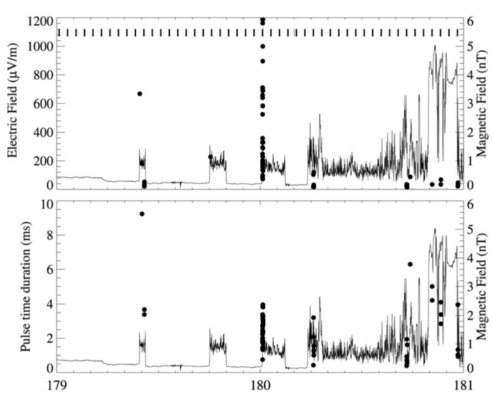

Figure 2. Solitary structures observed during crossing of Saturn's bow shock starting on June 27, 2004 (day 179): (top) peak-to-peak electric field amplitude of the solitary waves as a function of time and (bottom) solitary wave time duration as a function of time. The vertical bars at the top of the top plot indicate times when the dipole waveform receiver was taking data. The magnetic field is overlaid onto each plot to help organize the events.

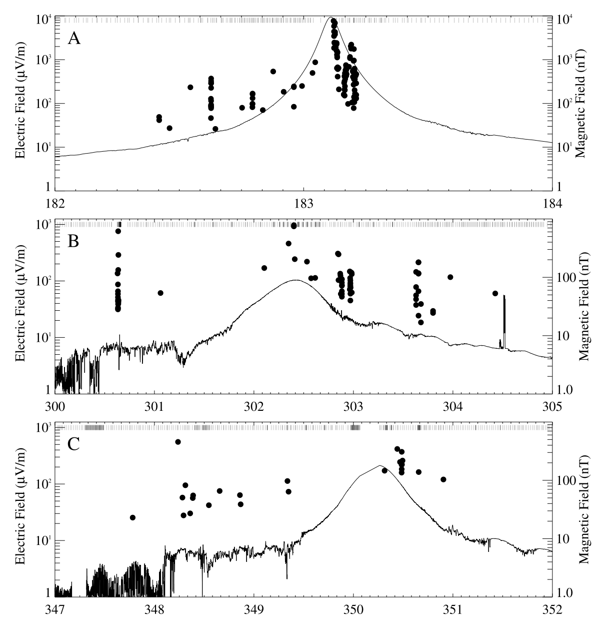

Figure 3. Peak-to-peak electric field amplitude of solitary structures observed from the first three Cassini Saturn closest approaches: (a) pulses observed during orbital insertion on 01 July, 2004; (b) pulses observed during the 28 October, 2004 periapsis; and (c) pulses from the 15 December, 2004 periapsis. All three passes occurred when Cassini was in the Saturn equatorial plane. The magnetic field is overlaid onto each plot to provide an overview of the distribution of observed events.

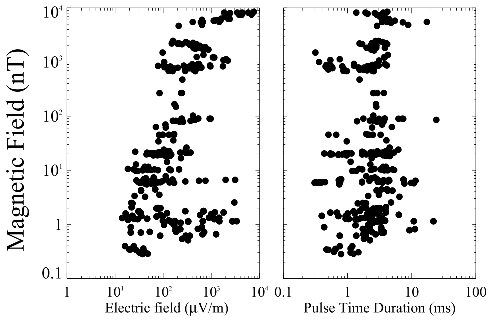

Figure 4. Scatter plots of (left) the pulse peak-to-peak electric field amplitude and (right) time duration plotted against the ambient magnetic field.

shows the peak-to-peak electric field amplitude of the solitary pulses observed during this encounter. Again, the vertical bars at the top of the plot indicate the times when data were taken and the ambient magnetic field is plotted on the right. The magnetic field peaks at ∼10000 nT and pulses are observed to have electric field amplitudes of up to 10 mV/m. To our knowledge, naturally occurring solitary waves have never been seen in such large magnetic fields. Figure 3b shows the peak-to-peak amplitudes of pulses observed at another Saturn periapsis (r = 6.2 R_S) on 28 October 2004 (day 302). The grouping of pulses on day 300 at ∼15:00:00 UT are seen in association with a close encounter of the moon Titan. Figure 3c shows the peak-to-peak electric field amplitude of the solitary pulses observed when Cassini approached Saturn (r = 4.7 R_S) on 15 December 2004 (day 350). Again, the large cluster of pulses seen at 08:00 UT on day 348 is associated with another Titan encounter. All of these plots show a tendency of increasing peak-to-peak electric field amplitude in association with increasing ambient magnetic field amplitude. Except for Saturn orbital insertion, all periapses are located outside of the F ring.

[9] As a summary of how the peak-to-peak amplitude and time duration behave as a function of the background magnetic field strength we present in the left panel of Figure 4 a scatter plot of the electric field amplitude plotted as a function of the ambient magnetic field for all of the pulse events in the study. There is a slight trend toward larger electric field amplitude in association with larger ambient magnetic field magnitudes. The right panel in Figure 4 shows the solitary pulse time duration plotted against the ambient magnetic field. Here there seems to be no observable trend in the data, a pulse with a duration of 1 ms can be seen at either low or high magnetic fields.

[10] To further characterize the solitary structures, we present in Figure 5 a histogram of the cosine of the angle between the antenna and the magnetic field. This gives a measure of the polarization of the solitary structures. Bear in mind that since we do not have full $\vec{E}$ measurements we do not know the exact polarization. However, we expect to see a clear preference of events occurring when the dipole antenna is aligned with the magnetic field if the polarization is magnetic field aligned. The solid line shows the occurrence frequency for all events in the study, and it shows that the majority of the events were seen when the antenna was nearly aligned with the magnetic field. The dash-dotted line shows events which were observed prior to Saturn orbital insertion, that is, all of the events shown in Figure 2 when Cassini was near the Saturn bow shock. Here as in the larger data set a majority of the pulses were found to be aligned with the magnetic field.

3. Discussion

[11] Our results show that while Cassini was in the solar wind on day 179 that few solitary structures were observed but that when the spacecraft passed through the Saturn bow shock the observations of solitary structures increased dramatically. The overall change in the magnetic field strength between the solar wind and the Saturn magnetosheath is on the order of a few nT but the change in the magnetic field variability is large. *Pickett et al.* [2004] suggest that turbulence in the Earth's magnetosheath may account for the observations of the solitary structures there and *Kurth et al.* [2001] found the majority of pulses seen at Europa to be observed in the moon's wake, a region of known turbulence. During this six-month study there were long periods during which no electrostatic solitary waves were observed. Each of these time periods corresponded to locations where the spacecraft was in regions of quiet magnetic field. With the exception of one event (not shown), solitary structures were observed only when Cassini either made one of its closest approaches to Saturn or one of its moons or when the spacecraft crossed the magnetosheath and bow shock boundaries.

[12] The solitary structure electric field amplitude increased as the magnitude of the magnetic field increased when the spacecraft neared periapsis. This observation is similar to what *Pickett et al.* [2004] reported for a survey of solitary structures in the Earth plasma environment. This behavior is shared by solitary waves observed at an interplanetary shock at 8.7 AU [*Williams et al.*, 2005]. The two hour period of time shortly after periapsis showed the largest observation rate of solitary structures of the entire study period. At this time the RPWS instrument showed

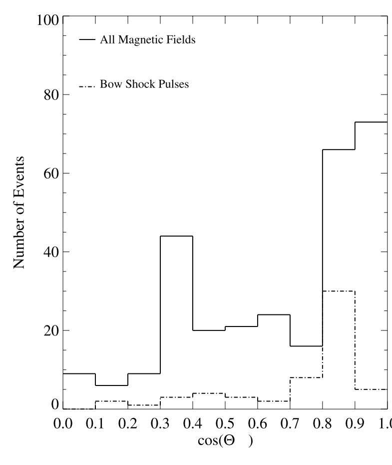

Figure 5. Histogram of the cosine of the angle between the antenna and the magnetic field. Two traces are shown. the solid line corresponds to all observations. The dash-dotted line corresponds to events which occurred before day 181. Over 75% of these pulses occur when Cassini was in the bow shock prior to Saturn orbital insertion.

evidence of auroral hiss [*Gurnett et al.*, 2005] and it is possible that Cassini was moving through a current system induced by an interaction between the corotating plasma and the Saturn rings [*Gurnett et al.*, 2005].

[13] Our observation of the tendency for solitary structures to be observed when the antenna was closely aligned with the magnetic field are consistent (see *Temerin et al.* [1982], *Kojima et al.* [1997], and *Mangeney et al.* [1999], who have shown that the polarization of double layers and solitary structures tended to be aligned with the ambient magnetic field). In the bow shock transition region *Bale et al.* [1998] has shown that polarizations showed no tendency to align with the magnetic field. Our results, shown in Figure 5, indicate that pulses observed at Saturn's bow shock tended to be polarized along the direction of the magnetic field. At this time we are unable to explain this seeming inconsistency.

[14] The observations from the RPWS instrument allow for two separate parameters in the measurement of solitary pulses, the time duration and the peak-to-peak electric field amplitude of each pulse. The time durations range from 150 μs–3 ms for WBR and 560 μs–50 ms for WFR. The survey results indicate that pulses were seen throughout the entire range of time durations available and it is likely that pulses of both higher and lower time durations should exist. Likewise, the electric field peak-to-peak amplitude was also limited in its range from ~0.25 μV/m to ~145 mV/m. In this case, however, the observations did not fill the entire range of amplitudes even though [*Ergun et al.*, 1998] have shown that solitary structures with 100's of mV/m amplitudes exist in the Earth auroral region.

[15] To summarize, we have observed solitary pulses in the space environment around the planet Saturn. These pulses range in peak-to-peak amplitude from a few μV/m to 10 mV/m, while their time durations range from hundreds of microseconds to 10 ms. The pulses are seen over 4 orders of magnitude in ambient magnetic field and are seen most often when the magnetic field is highly variable. There appears to be a trend toward larger electric field amplitudes when the ambient magnetic field magnitude is larger. No such trend occurs when comparing the magnetic field and pulse time duration. The pulses are observed most frequently when the electric field antenna is closely aligned with the magnetic field.

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References

Bale, S. D., P. J. Kellogg, D. E. Larson, R. P. Lin, K. Goetz, and R. P. Lepping (1998), Biploar electrostatic structures in the shock transition region: Evidence of electron phase space holes, *Geophys. Res. Lett.*, *25*, 2929–2932.

Cattell, C., J. Crumley, J. Dombeck, J. Wygant, and F. S. Mozer (2002), Polar observations of solitary waves at the Earth's magnetopause, *Geophys. Res. Lett.*, *29*(5), 1065, doi:10.1029/2001GL014046.

Dougherty, M. K., et al. (2004), The Cassini magnetic field investigation, *Space Sci. Rev.*, *114*, 331–383.

Ergun, R. E., C. W. Carlson, J. P. McFadden, F. S. Mozer, L. Muschietti, I. Roth, and R. J. Strangeway (1998), Debye-scale plasma structures associated with magnetic-field-aligned electric fields, *Phys. Res. Lett.*, *81*, 826–829.

Franz, J., P. Kintner, and J. Pickett (1998), Polar observations of coherent electric field structures, *Geophys. Res. Lett.*, *25*, 1277–1280.

Gurnett, D. A., et al. (2004), The Cassini radio and plasma wave investigation, *Space Sci. Rev.*, *114*, 395–463.

Gurnett, D. A., et al. (2005), Radio and plasma wave observations at Saturn from Cassini's approach and first orbit, *Science*, *307*, 1255–1259.

Kojima, H., H. Matsumoto, S. Chikuba, S. Horiyama, M. Ashour-Abdalla, and R. R. Anderson (1997), Geotail waveform observations of broadband/narrowband electrostatic noise in the distant tail, *J. Geophys. Res.*, *102*(A7), 14,439–14,455.

Kurth, W. S., D. A. Gurnett, A. M. Persoon, A. Roux, S. J. Bolton, and C. J. Alexander (2001), The plasma wave environment of Europa, *Planet. Space Sci.*, *49*, 345–363.

Mangeney, A., et al. (1999), WIND observations of coherent electrostatic waves in the solar wind, *Ann. Geophys.*, *17*, 307–320.

Matsumoto, H., H. Kojiima, T. Miyatake, Y. Omura, M. Okada, I. Nagano, and M. Tsutsui (1994), Electrostatic solitary waves (ESW) in the magnetotail: BEN wave forms observed by Geotail, *Geophys. Res. Lett.*, *21*, 2915–2918.

Pickett, J. S., L.-J. Chen, S. W. Kahler, O. Santolík, D. A. Gurnett, B. T. Tsurutani, and A. Balogh (2004), Isolated electrostatic structures observed throughout the Cluster orbit: Relationship to magnetic field strength, *Ann. Geophys.*, *22*, 2515–2523.

Temerin, M., K. Cerny, W. Lotko, and F. S. Mozer (1982), Observations of double layers and solitary waves in the auroral plasma, *Phys. Res. Lett.*, *48*, 1175–1179.

Williams, J. D., L.-J. Chen, W. S. Kurth, D. A. Gurnett, M. K. Dougherty, and A. M. Rymer (2005), Electrostatic solitary structures associated with the November 10, 2003, interplanetary shock at 8.7 AU, *Geophys. Res. Lett.*, *32*, L17103, doi:10.1029/2005GL023079.

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