Proposal for an ISSI International Team in Space Science

Plasma Coupling in the Auroral Magnetosphere–Ionosphere System (POLARIS)

Abstract

Astrophysical context. Fundamental processes in the plasma universe are often organized by magnetic fields and accompanied by energetic particles. Examples range from planetary aurorae and solar activity to astrophysical shocks and pulsar magnetospheres (Fig. 1). Magnetic coupling works across very different plasma regimes and may yield complex interaction patterns. An ideal test-bed for studying this type of fundamental plasma coupling is the geospace environment where the collisionless magnetospheric plasma interacts with the collisional polar ionosphere through exchange of energetic particles, electromagnetic fields and currents. While the magnetosphere–ionosphere (M–I) coupling in the morning and evening sectors is often rather steady and can be well described by simplified current systems and electromagnetic fields, the transition region in the midnight sector (Fig. 2), known as the *Harang region (HR)*, is much more dynamic. The current and field configuration is complex and essentially three-dimensional, and the HR is believed to play an important role in the substorm cycle. The auroral M–I system is typically far from equilibrium and the substorm phases correspond to different conditions of the large scale energy flux through this system, associated with loading / unloading of magnetic energy. Even if a direct connection is difficult to establish at present, similar systems may occur quite generally in magnetized astrophysical plasmas.

Project objectives. The project aims to investigate the M–I coupling modes in the HR, by exploring the 3-D configuration and temporal evolution of the system during the various substorm phases. Specific issues to be examined are the configuration of the auroral current circuit, the plasma convection and electric field, the energy conversion and transfer between magnetosphere and ionosphere. Due to a unique constellation of spacecraft missions and ground facilities, it is possible at present to probe the plasma and electromagnetic field in all the key regions of the M–I coupling chain. Data from the THEMIS mission in the inner plasma sheet, from the Cluster spacecraft at the top side of the auroral acceleration region (AAR), from low altitude satellites like FAST, REIMEI, or DMSP below the AAR, and from ground based observatories, enable a comprehensive exploration, with emphasis on conjugate events. ISSI provides optimum conditions for the work of an international team holding the required expertise. The project will include three ISSI workshops devoted to: a) the collisional, ionospheric end of the M–I system; b) the collisionless, magnetospheric end of the M–I system; c) investigation of major conjunction events, with data available from all the key regions. The project, to be executed by a team of 10 people, is expected to materialize in case study papers, discussing HR specific M–I coupling features, as well as one concluding paper, providing a comprehensive view over the M–I coupling in the HR during the substorm cycle.

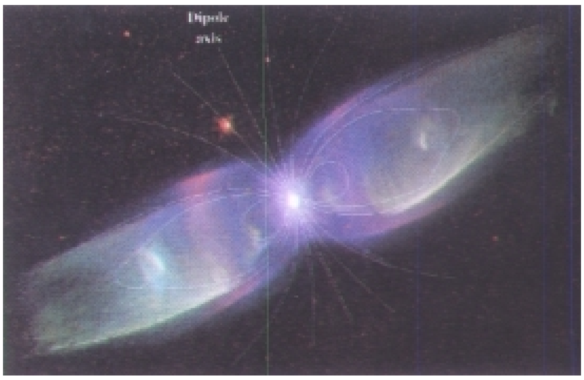

Figure 1. Hubble image of the planetary nebula M2-9, whose structure could be explained by a combined magnetic field-aligned plasma outflow and an equatorial expansion such as that in solar CMEs. From Lundin (2001).

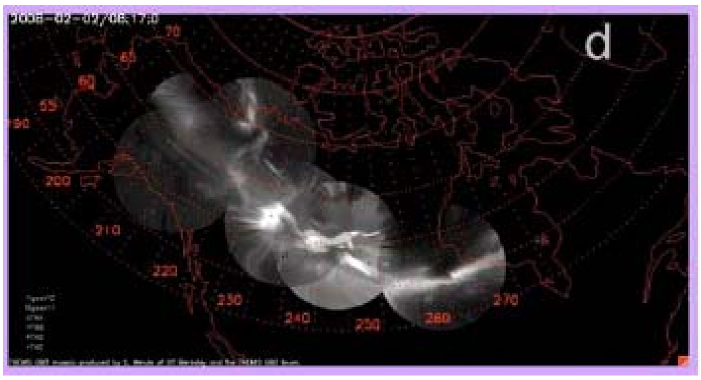

Figure 2. Images from THEMIS ground based observatories illustrating the spatial and temporal variability of the aurora near the midnight sector. The collage shows a snapshot of a highly dynamic aurora over northern Canada and Alaska. From Mende et al. (2009).

Scientific Rationale

Magnetic coupling and energetic particles in the plasma universe. Space-bourne solar observatories such as SOHO, TRACE, and STEREO have revealed the complex magnetic field structure in the solar atmosphere. Solar activity in general is organized by the magnetic field, including in particular the most dramatic events, such as coronal mass ejections and solar flares. The large-scale heliospheric magnetic field on the one hand, and the smaller-scale but much more intense geomagnetic field on the other, control the fluxes of galactic cosmic rays into the Earth's upper atmosphere. In the astrophysical context, energetic particles are associated with acceleration processes at magnetized shocks, with pulsar magnetospheres, and possibly even with jet formation in active galactic nuclei. Observations of all these phenomena, however, are of remote-sensing type and thus suffer e.g. from projection and propagation effects.

M-I coupling and the Harang region. The geospace environment is probed also *in-situ* by spacecraft missions, so we can achieve a more complete characterization of plasma regimes coupled by a magnetic field. Particle energization mechanisms potentially relevant in astrophysical context, most notably magnetic reconnection and parallel electric fields, make key contributions to magnetospheric dynamics and M–I coupling. From an observational point-of-view, the present situation is exceptionally fortunate as we have data from a fleet of scientific satellites in different magnetospheric regions and a network of ground-based observatories (Fig. 3). The project will focus on the investigation of the M–I coupling in the Harang region (HR), which makes the transition between the evening and morning sectors of the auroral oval, in terms of electric field and current configuration (Harang, 1946; Heppner, 1972; Baumjohann, 1983; Erickson et al, 1991; Koskinen and Pulkkinen, 1995; Amm et al., 2000; Lyons et al., 2003, 2009; Gkioulidou et al., 2009). The auroral activity in the HR (e.g. Nielsen and Greenwald, 1979; Zou et al., 2009) is thought to be closely associated with the substorm onset, but the details of this association are not yet fully understood (Weygand et al., 2008). M–I coupling in the HR covers a broad range of spatial and temporal scales and is achieved essentially by field-aligned currents (FACs) and Alfvén waves. A number of review papers on FACs and their M–I coupling role are included in Ohtani et al. (2000), while recent reviews on Alfvén waves are provided by Chaston (2006) and Keiling (2009). Unlike the modelling and simulation work, the observational evidence was limited so far by the one-point character of the satellite measurements, in fortunate cases conjugated with ground data. This setup allows to analyze M-I coupling processes essentially along the magnetic field, i.e., in one spatial dimension only. Measurements along the track of polar-orbiting satellites add latitude as a second dimension particularly useful in studies of stable east-west aligned auroral arcs. It is only recently that multi-point missions like THEMIS (Angelopoulos, 2008) and Cluster (Escoubet et al., 2001) have opened the gate toward 3-D examinations of the M–I coupling (e.g. Keiling et al., 2009).

The ionospheric, collisional end of the HR. The currents and plasma flow at the ionospheric end of the HR (Fig. 4a) are easiest to investigate. The closure of the FAC is realized both in meridional and longitudinal direction, reflecting the two topologies of the M–I current system (Fig. 4b), *Type 1* and *Type 2*, introduced by Boström (1964). Unlike in the evening and morning sectors of the auroral oval, where *Type 2* dominates – with meridional (perpendicular to the arc / oval) electric fields, FACs connected by meridional Pedersen currents, and divergence free longitudinal Hall electrojets – a mixed and complicated configuration is often observed in the HR, not yet fully explored and understod. The electric field is tilted westward, the FAC can be coupled to Pedersen and Hall currents flowing both in meridional and longitudinal direction (Marghitu et al., 2004, 2009), the FAC closure mechanisms can be both local and remote, depending on the location and substorm phase (Amm and Fujii, 2008). The plasma flow pattern can vary between a sharp shear reversal, associated with an upward FAC (as sketched in Fig. 4a), during the substorm expansion phase, and a rotational reversal, associated with weak (or missing) upward FAC, during quiet conditions (Kamide, 1978).

The magnetospheric, collisionless end of the HR. As already pointed out, a thorough examination of the HR magnetospheric 'headprint' was not possible until recently. The HR is believed to map to the inner plasma sheet, at altitudes of about 10 Earth radii (R_E), and a number of studies have brought convincing arguments in this respect (Erickson et al., 1991; Lyons et al., 2003, 2009; Gkioulidou et al., 2009). Several M–I coupling and substorm theories (e.g. Rothwell et al., 1988; Lui, 1991; Kan, 1993; Haerendel, 2009) suggest that the substorm onset is triggered by processes in this region, but the exact nature and sequence of these processes are matters of active research – and provide some of the key questions to be answered by the THEMIS mission. One such question, for example, is the load or generator character of the inner plasma sheet at substorm onset (e.g. Haerendel, 2009) – which could be addressed now based on multi-point data from THEMIS and Cluster, and on the newly developed techniques to process these data.

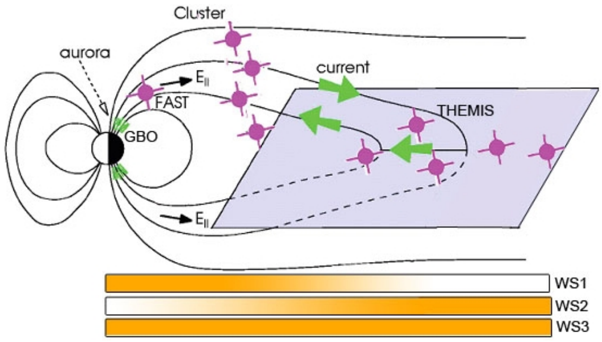

Figure 3. Sketch of the FAST, Cluster, and THEMIS spacecraft (not to scale), together with the GBOs, in the configuration to be used in the project. FAST (or another low altitude satellite) is located bellow the bottom boundary of the AAR (indicated by E_{II}), Cluster is close to perigee and near the AAR top side, while the three inner THEMIS satellites probe the inner plasma sheet around the equatorial plane. The three stripes at the bottom indicate the focus of the three ISSI workshops (WS1, WS2, WS3), namely (1) the low-altitude, collisional end, (2) the high-altitude, collisionless end, and (3) the whole M–I system.

Scientific goals

The central goal of the project is to explore the *3-D configuration* of the M–I coupled system in the HR and its *temporal evolution* by using the rich database of low altitude and ground data, as well as the multi-point capabilities of the Cluster and THEMIS missions. We expect that the features of the M–I coupling in the HR will be best organized in terms of phases of a magnetospheric substorm. Key issues to be addressed for each substorm phase are listed below, followed by detailed specific questions for each issue:

a. Three-dimensional topology of the current circuit;
b. Configuration of plasma convection and electric field;
c. Energy conversion and transfer between the magnetosphere and ionosphere.

a) What are the paths of the electrical current in the coupled plasma system in the HR?

At the ionospheric end of the current system we shall check if the FAC closure is i) meridional / longitudinal (perpendicular / parallel to the arc); ii) local / remote, iii) achieved by Pedersen / Hall current; iv) driven by conductance / electric field variations (Kamide and Kokubun, 1996) – in order to find typical ‘mixtures’ of the *Type 1* / *Type 2* configurations. At the magnetospheric end of the current system we shall be interested by the current magnitude, its radial / azimuthal orientation, and its driver – flow braking (Shiokawa et al., 1997) or pressure gradient (Birn et al., 1999). For the major conjunction events we shall check if the current at the magnetospheric end is consistent with the ionospheric closure topology, namely if the magnetospheric current is radial / azimuthal when the FAC closure is meridional / longitudinal. We shall also try to separate the DC and Alfvénic components of the current at the ionospheric, AAR, and magnetospheric level.

b) How do the electric field and the convection flow pattern change with the substorm phase?

The electric field match between the magnetosphere and ionosphere controls the nature of M-I coupling. We shall explore the spatial and temporal scales and also the causes of ‘imperfect’ M–I coupling, in particular the decoupling introduced by the AAR, the mismatch under non-stationary conditions, and the effect of the Alfvén waves. The relationship between the electric field and plasma flow will be investigated as well. At low altitude the frozen-in condition, $\mathbf{E}+\mathbf{V}\times\mathbf{B}=0$, is expected to hold, but in the magnetosphere violations were identified during the substorm expansion phase (McFadden et al., 2008). One particularly interesting question is to check the mapping of the HR in the magnetosphere, which we plan to do by comparing multi-point plasma flow data. Operationally, the electric field is essential for deriving the ionospheric current in (a), by Ohm’s law, $\mathbf{J}=\Sigma\bullet\mathbf{E}$ (with Σ the conductance tensor), as well as the local energy conversion, $\mathbf{E}\bullet\mathbf{J}$, and Poynting flux, $\mathbf{E}\times\mathbf{H}$, in (c).

c) How does the energy balance in the system change with the substorm phase?

The energy balance in the M–I system is the result of several energy conversion and transfer steps. In the magnetosphere, we shall check the sense of the energy conversion. Through the evaluation of $\mathbf{E}\bullet\mathbf{J}$ (Marghitu et al., 2006, 2009b; Hamrin et al., 2006, 2009a, 2009b) we shall check if the converted energy is mainly related to the bulk flow or to the thermal motion, and whether $\mathbf{E}\bullet\mathbf{J}$ is dominated by the radial term, E_rJ_r, or by the azimuthal term, $E_\phi J_\phi$. At low altitudes we plan to identify the relative contributions of Joule heating and particle precipitation to energy dissipation, and to compare the two terms under stationary and non-stationary conditions – when it is more likely to see ionospheric closure of the FAC by Hall currents and therefore a reduction of the Joule effect. At times, the ionosphere can behave as a generator, feeding energy to the magnetosphere – this ‘active’ role of the ionosphere will be investigated as well. We shall also explore the energy transfer, whose main vehicles are the Poynting and particle energy fluxes. Examination of Polar and FAST data showed that above / below the AAR the Poynting / particle energy flux dominates (Chaston, 2006) – it will be interesting to check this finding for selected events, at various stages of the substorm cycle.

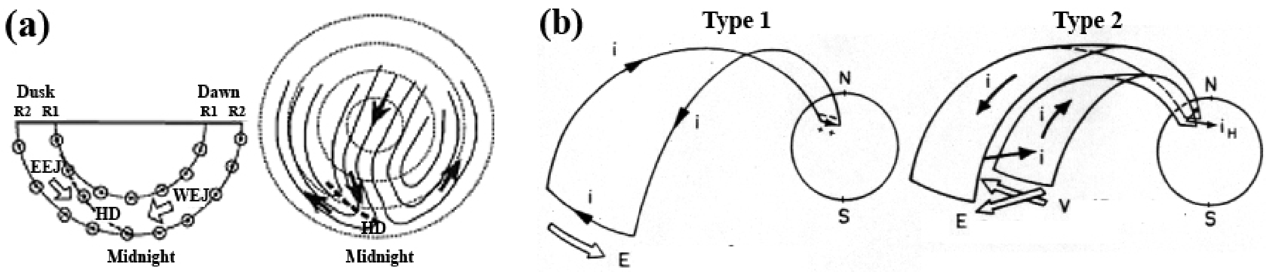

Figure 4. (a) Schematic picture of the ionospheric current and plasma flow in the HR (from Koskinen and Pulkkinen, 1995). EEJ / WEJ and R1 / R2, indicate the eastward / westward electrojet and Region 1 / Region 2 field-aligned current. (b) The two configurations of the auroral current circuit introduced by Boström (1964).

Implementation

At present, a unique constellation of spacecraft missions (Fig. 3) and ground based observatories (GBOs) provides comprehensive information from all the key regions of the M–I coupling chain, namely the inner plasma sheet, the AAR, and the ionosphere. The project relies on (northern hemisphere) winter data measured the THEMIS spacecraft in the inner plasma sheet, by the Cluster spacecraft closely above the AAR, and by the FAST satellite (Pfaff et al., 2001) below the AAR. Low altitude data from DMSP and REIMEI may add valuable information to the major conjunction events, when FAST is not available. Ground data from the THEMIS GBOs, MIRACLE network, EISCAT and SuperDARN radars, will provide ionospheric information. Depending on the results to be obtained, summer events could be investigated as well, to explore seasonal effects (this time with Cluster in the inner plasma sheet). The needed data are openly available and the team members have the required expertise to use it, as indicated in the ‘Team’ section.

The project will be organized as follows. We first study the two main elements of the system (ionosphere and magnetosphere) separately, and then bring the findings together to address the big picture. The emphasis will be on conjugate data. Each of these units will make the object of an ISSI workshop (WS).

The collisional element: ionospheric electrodynamics (WS1)

The first workshop will focus on the examination of 29 conjunction events from 1997 and 1998, between FAST and auroral cameras flown on a jet spacecraft (Stenbaek-Nielsen et al., 1998). The magnetic local time of all these events is around 21, which makes them ideal for a systematic examination of ionospheric electrodynamics in the HR. Relevant FAST data, the conjugate optical data, and geophysical indices (AE, Dst) for these events have already been collected together in two pdf files (one for 1997 and one for 1998) available at http://gpsm.spacescience.ro/ftp/om/polaris/2010/. A preliminary evaluation of the data (included in the pdf files) shows both complicated, mixed events, most of them in 1997, and rather ‘standard’, *Type 2* events, most of them in 1998. During the first ISSI workshop the individual events and possible reasons for the systematic difference between 1997 and 1998 will be examined in detail. Although these events are not conjugate to Cluster or THEMIS, the quality of the database is rather unique and we expect that the results will guide the further selection of magnetospheric events – to be explored during the second workshop. The low altitude data will be investigated by using the recently developed ALADYN method (Marghitu et al., 2004, 2009), based on satellite data, as well as well established inversion techniques, based on ground magnetic and electric field data (e.g. Inhester et al., 1992; Amm, 1995).

The collisionless element: flows, fields and particles in the magnetosphere (WS2)

When writing this proposal, THEMIS proceeds to the third tail season, each season covering about three months (the first two seasons at the beginning of 2008 and 2009), and conjugate ionospheric information is available from the comprehensive network of GBOs deployed in Canada and the northern USA. The three inner THEMIS probes visit the inner plasma sheet on a daily basis, while Cluster passes closely above the AAR every 2.4 days, in about the same time sector with THEMIS. The THEMIS team compiled comprehensive lists of THEMIS / Cluster, THEMIS / FAST, and THEMIS / Reimei conjunctions, as well as of substorm events, available at ftp://justice.ssl.berkeley.edu/events/. The size and orientation of the triangle formed by the three inner THEMIS probes change during the mission, providing conditions for exploring the inner plasma sheet on multiple scales. Analysis tools for multi-point data developed within the Cluster community (Paschmann and Daly, 1998, 2008) have been recently adapted to three-spacecraft measurements (Vogt et al., 2009), becoming suitable to be used with THEMIS data. This makes possible the evaluation of the gradients needed in the project, for example $\nabla\times\mathbf{B}$, the pressure gradient, or the Poynting flux divergence.

The coupled system: study of major conjunction events and comparison with models (WS3)

The project will be concluded by a detailed examination of major conjunction events, ideally at least one event for each substorm phase. The expected outcome is a comprehensive picture of the M–I coupling modes in the Harang region, depending on the substorm phase. We hope to identify transient effects during substorm onset, possibly mediated through Alfvénic disturbances propagating along the ambient magnetic field lines (e.g., Vogt et al., 1999). Several plasma wave detection and identification techniques for multipoint measurements exist, e.g., the wave telescope / k-filtering approach (for a review see Pinçon and Glassmeier, 2008) or the recently developed wave surveyor technique (Vogt et al., 2008). The observed events will be compared with established quasi-static and transient M–I coupling models (e.g. Lysak, 1990; Vogt, 2002; Paschmann et al., 2003). The traditional 'active' role of the magnetosphere and 'passive' role of the ionosphere will be examined for each substorm phase.

Timeliness

The project takes advantage of a unique constellation of satellites, concentrated in critical points of the M–I coupling chain. The multi-point measurements of Cluster and THEMIS, assisted by a dense network of GBOs and low altitude satellites, together with the mature stage of the multi-spacecraft data analysis methods, open unprecedented opportunities to investigate the temporal evolution and spatial configuration of the M–I coupling, as well as its role in substorm physics.

Expected output

We anticipate increased visibility of the M–I coupling and Harang region in publications and conference talks. The completion of the tasks outlined above is expected to materialize in several case study papers. The project findings will be summarized in a concluding review paper.

Added value by ISSI

ISSI provides optimum conditions for getting together an international team holding appropriate expertise and for the required brain storming effort. While the suggested topic is too large to be handled in a conference session, we believe that it fits the size and time frame of the proposed ISSI team, and can be properly addressed by the sustained interaction within the team as well as the foreseen sequence of workshops.

Team

Ten people have confirmed their participation in the project, to be co-chaired by Octav Marghitu and Joachim Vogt. The relevant expertise is briefly indicated below. Contact information and CVs are attached.

Olaf Amm (Finland):	Ionospheric electrodynamics, M–I coupling, Cluster and MIRACLE data.
Harald U. Frey (USA):	Auroral physics, M–I coupling, optical and THEMIS data.
Maria Hamrin (Sweden):	Auroral physics, M–I coupling, multi-spacecraft techniques.
Tomas Karlsson (Sweden):	Ionospheric electrodynamics, M–I coupling, Cluster data.
Andreas Keiling (USA):	Alfvén waves, M–I coupling, Cluster and THEMIS data.
Octav Marghitu (Romania):	Ionospheric electrodynamics, M–I coupling, Cluster and FAST data.
Rumi Nakamura (Austria):	Tail and substorm physics, M–I coupling, Cluster and THEMIS data.
Hans Nilsson (Sweden):	Ion outflow, M–I coupling, Cluster and EISCAT data.
Joshua Semeter (USA):	M–I coupling, optical data, radar and optical data.
Joachim Vogt (Germany):	M–I coupling, multi-spacecraft techniques, Cluster and optical data.

Schedule

Workshop 1, fall 2010: Discussion of selected events with emphasis on the collisional, ionospheric end of the M–I system. Case studies appropriate for publication. Streamlining of further work.

Workshop 2, spring 2011: Discussion of selected events, with emphasis on the collisionless, magnetospheric end of the M–I system. Case studies appropriate for publication.

Workshop 3, spring 2012: Discussion of major conjunction events. M–I coupling modes and relevance for M–I coupling models, depending on the substorm phase. Discussion of the concluding review paper.

Financial support and facilities required from ISSI

Standard support, as described in Section 6 of the "Call for proposals". Living expenses in Bern for the team members (10 people), as well as reimbursement of travel expenses for one of the co-chairs or for another team member. Room, projector, Internet access, coffee machine.

Appendix A – References

Amm, O (1995), Direct determination of the local ionospheric Hall conductance distribution from two-dimensional electric and magnetic field data: Application of the method using models of typical ionospheric electrodynamic situations, J. Geophys. Res., 100, 21473–21488.

Amm, O., P. Janhunen, H.J. Opgenoorth, T.I. Pulkkinen, and A. Viljanen (2000), Ionospheric shear flow situations observed by the MIRACLE network, and the concept of Harang discontinuity, in: Magnetospheric current systems (eds. S. Ohtani, R. Fujii, M. Hesse, and R.L. Lysak), Geophys. Monograph 118, AGU, 227–236.

Amm, O., and R. Fujii (2008), Separation of Cowling channel and local closure currents in the vicinity of a substorm breakup spiral, J. Geophys. Res., 113, A06304, doi:10.1029/2008JA013021.

Angelopoulos, V. (2008), The THEMIS Mission, Space Sci. Rev., doi: 10.1007/s11214-008-9336-1.

Baumjohann, W. (1983), Ionospheric and field-aligned current systems in the auroral zone: A concise review, Adv. Space Res., 2, 55–62.

Birn, J., M. Hesse, G. Haerendel, W. Baumjohann, and K. Shiokawa (1999), Flow braking and the substorm current wedge, J. Geophys. Res., 104, 19,895– 19,904, doi:10.1029/1999JA900173.

Boström, R. (1964), A model of the auroral electrojets, J. Geophys. Res., 69, 4983–4999.

Chaston, C.C. (2006), ULF waves and auroral electrons, in: Magnetospheric ULF waves: Synthesis and new directions (eds. K. Takahashi, P.J. Chi, R.E. Denton, and R.L. Lysak), Geophys. Monograph 169, AGU, 239–257.

Erickson, G.M., R.W. Spiro, and R.A. Wolf (1991), The physics of the Harang discontinuity, J. Geophys. Res., 96, 1633–1645.

Escoubet, C. P., M. Fehringer, and M. Goldstein (2001), The Cluster mission, Ann. Geophys., 19, 1197–1200.

Gkioulidou, M., C.-P. Wang, L.R. Lyons, and R.A. Wolf (2009), Formation of the Harang reversal and its dependence on plasma sheet conditions: Rice convection model simulations, J. Geophys. Res., 114, A07204, doi:10.1029/2008JA013955.

Haerendel, G. (2009), Poleward arcs of the auroral oval during substorms and the inner edge of the plasma sheet, J. Geophys. Res., 114, A06214, doi:10.1029/2009JA014138.

Hamrin, M., O. Marghitu, K. Rönnmark, B. Klecker, M. André, S. Buchert, L.M. Kistler, J. McFadden, H. Rème, and A. Vaivads (2006), Observations of concentrated generator regions in the nightside magnetosphere by Cluster/FAST conjunctions, Ann. Geophys., 24, 637–649.

Hamrin, M., P. Norqvist, O. Marghitu, S. Buchert, B. Klecker, L.M. Kistler, and I. Dandouras (2009), Occurrence and location of concentrated load and generator regions observed by Cluster in the plasma sheet, Ann. Geophys., 27, 4131–4146.

Hamrin, M., P. Norqvist, O. Marghitu, A. Vaivads, B. Klecker, L.M. Kistler, and I. Dandouras (2009), Scale size and life time of energy conversion regions observed by Cluster in the plasma sheet, Ann. Geophys., 27, 4147-4155.

Harang, L. (1946), The mean field of disturbance of polar geomagnetic storms, Terrest. Magn. Atm. Electr., 51, 353–380.

Heppner, J.P. (1972), The Harang discontinuity in auroral belt ionospheric currents, Geofys. Publ., 29, 105.

Iijima, T., and T.A. Potemra (1978), Large-scale characteristics of field-aligned currents associated with substorms, J. Geophys. Res., 83, 599–615.

Inhester, B., J. Untiedt, M. Segatz, and M. Kürschner (1992), Direct determination of the local ionospheric Hall conductance distribution from two-dimensional electric and magnetic field data, J. Geophys. Res., 97, 4073-4083.

Kamide, Y. (1978), On current continuity at the Harang discontinuity, Planet. Space Sci., 26, 237.

Kamide, Y., and S. Kokubun (1996), Two-component auroral electrojet: Importance for substorm studies, J. Geophys. Res., 101, 13,027– 13,046.

Kan, J. (1993), A global magnetosphere–ionosphere coupling model of substorms, J. Geophys. Res., 98, 17263–17275.

Keiling, A. (2009), Alfvén waves and their roles in the dynamics of the Earth's magnetotail: A review, Space Sci. Rev., 142, 73–156, doi: 10.1007/s11214-008-9463-8.

Keiling, A., V. Angelopoulos, A. Runov, J. Weygand, S.V. Apatenkov, S. Mende, J. McFadden, D. Larson, O. Amm, K.-H. Glassmeier, and H.U. Auster (2009), Substorm current wedge driven by plasma flow vortices: THEMIS observations, J. Geophys. Res., 114, A00C22, doi:10.1029/2009JA014114.

Koskinen, H., and T. Pulkkinen (1995), Midnight velocity shear zone and the concept of Harang discontinuity, J. Geophys. Res., 100, 9539–9547.

Lui, A.T.Y. (1991), A synthesis of magnetospheric substorm models, J. Geophys. Res., 96, 1849-1856.

Lundin, R. (2001), Auroral particle acceleration processes: The legacy of Hannes Alfvén, Phys. Chem. Earth (C), 26 (1–3), 13–23.

Lyons, L., C.-P. Wang, and T. Nagai (2003), Substorm onset by plasma sheet divergence, J. Geophys. Res., 108, 1427, doi:10.1029/2003JA010178.

Lyons, L.R., C.-P. Wang, M. Gkioulidou, and S. Zou (2009), Connections between plasma sheet transport, Region 2 currents, and entropy changes associated with convection, steady magnetospheric convection periods, and substorms, J. Geophys. Res., 114, A00D01, doi:10.1029/2008JA013743.

Lysak, R. (1990), Electrodynamic coupling of the magnetosphere and ionosphere, Space Sci. Rev., 52, 33–87.

Marghitu, O., B. Klecker, G. Haerendel, and J. McFadden (2004), ALADYN: A method to investigate auroral arc electrodynamics from satellite data, J. Geophys. Res., 109, A11305, doi:10.1029/2004JA010474.

Marghitu, O., M. Hamrin, B. Klecker, A. Vaivads, J. McFadden, S. Buchert, L.M. Kistler, I. Dandouras, M. André, and H. Rème (2006), Eperimental investigation of auroral generator regions with conjugate Cluster and FAST data, Ann. Geophys., 24, 619–635.

Marghitu, O., T. Karlsson, B. Klecker, G. Haerendel, and J. McFadden (2009a), Auroral arc and oval electrodynamics in the Harang region, J. Geophys. Res., 114, A03214, doi:10.1029/2008JA013630.

Marghitu, O., M. Hamrin, B. Klecker, K. Rönnmark, S. Buchert, L.M. Kistler, M. André, and H. Rème (2009b), Cluster observations of energy conversion regions in the plasma sheet, in: The Cluster Active Archive (eds. H. Laakso, M. Taylor, C.P. Escoubet), Springer series on Astrophysics and Space Science Proceedings, 453–459.

McFadden, J.P., C.W. Carlson, D. Larson, J. Bonnell, F. Mozer, V. Angelopoulos, K.-H. Glassmeier, U. Auster (2008), THEMIS ESA first science results and performance issues, Space Sci. Rev., doi: 10.1007/s11214-008-9433-1.

Mende, S., V. Angelopoulos, H.U. Frey, E. Donovan, B. Jackel, K.-H. Glassmeier, J.P. McFadden, D. Larson, and C.W. Carlson (2009), Timing and location of substorm onsets from THEMIS satellite and ground based observations, Ann. Geophys., 27, 2813–2830.

Nielsen, E., and R. Greenwald (1979), Electron flow and visual aurora at the Harang discontinuity, J. Geophys. Res., 84, 4189–4200.

Ohtani, S.-I., R. Fuji, M. Hesse, and R.L. Lysak (eds) (2000), Magnetospheric current systems, Geophys. Monograph 118, AGU, Washington DC.

Paschmann, G., and P. Daly (eds.) (1998), Analysis methods for multi-spacecraft data, ISSI Scientific Report Series, SR-001.

Paschmann, G., S. Haaland, and R. Treumann (eds.) (2003), Auroral plasma physics, ISSI Space Science Series, Vol. 15.

Paschmann, G., and P. Daly (eds.) (2008), Multi-spacecraft analysis methods revisited, ISSI Scientific Report Series, SR-008.

Pfaff, R., C. Carlson, J. Watzin, D. Everett, and T. Gruner (2001), An overview of the Fast Auroral SnapshoT (FAST) satellite, Space Sci. Rev., 98, 1–32.

Pinçon, J.-L., and K.-H. Glassmeier (2008), Multi-spacecraft methods of wave field characterisation, in: Multi-spacecraft analysis methods revisited, (eds. G. Paschmann and P. Daly), ISSI SR-008, 47–54.

Rothwell, P., L. Block, M. Silevitch, and C.-G. Fälthammar (1988), A new model for substorm onsets: The pre-breakup and triggering regimes, Geophys. Res. Lett., 15, 1279–1282.

Shiokawa, K., W. Baumjohann, and G. Haerendel (1997), Braking of high-speed flows in the near-Earth tail, Geophys. Res. Lett., 24, 1179– 1182, doi:10.1029/97GL01062.

Stenbaek-Nielsen, H., T. Hallinan, D. Osborne, J. Kimball, C. Chaston, J. McFadden, G. Delory, M. Temerin, and C. Carlson (1998), Aircraft observations conjugate to FAST: Auroral are thicknesses, Geophys. Res. Lett., 25, 2073–2076.

Vogt, J., G. Haerendel, and K.-H. Glassmeier (1999), A model for the reflection of Alfvén waves at the source region of the Birkeland current system: The tau generator, J. Geophys. Res., 104, 269–278.

Vogt, J. (2002), Alfvén wave coupling in the auroral current circuit, Surveys in Geophysics, 23, 335–377.

Vogt, J., Y. Narita, and O.D. Constantinescu (2008), The wave surveyor technique for fast plasma wave detection in multi-spacecraft data, Ann. Geophys., 26, 1699–1710.

Vogt, J., A. Albert, and O. Marghitu (2009), Analysis of three-spacecraft data using planar reciprocal vectors: methodological framework and spatial gradient estimation, Ann. Geophys., 27, 3249–3273.

Weygand, J., R. McPherron, H. Frey, O. Amm, K. Kauristie, A. Viljanen, and A. Koistinen (2008), Relation of substorm onset to Harang discontinuity, J. Geophys. Res., 113, A04213, doi:10.1029/2007JA012537.

Zou, S., L.R. Lyons, C.-P. Wang, A. Boudouridis, J.M. Ruohoniemi, P.C. Anderson, P.L. Dyson, and J.C. Devlin (2009), On the coupling between the Harang reversal evolution and substorm dynamics: A synthesis of SuperDARN, DMSP, and IMAGE observations, J. Geophys. Res., 114, A01205, doi:10.1029/2008JA013449.