

Proposal for NSF GEM focus group “Multi-scale Electrodynamics of Magnetosphere-Ionosphere Interactions”

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Abstract

Observations from satellites, sounding rockets, and radars conducted in the high-latitude magnetosphere and the ionosphere frequently demonstrate intense electromagnetic fields, currents, and density structures which properties cannot be explained by studying the magnetosphere or the ionosphere separately. In particular, many questions of what define frequencies of intense, small-scale ULF waves, how and where these waves are generated, and how they are connected to electron acceleration, ion outflow, increase of plasma temperature, formation of density cavities, and many other phenomena related to discrete auroral arcs and more general questions of redistribution of the plasma content between the ionosphere and magnetosphere remain unanswered. These questions can be answered only if they will be studied considering the ionosphere and the magnetosphere as a single, coupled, complex system, without separating them apart. The objective of this NSF GEM working group will be to bring together current state-of-the-art in theory, modeling, and observations connecting ULF/ELF electromagnetic waves, magnetic field-aligned currents, disturbances in the plasma density, temperature, and electron and ion motion occurring in the auroral and subauroral regions and to develop a comprehensive numerical models with predictive capabilities explaining observations in quantitative detail.

Proposal

Electrodynamics of magnetosphere-ionosphere interactions at high altitude involving ultra-low-frequency (ULF) Alfvén waves have been studied extensively for almost 50 years [e.g., *Radoski*, 1967; *Cummings et al.*, 1969]. The initial goal of these studies was to explain geomagnetic pulsations in Pc5-Pc6 frequency range in the auroral zone as measured by ground-based magnetometers. Later, interest in Alfvén waves steadily increased when observations showed that discrete fluxes of keV electrons causing discrete aurora were often correlated with intense, localized electromagnetic disturbances, which were sometimes interpreted as dispersive Alfvén waves [*Xu et al.*, 1993; *Marklund et al.*, 1994; *Samson et al.*, 1991, 1996; *Lotko et al.*, 1998; *Chaston et al.*, 2002, 2003; *Figueiredo et al.*, 2005]. Observations also showed that these waves carry significant power fluxes toward the ionosphere [*Wygant et al.*, 2000; *Keiling et al.*, 2001] and frequently correlate with ion outflows, density cavities, and heating and redistribution of plasma between the ionosphere and the magnetosphere [e.g., *Lundin et al.*, 1994; *Stasiewicz et al.*, 1998; *McFadden et al.*, 1999; *Lynch et al.*, 1999; *Chaston et al.*, 2000, 2006], which meant that they play an extremely important role in magnetosphere-ionosphere (MI) interactions.

In classical studies of MI coupling, two parts of the system were considered separately, and the eigensolutions of one part have been used as a known parameter to find the solution of another part. The failure of this approach can be illustrated by the fact that despite numerous theoretical and experimental studies, one of the most fundamental questions of auroral studies, namely, what causes the formation of narrow, discrete auroral arcs, has not been answered yet [e.g., *Borovsky*, 1993]. Comprehensive reviews of these studies by *Stasiewicz et al.* [2000],

Pashmann et al. [2002], and *Keiling* [2009] reveal that they can be split into two groups depending on which part of the MI system is considered to be the “main maker” of the discrete aurora. The first group explains them with pure magnetospheric effects. Two of the most popular mechanisms from this group are 1) phase mixing of Alfvén waves propagating toward the ionosphere across strong transverse gradients in the Alfvén velocity [e.g., *Genot et al.*, 1999] and 2) magnetospheric field line resonances (FLRs) [*Southwood*, 1974, *Chen and Hasegawa*, 1974, *Samson et al.*, 1992].

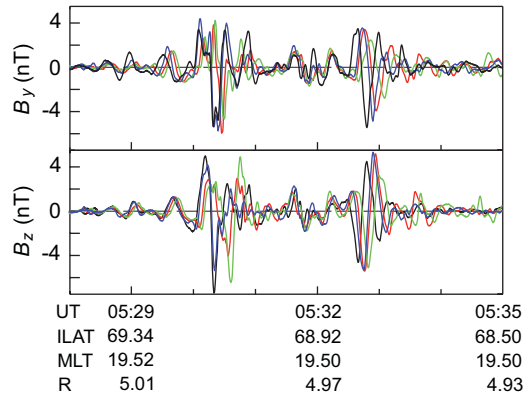


Figure 1. Small-scale ULF waves detected by the Cluster satellites in the magnetosphere [*Karlsson et al.*, 2004].

scale, intense, electromagnetic structures and discrete auroral arcs in the global magnetospheric resonator [*Sato*, 1978; *Watanabyet al.*, 1993; *Pokhotelov et al.*, 2002].

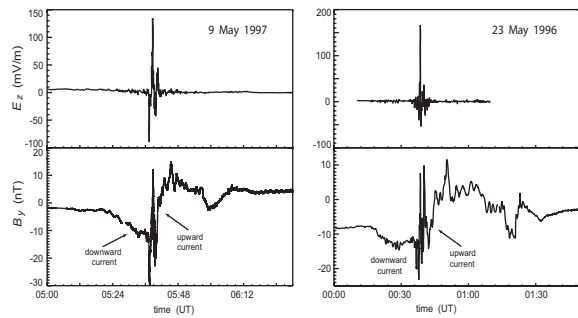


Figure 2. Electric and magnetic fields measured by the Polar satellite [*Keiling et al.*, 2005]

are 20-40 s, which is not consistent with periods associated with either the Alfvénic ionospheric resonator typical field line resonances or substorm onset related Pi2 oscillations” [*Karlsson et al.*, 2004]. A number of similar observations have been published by *Johansson et al.* [2004; 2005; 2006]. These observations are in qualitative agreement with data from the Polar satellite (see Figure 2), which demonstrate intense, small-scale electromagnetic structures in the plasma sheet boundary layer at the geocentric distance between 5 and 6 R_E [*Keiling et al.*, 2005].

The major progress in understanding spatial characteristics and temporal dynamics of electromagnetic and density structures at low altitudes has been achieved in simulations where

Another group of studies explains the formation of discrete arcs by the active ionospheric response (feedback) on dynamics of large-scale magnetic field-aligned currents (FACs) interacting with the ionosphere. Probably the most well-known example from this group is ionospheric feedback instability [*Atkinson*, 1970] inside the so-called ionospheric Alfvén resonator (IAR) [*Polyakov and Rapoport*, 1981; *Trakhtengerts and Fildstein*, 1984; *Lysak*, 1991] formed by the ionosphere and the maximum in the Alfvén speed at the altitude $\sim 1 R_E$. The ionospheric feedback instability has also been used to explain small-

Recent observations from FAST, Polar, and Cluster satellites reveal that there is a great number of waves and plasma phenomena in the magnetosphere which cannot be explained with neither of these two approaches. For example, Figure 1 (adopted from *Karlsson et al.* [2004]) shows small-scale electromagnetic structures

measured by Cluster satellites on 19 May 2002 at an altitude of 4 R_E . “The periods of these waves

the active ionospheric feedback has been self-consistently included in the models describing ULF waves in the magnetosphere [e.g., *Streltsov and Lotko*, 2004; 2005]. Figure 3, which is adopted from these studies, illustrates the generation of small-scale, intense electric fields and currents by such interactions. It shows that in excellent agreement with the observations illustrated in Figure 2, the small-scale waves are generated in the ionosphere on the boundary between the upward and downward current channels. This happens because a strong gradient in the ionospheric conductivity is formed in this location, and the perpendicular electric field in the ionosphere associated with the pair of FACs maximizes here.

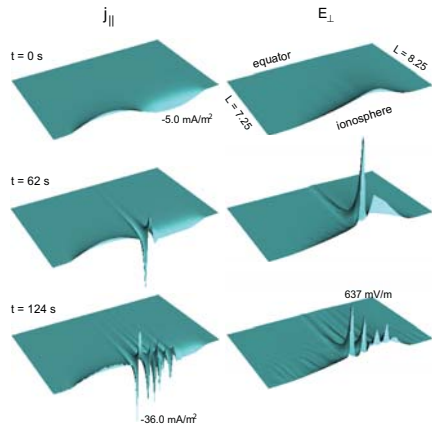


Figure 3. Interactions between two upward and downward large-scale FACs and the ionosphere. [*Streltsov and Lotko*, 2004].

Another example of a good, quantitative agreement between numerical simulations of small-scale Alfvén waves produced by the active interactions between large scale, quasi-static FACs and the ionosphere is shown in Figure 4 (reproduced from *Streltsov and Karlsson* [2008]). These simulations reproduce quite well structure of small-scale wave measured by the Cluster satellite illustrated in Figure 1.

Therefore, a self-consistent, multi-scale, multi-fluid electromagnetic coupling between the ionosphere and the magnetosphere is the key factor explaining various electromagnetic, luminous, and plasma structures in the ionosphere and the low-latitude magnetosphere. In this coupling, the ionosphere and the magnetosphere should be considered as a unified, complex system, and it should

be studied as such with corresponding numerical models.

We propose to form a new NSF-GEM working group, which goal will be to bring together current state-of-the-art in theory, modeling, and observations connecting ULF/ELF electromagnetic waves, magnetic field-aligned currents, disturbances in the plasma density, temperature, and electron and ion motion occurring in the auroral and subauroral regions and to develop a comprehensive numerical models with predictive capabilities explaining observations in quantitative detail. These models can be based on coupled existing multi-scale and multi-component numerical models describing dynamics of the ionospheric plasma (like the SAMI3 model, developed at NRL [*Huba et al.*, 2000]) and the propagation of multi-scale ULF waves/magnetic field-aligned currents in the magnetosphere (like the multifluid, dispersive MHD model developed at Dartmouth College [*Streltsov et al.*, 2008]), or they can be developed “from scratch”. **The ultimate goal of these comprehensive, multi-fluid, wave-**

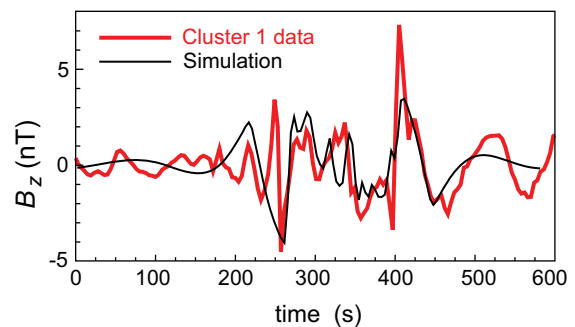


Figure 3. Simulations of small-scale electromagnetic structures measured by Cluster [*Streltsov and Karlsson*, 2008].

particle numerical models with predictive capabilities will be not just to EXPLAIN *post factum* relevant observations, but also to PREDICT with quantitative detail multi-scale dynamics of the electric fields, currents, and plasma in the low-altitude magnetosphere and the ionosphere for different geomagnetic conditions.

These models will be tested and tuned by comparing the numerical results and experimental data measured by satellites, sounding rockets, ground radar, magnetometers, and optical cameras in the auroral and sub-auroral zone. These observations include data from past/current satellite missions like FAST, Polar, Cluster, and THEMIS, as well as data from sounding rockets (CASCADE-2 and the future experiment, MICA), ground optical imagers, and radars.

The quantitative, detailed predictions from these models can be verified with results from active experiments in the near-Earth space environment. One example of such active experiments is the generation of large-amplitude ULF/ELF electromagnetic waves in the magnetosphere by heating the ionosphere with powerful RF transmitters (like High Frequency Active Auroral Research Program (HAARP) facility in Alaska). Preliminary results from these experiments already demonstrate the potential capability of such transmitters to generate large-amplitude waves detectable on the ground [e.g., *Blagovechenskay et al.*, 2000; *Streltsov et al.*, 2010] and on satellites [e.g., *Robinson et al.*, 2000].

Although we expect that these models will be developed, tuned, and tested with a great number of experimental results collected in the high latitude ionosphere and magnetosphere, the scope of applications of these models will be much broader. It is anticipated that with some minor modifications, primarily related to the background parameters, they will be used to explain results from past and current observations and to plan future satellite and sounding rocket missions at high latitudes (auroral and sub-auroral zones), middle latitudes (outer radiation belt), and low latitudes (low-latitude ionospheric Alfvén resonator, inner radiation belt, equatorial spread-F).

The results from this working group will have two major impacts on NSF-GEM activity:

1. These models will significantly contribute to the understanding of the most fundamental questions of multi-scale plasma and electrodynamic coupling between the ionosphere and the magnetosphere of the Earth.
2. The developed algorithms will be used as modules in global MHD simulations (GGCM), particularly in the so-called “gap” region, to provide a continuous, physical coupling between plasmas and electromagnetic fields in the ionosphere and the magnetosphere.

The activity period of this working group will be 4.5 years: 01/2011-06/2015

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