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GEOSPACE PLASMA DYNAMICS
Laboratory Annual Task Report (FY11)

Daniel Ober

1 March 2012

Technical Report

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Project Manager

//signed//

Joel Mozer, PhD
Division Chief, RVB

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

This annual report provides a summary of progress made during FY11 on AFOSR task titled "Geospace Plasma Dynamics." The goal of this research effort is to develop a detailed knowledge of the space environment by analyzing satellite data and developing the theories needed to explain the observations. In this way we hope to improve our capability to predict the state of the space environment. This effort includes 4 basic research efforts. They are 1) Investigate the spatial and temporal evolution of the turbulent field-aligned Birkeland current system, 2) Investigate solar wind-magnetosphere-ionosphere coupling processes, 3) Specify and predict long-term (3 day) forecast of the low-latitude ionosphere using first principles models, and 4) Investigate the physics of penetration electric fields.

15. SUBJECT TERMS
Solar wind, Birkeland currents, plasma waves, plasma bubbles, magnetosphere, ionosphere, penetration electric fields

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Laboratory Annual Task Report (FY11)

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Title: Geospace Plasma Dynamics

Reporting Period: 1 October 2010 – 30 September 2011

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Research Objectives:

1. Investigate the spatial and temporal evolution of the turbulent field-aligned Birkeland current system,
2. Investigate solar wind-magnetosphere-ionosphere coupling processes,
3. Specify and predict long-term (3 day) forecast of the low-latitude ionosphere using first principles models, and
4. Investigate the physics of penetration electric fields.

Technical Summary:

Objective 1. Investigate the spatial and temporal evolution of the turbulent field-aligned Birkeland current system.

Calculated the self-consistent parallel E-field for downward auroral-current regions.

The solar wind drives currents in the Earth's magnetosphere which, in turn, drives currents that flow in the Earth's ionosphere. However, it is only recently with the advent of detailed satellite measurements in the inner magnetosphere, that we are beginning to understand how the Birkeland current system really works. There was no theory that satisfactorily explained the satellite observations for either the upward (away from the earth) or downward (towards the earth) field-aligned currents. Recently, a new fluid theory in the guiding-center and gyrotropic approximation derivable from the ensemble-averaged, Vlasov-Maxwell equations that included the effect of wave-particle interactions for weakly turbulent, weakly inhomogeneous, nonuniformly magnetized plasma was given by Jasperse, Basu, Lund and Bouhram [Phys. Plasmas 13, 072903 (2006)]. The goal is to apply this theory to determine the current-voltage relationship for the Earth's magnetosphere-ionosphere system.

This year we have made two important advances. (1) We showed that our general theory for turbulent Birkeland current system when applied to downward-current regions when electrostatic ion-cyclotron turbulence is present can be used to calculate the self-consistent, E-field parallel (Epar) to the B-field, and the potential increase along B. We also showed that the anomalous resistivity makes a small contribution to Epar but the anomalous heating of the ions and cooling of the electrons make a large contribution to Epar. (2) We also obtained a new, nonlinear formula for the current-voltage relationship in downward Birkeland current sheets when electrostatic ion-cyclotron turbulence is present. This formula will be of use in MHD codes that couple the magnetosphere to the ionosphere.

Developed Kinetic Model of Plasma Waves in the Earth's Magnetosphere.

Collective processes (waves and instabilities) and the associated anomalous effects (momentum and energy transport) due to wave-particle interactions play a major role in determining the state of the collisionless plasma, such as that found in the Earth's magnetosphere. In particular, ion- cyclotron instability and the turbulence resulting from it are commonly observed in the downward Birkeland current region. The anomalous momentum and energy transports due to ion-cyclotron turbulence, when included in the multi-moment fluid theory, such as that developed at AFRL, result in a self-consistent model of the state of the turbulent plasma in the downward Birkeland current region. In addition to the well-known free energy sources for the ion-cyclotron instability (e.g., field-aligned current, electron beam, ion beam, etc.), bump-on-tail type of electron velocity distribution, which is observed in the downward Birkeland current region, can also excite the instability. Furthermore, satellite-measured particle velocity distributions in the magnetosphere are often better modeled by non-Maxwellian distributions, such as flat-top distribution and Lorentzian (kappa) distribution. It is, therefore, necessary to study the spectral characteristics (frequency vs. wave number) and the other stability properties of the ion-cyclotron instability in various non-Maxwellian plasmas. For this purpose, analysis of the kinetic dispersion relation of the instability, which is derived from the Vlasov-Maxwell theory, is required. Since tractable analytical study of the dispersion relation is restricted to a severely limited parameter space, numerical analysis is essential for a comprehensive parametric study.

This year, we developed a numerical code that solves the kinetic dispersion relation of electrostatic ion-cyclotron instability for Maxwellian as well as for various forms of non-Maxwellian velocity distribution of the charged particles, including particle drifts and temperature anisotropies. With this code, we studied the stability properties (growth rates, unstable spectra, etc.) of: (1) bump-on-tail electron velocity distribution (Maxwellian and flat-top), and (2) current-carrying, kappa-type electron velocity distribution, including the effects of ion temperature anisotropy. Results of the first study were used in our multi-moment fluid theory to determine the self-consistent, quasisteady state of the turbulent plasma in the downward Birkeland current region. The second study illustrated the interesting quantitative differences between the spectral characteristics of the ion-cyclotron instability in Maxwellian and kappa distribution plasmas. This may be useful in interpreting the satellite-measured wave data.

Objective 2. Investigate solar wind-magnetosphere-ionosphere coupling processes

A global magnetohydrodynamic model of the coupled solar wind-magnetosphere-ionosphere system is being used to study the flow of energy and momentum through the magnetosphere-ionosphere system during extreme events. Research efforts are focused on understanding the response of the magnetosphere-ionosphere system during times when there are shocks or discontinuities in the solar wind associated with coronal mass ejections, magnetic clouds, or high speed streamers. It is found that the response of the magnetosphere-ionosphere system is highly non-linear and strongly dependent on the specific nature of the solar wind structure impinging the magnetosphere.This year we used our MHD model to study the interaction of heliospheric current sheets with the magnetosphere-ionosphere system. For this event we completed 4 simulations for varying solar wind conditions characteristic of strongly driven conditions (high magnetic field strength) and for a heliospheric current sheet (low magnetic field strength and high plasma beta). We found that for typical conditions coupling occurs primarily through merging at the dayside magnetopause. However, for the low magnetic field strength and high plasma beta conditions, coupling was occurring through a mixture of weak merging at the dayside magnetopause and through a viscous interaction in the low-latitude boundary layer. Heliospheric current sheet crossings occur regularly and despite the low magnetic fields associated with them, they are drivers of magnetic activity. This point is important to understand for correctly predicting the dynamics of space weather events.

Objective 3. Specify and predict long-term (3 day) forecast of the low-latitude ionosphere using first principles models.

One of the key issues concerning the formation of equatorial plasma bubbles and the radio scintillation that they cause is the mechanism and structure of the phenomena that trigger them. Usually, simulations of the generation of plasma bubbles rely on some arbitrary initial perturbation that develops into the bubble as a consequence of the Rayleigh-Taylor and other plasma instabilities. For this study (done with the 3-d plasma bubble model developed by this team), we instead began with no initial plasma perturbation, but relied on the structured winds and dynamo electric fields of a run of the Whole Atmosphere Model (WAM) to naturally generate the plasma perturbations that develop into bubbles when the plasma becomes unstable. We found that, as a consequence of the structured winds and fields from WAM, equatorial plasma bubbles developed with structures unlike those any simple perturbation would have produced.

WAM is a 150-layer general circulation model developed at the University of Colorado. It is based on the US National Weather Service's operational Global Forecast System (GFS) model, but extended upward to cover the atmosphere from the ground to about 600 km. It relies on tropospheric data assimilation to capture some of the variability of the thermosphere. It was developed as part of the Integrated Dynamics through Earth's Atmosphere (IDEA) project led by T. Fuller-Rowell to study the generation, vertical propagation, possible nonlinear interactions, and effects of planetary waves and tides originating in the lower atmosphere, as part of an effort to understand the variability of the upper atmosphere and ionosphere.

Objective 4. Investigate the physics of penetration electric fields.

This year we compared the annual rate of equatorial instabilities triggered by penetration electric fields to the annual sunspot number. When the ionospheric equatorial electric field exceeds a threshold the resulting instability causes disruption to AF communication and GPS-based systems. The solar wind, via a transpolar potential, drives currents through the ionosphere such that, at times, this threshold is reached if the transpolar potential is sufficiently high. Solar wind data for the period 1998-2009 was used to determine the annual probability of the critical potential being attained. The estimated annual rate for the corresponding equatorial electric field exceeding threshold was found to be between < 1% in 2009 to 40 % in 1999, and is proportional to the annual sunspot number. It is suggested that this feature can be used to estimate the near-future rate of threshold events by maintaining a continuous tabulation of the Hill-Siscoe transpolar potential. Application of the model to C/NOFS satellite data indicates that an equatorial instability threshold in the 0.50 mV/m to 0.75 mV/m range would be consistent with the observation of dawn bubbles in 2008.

Funding Summary by Cost Category ($k)

In-House	Capital Equipment	On-Site Contractor	Total
460	2	100	562

Appendix A (92VS01COR)

In-House Activities

PERSONNEL:

Air Force Employees: John R. Jasperse, Ph.D., Physicist, 0.6 MY

Bamandas Basu, Ph.D., Physicist, 0.6 MY

Paul L. Rothwell, Ph.D., Physicist, 0.4 MY

John M. Retterer, Ph.D., Physicist, 0.2 MY

Daniel M. Ober, Ph.D., Physicist, 0.2 MY

On-Site Contractors: Nagendra Singh, Ph.D., Physicist, 0.5 MY

Neil Grossbard, M.S., Mathematician, 0.7 MY

Visitors:

Publications:

Articles in Peer Reviewed Publications

Basu, B., J. R. Jasperse, E. J. Lund and N. Grossbard (2011), Origin of ion-cyclotron turbulence in the downward Birkeland current region, Phys. Plasmas, 18, 022901.

Basu B. and N. J. Grossbard (2011), Ion-cyclotron instability in current-carrying Lorentzian (kappa) and Maxwellian plasmas with anisotropic temperatures: A comparative study, Phys. Plasmas., 18, 092106.

Gentile, L. C., W. J. Burke, P. A. Roddy, **J. M. Retterer**, and R. T. Tsunoda (2011), Climatology of Plasma Density Depletions Observed by DMSP in the Dawn Sector, J. Geophys. Res., 115, A07316, doi:10.1029/2010JA015324.

Jasperse, J. R., **B. Basu**, E. J. Lund and N. Grossbard (2011), Anomalous transport effects on the parallel E-field in downward auroral-current regions of the Earth's magnetosphere, J. Geophys. Res., 116, A00K11, doi:10.1029/2010JA016314.

Kelley, M. C., J. J. Makela, O. de La Beaujardière, and **J. M. Retterer** (2011), Convective Ionospheric Storms: A Review, Rev. Geophys., 49, RG2003, doi:10.1029/2010RG000340.

Maynard, N. C., C. J. Farrugia, W. J. Burke, **D. M. Ober**, J. D. Scudder, F. S. Mozer, C. T. Russell, H. Rème, C. Mouikis, and K. D. Siebert (2011), Interactions of the heliospheric current and plasma sheets with the bow shock: Cluster and Polar observations in the magnetosheath, J. Geophys. Res., 116, A01212, doi:10.1029/2010JA015872.

<u>Articles Submitted for Publication</u>

Farrugia, C. J., N. C. Maynard, N. V. Erkaev, W. Burke, P. E. Sandholt, **D. M. Ober**, A. Szabo, K. D. Siebert (2011), Disconnection of the Geomagnetic Tail, J. Geophys. Res., submitted.

Huang, C.-S., **J. M. Retterer**, O. de La Beaujardiere, P. A. Roddy, D. E. Hunton, J. O. Ballenthin, and R. F. Pfaff (2011), Observations and simulations of formation of broad plasma depletions through merging process, J. Geophys. Res., submitted.

Retterer J. M. and W. J. Burke (2011), The Origin of the Late-Night Plasma Bubbles Observed by C/NOFS, Geophys. Res. Lett, submitted.

Retterer, J. M., T. Fuller-Rowell, T.-W. Fang, and F. Wu (2011), Equatorial Plasma Bubbles Generated by the Fields of WAM, the Whole Atmosphere Model, Geophys. Res. Lett., submitted.

Rothwell, P. L., **J. R. Jasperse**, and N. J. Grossbard (2011), I. Comparison of penetration electric fields created by the solar wind with Jicamarca data using SWAGE, J. Geophys. Res., submitted.

Rothwell, P. L. (2011), II. Using SWAGE to estimate the annual rate of large vertical drifts at Jicamarca during 1998-2009, J. Geophys. Res., submitted.

Su, Y.-J., **J. M. Retterer**, R. F. Pfaff, P. A. Roddy, O. de La Beaujardière, and J. O. Ballenthin (2011), Assimilative Modeling of Observed Post-Midnight Equatorial Plasma Depletions in June 2008, J. Geophys. Res., submitted.

Invited Lectures

Jasperse J. R., and **B. Basu** (2011), Anomalous transport effects in auroras, ESSE Conference, Kona, Hawaii.

Jasperse J. R., and **B. Basu** (2010), What supports the parallel E field in downward Birkeland currents?, COSPAR Conference, Bremen, Germany.

Retterer J. M. (2010), Ionospheric Radio Scintillation: A diagnostic of ionospheric structure and plasma turbulence, lecture at BU CISM Summer School for Space Weather, Boston University.

Retterer J. M. (2010), Radio Scintillation over Africa, Fall AGU Meeting, San Francisco, CA.

Retterer J. M. (2011), PBMOD, CEDAR, Boulder, CO.

Retterer J. M. (2011), Equatorial Plasma Bubbles Generated by the Fields of WAM, the Whole Atmosphere Model, CEDAR, Boulder, CO.

Contributed Presentations

Basu, B. and N. J. Grossbard (2010), Ion cyclotron instability in current-carrying Lorentzian (Kappa) and Maxwellian plasmas with anisotropic temperatures: A comparative study, Fall AGU Meeting, San Francisco, CA.

Jasperse, J. R., **B. Basu** and E. Lund (2010), What supports the parallel electric field in the turbulent Birkeland current regions of the Earth's magnetosphere? A new paradigm, Fall AGU Meeting, San Francisco, CA

Lund, E., **J. R. Jasperse**, **B. Basu** and N. Grossbard (2010), Electrostatic ion-cyclotron turbulence and the self-consistent parallel electric field in downward auroral current regions, GEM Workshop, Snowmass Village, CO.

Retterer, J. M. (2010), Modeling the Climatology of Equatorial Plasma Bubbles Observed by DMSP Satellites Using Plasma Drifts Observed by C/NOFS, Fall AGU Meeting, San Francisco, CA.

Rothwell, P. L. and **J. R. Jasperse** (2010), Comparing the equatorial electric field using the Tsyganenko R1 and R2 models and the Hill-Siscoe polar cap potential as inputs, COSPAR international conference, Bremen, Germany.

Rothwell, P. L., **J. R. Jasperse**, and Neil J. Grossbard (2010), SWAGE and the transpolar potential as related to solar wind structure during 1998-2005, Fall AGU meeting, San Francisco, CA.

Professional Activities

J. R. Jasperse, B. Basu, P. L. Rothwell, J. M. Retterer, and D. M. Ober have each served as reviewers for one or more of the following during the past year: NASA, NSF, AFOSR, Annales Geophysicae, Astrophysical Journal, Geophysical Research Letters, IEEE Transactions on Plasma Science, Journal of Atmospheric and Terrestrial Physics, Journal of Geophysical Research, Journal of Spacecraft and Rockets, Physics of Plasmas, Planetary and Space Science, and Radio Science.

J. R. Jasperse has also served as Co-Editor of the Physics of Space Plasmas from 1981 to the present.

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