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| **Type of Report** | Final Scientific/Technical Report |
| **DOE Grant Number** | DE-FG02-07ER54943 (Partner) |
| **Name and Address of the Recipient** | The University of Iowa<br>Sponsored Programs<br>100 Gilmore Hall, Room 2<br>Iowa City, IA 52242 |
| **Project Title** | Collaborative Research: Dynamics of Electrostatic Solitary Waves on Current Layers |
| **Name of the Principal Investigator** | Jolene S. Pickett |
| **Period Covered by the Report** | August 1, 2007 through July 31, 2012 |
| **Consortium/Teaming Members** | Li-Jen Chen, Principal Investigator<br>University of New Hampshire<br>DOE DE-FG02-07ER54941 (Prime)<br><br>Paul Kintner, Principal Investigator<br>Cornell University<br>DOE DE-FG02-07ER54942 (Partner) |
| **Signature** | Prepared by:<br><br>______________________________<br>Jolene S. Pickett<br>Principal Investigator |

## 1.0 Executive Summary

The research carried out under the subject grant has provided insight into the generation of Electrostatic Solitary Waves (ESWs), which are nonlinear structures observed in space plasma data. These ESWs, appearing as pulses in the electric field time series data, represent the presence of several hundred meters to kilometer size positive potential structures, similar to champagne bubbles, where the electrons have been depleted, and which travel along Earth's magnetic field lines. The laboratory experiments carried out at the UCLA LAPD under the grant allowed us the opportunity to change various plasma and field conditions within the plasma device, and experiment with injection of suprathermal electron beams, in order to create ESWs. This then allowed us to determine the most likely method of generation of the ESWs. By comparing the properties of the ESWs observed in the LAPD to those observed in space and the plasma and field conditions under which those ESWs were observed in both locations, we were able to evaluate various ESW generation mechanisms. The findings of the laboratory experiments are that ESWs are generated through a lower hybrid instability. The ESWs observed in Earth's auroral current regions have similar characteristics to those generated by the laboratory when referenced to basic plasma and field characteristics, leading us to the conclusion that the lower hybrid drift instability is certainly a possibility for generation of the ESWs, at least in the auroral (northern/southern lights) regions. Due to space instrumentation insufficiencies and the limitations on telemetry, and thus poor time resolution, it is not possible to determine absolutely what generates these bubbles in space, but the laboratory experiments and supporting simulations have helped us to further our understanding of the processes under which they are generated. The public benefits from the findings of this research because the research is focused on current layers around Earth, which are affected by our Sun's activity. Understanding how these current layers are affected by the Sun provides insight into why radio communications are sometimes affected on Earth and how these layers help protect and facilitate our life on Earth.

## 2.0 Comparison of Accomplishments to Goals and Objectives

The University of New Hampshire had responsibility under the prime grant referenced on Page 1 of this report for carrying out the major objectives and goals of this study. We list here only those goals and objectives which were to be carried out at The University of Iowa.

**Goal 1**: Participate in three LAPD solitary wave experiment to a) generate thin current layers with different widths and current densities, b) probe and measure solitary wave properties, and establish their inter-dependence with the current layer properties, and c) quantify the effective resistivity due to solitary waves at current layers, and examine how solitary waves affect low frequency wave phenomenon.

**Goal 1 Accomplishments**: The Principal Investigator under the subject Grant at Iowa , Jolene Pickett, was unable to support the first LAPD experiment due to other commitments to NASA. She participated remotely by providing input on the plasma conditions needed to produce solitary waves in the experiments, and reviewed the results. The results showed that not many solitary waves were produced, and that some of the experiment set-up parameters (background magnetic field, beam voltage, etc.) needed to be adjusted in future experiments to more accurately represent thin layers in space. In addition, some more instrumentation needed to be developed to better probe what was going on inside the plasma device.

The Principal Investigator actively supported the second LAPD experiment, reviewing results as each parameter was changed to see the effect. She participated in the analysis of those results with the lead investigators at New Hampshire, the results of which were two publications with lead author Bertrand Lefebvre.

The third LAPD experiment did not take place as it was proving difficult to arrange for the facilities. The reason for this is that an extension of the grant was requested and approved due to the illness and subsequent death of the Principal Investigator at Cornell University who was one of the other experts in carrying out those experiments. After such a long time since the second experiment (over two years) and with the loss of one of the key experimenters, as well as the difficulty in reassembling the specialty probes needed for the third experiment, it was agreed that the third experiment be cancelled and the grant allowed to conclude without further extension requests.

**Goal 2:** Survey Cluster WBD waveform data for current layer crossings at the bow shock and magnetopause, and for Cluster reconnection events that have been published previously. Combine all the joint analysis on Cluster data to establish the inter-relationship between solitary waves and current layers and publish results.

**Goal 2 Accomplishments:** The Principal Investigator at Iowa, along with the assistance of an undergraduate student, surveyed the pertinent Cluster WBD waveform data obtained at boundary/thin current layers to determine whether solitary waves were present and if so, extract the properties of those solitary waves for comparison to those observed in the LAPD experiments. We catalogued the events, analyzed the solitary waves at two key regions: reconnection region in the magnetotail during a super substorm, and at bow shock crossings, and compared those solitary waves to those observed in the LAPD experiments. Our results were published in a respected, peer-reviewed journal, as well as presented at international and national conferences. Most recently we started to investigate the ESWs observed in Earth's auroral acceleration region, and the first results were just presented at a workshop in Boulder, Colorado. We found a strong similarity of the ESWs in that region to those generated in the LAPD, suggesting a common generation mechanism.

**Goal 3:** Assist the Principal Investigator at the lead institute, New Hampshire, in loading the existing analytical solutions for solitary waves into PIC code to study their stability and mutual interaction and use the PIC code to set up current layers of different properties and record the properties of solitary waves produced therein to establish the inter-dependence between solitary waves and the current layers.

**Goal 3 Accomplishments**: William Daughton, Co-Investigator at Iowa, was to have carried out this work at Iowa under the subject grant. He left Iowa for Los Alamos National Laboratory about the time that this grant was awarded. Since Prof. Daughton could not carry on this work from Los Alamos, the work was instead picked up by the PI at the lead grant's institute, New Hampshire, and the funds associated with this work transferred from Iowa to New Hampshire. Thus, nothing was accomplished on this goal at Iowa since the work was transferred to the lead grant at new Hampshire.

3.0 Summary of Project Activities

(a) LAPD/Laboratory Experiments

The first UCLA LAPD (Large Plasma Device) laboratory experiments were run during the last days of April and first few days of May, 2008. Unfortunately, the Iowa Principal Investigator (PI), Jolene Pickett, was unable to attend these experiments as planned due to being on travel to NASA Headquarters, the European Geophysical Union annual conference in Vienna, Austria and the Nonlinear Wave Workshop in Beaulieu, France the second through fourth weeks of April. However, she has been available through email for discussions with the New Hampshire and Cornell PIs about the planning, set-up and carrying out of these experiments. During these experiments, very few Electrostatic Solitary Waves (ESWs) were generated. Thus, it was clear that further tests needs to be conducted in order to consistently produce ESWs and to clearly establish the mechanism of their generation. Further, it was determined that more sophisticated probes needed to be developed in order to better understand what the conditions were inside the plasma device during the tests.

The Iowa PI participated in the planning and carrying out of the second LAPD experiments conducted at UCLA during the week of 2 February 2009. During these experiments the UCLA LAPD on-site scientific and technical team, with direction and advice from the New Hampshire, Cornell and Iowa scientists, was able to consistently generate the electrostatic solitary waves (ESWs), which are the subject of this grant, using a suprathermal electron beam parallel to the magnetic field. Several interesting features of the generated ESWs during these experiments were analyzed and the results published in two respected, peer-reviewed journals. The Iowa PI participated in the analysis and writing of those papers, which had Bertrand Lefebvre of New Hampshire as first author (see section 4 for the citations). They found that the ESWs were generated through a lower hybrid instability driven by parallel currents or electron beams.

Since the third LAPD experiment could not be carried out due to the illness and death of the Cornell PI, and the subsequent lapse of too much time as discussed in section 2, the tests were cancelled. Thus the remaining funds at Iowa, which are being returned to DOE, represent the funds associated with the labor and travel costs of the PI associated with that experiment, as well as the travel costs not used by the PI for the first LAPD experiment.

(b) Analysis of Space Experiment Data

The Iowa PI and an undergraduate student set aside one week in February 2008 to look through the Cluster Wideband (WBD) plasma wave receiver data set for events of interest to the subject grant, i.e., events involving the crossing of current layers in space. Several examples of electrostatic solitary waves (ESWs) observed on multiple Cluster spacecraft were identified for the key current layers, namely, bow shock, magnetopause, cusp, magnetotail reconnection layer, and plasmasheet boundary layer. For the chosen events, we ran an existing software program that automatically detects ESWs of type bipolar (pulses with one positive peak followed by one negative peak, or vice versa) and tripolar (pulses with one positive peak surrounded by two negative peaks, or vice versa) [Pickett et al., *Annales Geophysicae*, 2004]. We then prepared several plots showing the amplitudes and time durations of these ESW pulses vs. time, the angle of the antenna to the background magnetic field for each detected pulse vs. time (which provides clues as to the generation mechanism, i.e., a field-aligned process vs. oblique or perpendicular), and histograms of the distribution of detections vs. angle over the entire event.

Although it was a very difficult and complex task, we also ran some existing software to look for possible correlations of ESWs observed on one spacecraft being detected at some lag time on another spacecraft. During any particular small time interval (< 100 ms), it is possible to have ESWs propagating in both directions at different velocities or in the same direction at different velocities. Thus, our approach was to try and find patterns of ESWs that correlated across two different spacecraft separated by several km. We did this by making several passes through the data because of the possibilities of oppositely directed or differing velocities. In spite of the difficulties, we identified several propagation events in the magnetosheath near the magnetopause. From these correlations we were able to obtain the velocity and parallel (to the magnetic field) size of the structures (electron or ion holes) which are represented by the ESWs, as well as a lower bound on the perpendicular size based on the separation of the two spacecraft. Pickett et al. (2010) found velocities on the order of 1500 to 2500 km/s, parallel sizes on the order of 1 km and perpendicular sizes on the order of 30-90 km or greater, most traveling toward the magnetopause (see citation in section 4).

After identifying the events and determining the properties of the ESWs, we began to compare some of the ESW measurements from the Cluster WBD instrument to the simultaneous measurements made by the Cluster Electron Drift Instrument (EDI). We found a good correlation between the detection of ESWs and the presence of currents as determined by EDI. This was important because the LAPD experiments pointed to the possibility that the ESWs observed in space might be generated through a mechanism involving parallel (to the magnetic field) currents. We also revisited a feature reported by Pickett et al. [*Nonlinear Processes in Geophysics*, 2005] in the Cluster WBD data obtained in the magnetosheath, which constitutes a current layer similar to that being studied in the LAPD experiments. That feature involves the periodic generation of solitary waves with decreasing amplitude for each successive solitary wave, something that was observed in the LAPD experiments and discussed in the published works from the laboratory experiments. We also concentrated on an interesting event with ESWs present at the plasmapause boundary layer, which is yet another current layer, in the Cluster WBD measurements. The generation of the ESWs appeared to be modulated at 1.5 Hz, consistent with a Pc1 type wave [Pickett et al., *Geophysical Research Letters*, 2010]. Although the ESWs in that event appeared to be generated through a Buneman type instability, as opposed to the Lower Hybrid Instability observed in the LAPD experiments, it proved that lower frequency waves, such as Pc 1 waves, can interact with an electron beam to produce the type of ESW modulation observed in the LAPD experiments.

The PI of the subject grant published a paper in the *Nonlinear Processes in Geophysics* journal in 2009 in which the space-based observations of ESWs in the plasmasheet during a super-substorm onset were compared to ESWs produced in the LAPD experiments carried out under the subject grant and its associated components (Pickett et al., 2009; see Section 4 for reference). We concluded from these comparisons that the ESW amplitudes in space are considerably smaller than those observed in the LAPD, but the time durations of both space and LAPD ESWs are only slightly larger than the local electron plasma periods, suggesting that both are electron-mode solitary waves.

The PI recently began to study ESWs generated in the heart of Earth's auroral acceleration region (AAR) using Cluster WBD waveform data. This work could not begin until 2010, since the Cluster spacecraft orbit did not begin to traverse this very dynamic region until about 2009. The PI spent a lot of her time in July 2012, the last month of this grant, studying the properties of the auroral ESWs in relation to the LAPD generated ESWs. The AAR region has both upward and downward current regions, and ESWs are observed in both of these regions. The Cluster WBD instrument is uncovering ESWs long hidden from past researchers due to the higher time resolution of the instrument, as well as its continuous measurement through the region, as opposed to typical one minute bursts. She compared the properties of the ESWs in the region to those of the LAPD laboratory experiment, as well as simulations carried out by Ghosh et al. [*J. Geophys. Res.*, 2011] of auroral current layer processes, and found an unexpected correlation across all three of these. The ESWs observed in space by WBD are found in the presence of lower frequency waves slightly above the lower hybrid frequency, similar to the LAPD and simulation results. Since parallel currents are observed in the space observations, there exists the possibility that the space ESWs are generated through the same mechanism as determined by the laboratory experiment and simulations, that being the lower hybrid instability. The space community has long believed that these ESWs were created through beam or two-stream instabilities. Thus, further investigation of these space measurements with regard to the LAPD results is warranted, but that investigation will need to continue under the PI's grant through NASA.

The Iowa PI discussed the LAPD experiments and her results at several international and national conferences. As part of her invited talk at the Nonlinear Wave Workshop in Beaulieu on 21 April 2008, she described the experiments that were being carried out at the LAPD over the course of this grant. She also discussed how the results of these LAPD experiments would be blended into the theory and simulation portions of the work being carried out at the University of New Hampshire, the lead institute. Then she presented some of the results of the space observations discussed above. There was a tremendous amount of feedback from the small group (~50) scientists specializing in nonlinear waves such as these. It was clear to everyone there that the space observations alone could not definitively answer the key questions of how these ESWs are generated and what their function is in the numerous current layers at which they are observed in space. Everyone was most enthusiastic that the LAPD experiments will provide the link to space observations through theory and simulation. The Iowa PI also discussed the results from the reconnection event during the super-substorm at the COSPAR conference in Montreal in 2008 (see results in the published paper), and the results of her study of bow shock ESWs in comparison to LAPD-generated ESWs at the International Union of Radio Science meeting in Chicago in 2008 and the national American Geophysics Union annual meeting in San Francisco in 2008. Finally, the first results of the auroral acceleration region study discussed above have been presented in Colorado in September 2012, after the end of this grant, and the further results of this study will be presented later this year in San Francisco, with both presentations acknowledging support under this grant.

In conclusion, by participating in both the laboratory experiments at the UCLA LAPD, which generated ESWs, and by being the prime investigator of ESWs observed in space, the Iowa PI has been able to gain insight into the generation of the ESWs in space. Because the instrumentation in space that provides supporting data to help determine the ESW generation mechanism, such as electron instruments, have insufficient time resolution, and it is impossible to control any aspect of these experiments, such as the magnetic field, the plasma density, etc., the laboratory experiments, along with the simulations, provide a most valuable path for understanding nonlinear physical processes in space out of which these nonlinear ESWs are produced.

(c) PIC simulations

Because Professor Bill Daughton, a Co-Investigator on the Iowa grant and who was to be partially funded under this grant, moved to Los Alamos National Laboratory from The University of Iowa during the first year of this grant, no progress was made at Iowa in the area of instructing the New Hampshire PI, Dr. Li-Jen Chen, in the use of his PIC simulations for generating solitary waves. As a result, funds allocated for Prof. Daughton's work at Iowa on this grant began to accumulate. These funds were thus requested to be transferred to New Hampshire so that the work could be carried out there by the PI on the New Hampshire grant. That request was approved and the funds transferred on August 1, 2009.

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## 3.0. Public Release of Results

Public release of the results was made, or will be made, in the following publications and presentations. In all cases, the subject award was clearly acknowledged within the publication or on a slide of the presentation.

(a) Publications:

Pickett, J. S., L.-J. Chen, O. Santolík, S. Grimald, B. Lavraud, O. P. Verkhoglyadova, B. T. Tsurutani, B. Lefebvre, A. Fazakerley, G. S. Lakhina, S. S. Ghosh, B. Grison, D. A. Gurnett, R. Torbert, N. Cornilleau-Wehrlin, I. Dandouras, and E. Lucek, Electrostatic Solitary Waves in Current Layers: From Cluster Observations during a Super-substorm to Beam Experiments at the LAPD, *Nonlinear Processes in Geophysics*, 16, 431-442, June 25, 2009.

Lefebvre, Bertrand, Li-Jen Chen, Walter Gekelman, Paul Kintner, Jolene Pickett, Patrick Pribyl, Stephen Vincena, Franklin Chiang, and Jack Judy, Laboratory Measurements of Electrostatic Solitary Structures Generated by Beam Injection, *Physical Review Letters.*, 105, 115001, DOI: 10.1103/Phys.Rev.Lett.105.115001, Sep. 10, 2010.

Lefebvre, B., L.-J. Chen, W. Gekelman, P. Kintner, J. Pickett, P. Pribyl, and S. Vincena, Debye-Scale Solitary Structures Measured in a Beam-Plasma Laboratory Experiment, *Nonlinear Processes in Geophysics.*, 18, 41-47, doi:10.5194/npg-18-41-2011, Jan. 25, 2011.

Pickett, J. S., I. W. Christopher, B. Grison, S. Grimald, O. Santolik, P. M. E. Decreau, B. Lefebvre, M. J. Engebretson, L. Kistler, D. Constantinescu, L.-J. Chen, Y. Omura, G. S. Lakhina, D. A. Gurnett, N. Cornilleau-Wehrlin, A. N. Fazakerley, I. Dandouras, and E. Lucek, On the Propagation and Modulation of Electrostatic Solitary Waves Observed Near the Magnetopause on Cluster, in "Modern Challenges in Nonlinear Plasma Physics: a Festchrift Honoring the Career of Dennis Papadopoulos", D. Vassiliadis, S. F. Fung, X. Shao, I. A. Daglis, and J. D. Huba (eds.), AIP Conference Proceedings 1320, American Institute of Physics, Melville, NY, pp. 115-124, ISBN 978-0-7354-0875-3, December, 2010.

(b) Presentations:

Pickett, J. S., L.-J. Chen, and I. W. Christopher, Characteristics of electrostatic solitary waves observed in current layers in space and in laboratory plasmas, presented by J. S. Pickett at The Seventh International Workshop on Nonlinear Waves and Turbulence in Space Plasmas, Beaulieu, France, 21 April 2008.

Pickett, J. S., L.-J. Chen, I. W. Christopher, S. S. Ghosh, B. Grison, D. Gurnett, G. S. Lakhina, B. Lavraud, O. Santolík, B. Tsurutani, O. Verkhoglyadova, and D. L. Winningham, Electrostatic Solitary Waves Observed by Cluster in Association with Substorms and Magnetic Reconnection in the Magnetotail, oral presentation by J. S. Pickett at the 37th COSPAR Scientific Assembly, Montreal, Canada, 13-20 July 2008.

Pickett, J. S., L.-J. Chen, I. W. Christopher, J. M. Seeberger, S. S. Ghosh, B. Grison, D. A. Gurnett, G. S. Lakhina, B. Lavraud, A. Masson, O. Santolík, B. Tsurutani, and D. L. Winningham, Electrostatic Solitary Structures Near and at Earth's Bow Shock, invited oral presentation by J. S. Pickett at the XXIX General Assembly of the International Union of Radio Science, Chicago, Illinois, USA, 7-16 August 2008.

Pickett, Jolene S., Li-Jen Chen, Ivar W. Christopher, Joanne M. Seeberger, and Suktisama Ghosh, Statistical Properties and Stability of Electrostatic Solitary Waves Observed at Shock Crossings by the Cluster and Cassini Spacecraft, poster presentation by Jolene S. Pickett at the Fall 2008 American Geophysical Union Meeting, 14-19 December 2008.

Pickett, J. S., R. Pottelette, and I. W. Christopher, Exposing Hidden Electron Holes in the Auroral Current Regions with Cluster, presented at the 3rd Cluster and THEMIS Workshop, Boulder, Colorado, October 1-5, 2012.

Pickett, Jolene S., Raymond Pottelette, Ivar Christopher, Collin Forsyth, and Andrew Neil Fazakerley, Revealing Hidden Electron Holes in the Auroral Current Regions with Cluster, to be presented at the 2012 Fall Meeting, AGU, San Francisco, California, December 3-7, 2012.