IONOSPHERE-MAGNETOSPHERE-THERMOSPHERE SCIENCE IN CANADA AND OPPORTUNITIES FOR SWARM

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ABSTRACT/RESUME

With the world's largest accessible land mass under the auroral oval, Canada has exploited its unique position by deploying wide-spread instrument arrays dedicated to the study of high-latitude geospace. The Canadian GeoSpace Monitoring (CGSM) array is currently being upgraded, and during the Swarm mission will cover a large portion of Canada with magnetic, optical, and radio (ionosonde, riometer, and Canadian SuperDARN) measurements. The THEMIS ground-based camera and magnetometer array will augment this coverage further at 20 additional sites throughout Canada, and at higher time resolution. Together with these arrays and others throughout the world, Swarm's precision multi-point measurements of magnetic fields, electric fields and plasma parameters will bring a powerful and comprehensive new dataset to studies of auroral electrodynamics and auroral arc formation, global ionospheric current and convection systems, low-frequency plasma instabilities, magnetosphere-ionosphere-thermosphere coupling, and ion heating and outflow.

1. SCIENTIFIC THEMES

Swarm will be able to address a broad spectrum of scientific questions in regions ranging from the Earth's core to the magnetosphere. For this reason, it will operate more as a facility with a wide range of users than as a targeted scientific mission. The scientific themes reviewed below explore aspects of the scientific potential of Swarm in the area of I-T-M science. The original Swarm proposal to ESA describes the basic scientific motivations of the mission; this document emphasizes scientific questions of particular relevance to the Canadian space research program, through the scientific interest of its participants and collaborators, and through the ground and space-based instrumentation that Canada can bring to bear on Swarm-related science.

1.1. Auroral electrodynamics and field-line resonances

What causes auroral arcs? What is the role of field-line resonances? What is the role of cross-arc plasma drift? How do auroral arcs relate to field-aligned currents, convection systems and their boundaries?

Auroral arcs are basic and characteristic structures through which energy originating in the solar wind is channeled to and dissipated in the upper atmosphere. They result from an interplay between electric currents and electric fields structured in the magnetosphere, and the dissipating (though active) ionosphere. To this day, many of the most basic questions surrounding auroral arc formation remain unanswered, including the nature of the generator that powers them, the cause of their characteristic shapes and scale sizes, the rising/falling latitudinal dependence associated with "inverted-V" electron acceleration, the reason arcs often form as multiple parallel curtains, and others.

There are many theories of auroral arc formation, however few make specific, quantitative predictions of the arc electromagnetic field structure, and still fewer do so self-consistently. In fact only one type of theory - field-line resonance (FLR) theory - starts with a specific and plausible source (compressional-mode Alfvén waves in the magnetosphere) and makes quantitative predictions of the electromagnetic field structure, plasma density, electron acceleration, and other parameters [1]. Quantitative comparisons with fields measured in-situ have shown very good agreement in a few cases [2], and although some arcs indeed oscillate at FLR frequencies [3,4], it remains to be determined through observations how generally FLR theory applies to arcs.

A second class of arc theory relies on a component of plasma convection normal to elongated arc structures and field-aligned current sheets [5,6], also resulting in specific predictions of electromagnetic structure of arcs and, in some cases, electron acceleration. The cross-arc or "proper" velocity of these arcs is thought to be of the order of tens or hundreds of m/s. However, the proper drift is superimposed on much higher plasma drifts tangential to the arc, making its measurement elusive. Despite innovative attempts [7,8], it remains unclear whether such proper motion is present always or only sometimes. By providing inertial-frame drift vectors accurate to 50 m/s or better, Swarm will be the first satellite mission capable of resolving, on a regular basis, such subtle relations between electric and magnetic fields in the vicinity of auroral arcs, and therefore of testing both the basic assumption (cross-arc plasma drift) and predictions (electromagnetic field structure) of this type of theory.

Although Swarm will carry no instruments to measure charged particle precipitation, extensive ground-based camera arrays in Canada will be able to image auroral forms through which Swarm will fly (see CGSM and THEMIS below.) We note that, at 16 samples/s, the Swarm electric field instrument will not be able to resolve the smallest scales (~100 m) associated with auroral arcs. Nevertheless, Swarm's new generation of field resolution will bring significant and new information to bear on the still-unexplained phenomenon of mesoscale auroral arc formation.

1.2. Magnetosphere-Ionosphere-Thermosphere energy coupling through Poynting flux

The solar wind/magnetosphere dynamo generates as much as 10^{13} W of electrical power in geospace. Where and how is this electromagnetic energy dissipated? How does the neutral atmosphere respond?

The Poynting vector measured on a flux tube above the ionosphere is, to a good approximation, equal to the net power dissipated inside that flux tube below the satellite [9]:

$$\mathbf{E} \times \mathbf{H} = \int_{ionosphere} \mathbf{J} \cdot \mathbf{E} dh = \int_{ionosphere} \sigma_P \mathbf{E}^2 dh = \textstyle\sum_P \mathbf{E}^2 \quad (1)$$

where Σ_P is the height-integrated Pedersen conductivity of the ionosphere. That is, Poynting flux measures height-integrated energy dissipation via "remote sensing", and allows local and, by integrating over orbital trajectories, global estimates of Joule dissipation in the ionosphere/thermosphere. These estimates in turn serve to characterize both magnetospheric activity and ionospheric forcing and heating of the neutral atmosphere. In some cases, thermospheric winds can dominate magnetospheric forcing, forming a neutral wind dynamo that generates a telltale upward Poynting vector [10,11].

Typical Poynting fluxes found in the active auroral zone are of order 1-100 mW/m^2. **Swarm will be able to measure 3-D Poynting vectors to an accuracy of 1 μW/m^2.** This level is characteristic of small perturbations to the quiet ionosphere, for example internal gravity waves and traveling ionospheric disturbances. Resolving them will open a new window on the behavior of upper atmospheric regions and their coupling.

In addition to energy dissipation, Poynting flux provides a measure of height-integrated ionospheric Pedersen current (Σ_P **E**) on the flux tube below the satellite. This has numerous scientific applications. For example, the Region I current systems can close via the more equatorward Region II systems, or directly across the polar cap. Knowing the relative importance of these two basic possibilities is fundamental to understanding global magnetospheric current systems and their closure. Yet it has remained elusive, in part because of incomplete coverage of the polar cap by ground magnetometer networks, and because low ionospheric conductivities inhibit Hall currents responsible for magnetic perturbations measured on the ground. Nevertheless, recent ground-based measurements within the polar cap indicate that a significant portion of the Region I currents do in fact flow across (and dissipate energy within) the polar cap [12].

Swarm's multipoint in-situ measurements will allow for a quantitative assessment of the Region I/II field-aligned current system balance, and thus will allow reliable estimates of the cross-polar-cap currents. At Swarm's nominal, 500-km altitude, field-aligned electric currents can be estimated from the curl of **B**. With a single satellite, one usually assumes that currents are formed into elongated sheets, and computes a spatial derivative along the spacecraft trajectory. Two of the Swarm satellites separated laterally by tens of km, and will fill in the remaining horizontal curl component, freeing the FAC estimate of any morphological assumptions. This will be the first opportunity ever to estimate, simultaneously and on a regular basis, the full field-aligned component of the electric currents and the cross-field currents via which they close in the ionosphere. These novel measurements will be available in two orbital planes separated by several hours in local time, at a spatial resolution of ~500 m. High spatial resolution is valuable in light of increasing evidence that some of the most intense plasma flows and electrical currents are concentrated at the smallest scales. For example, the dayside cusp ionosphere is known to be a region where highly structured Joule heating; this heating is intense enough to affect satellite drag via localized upwelling of the neutral atmosphere [13].

Obviously, even a three-satellite constellation such as Swarm will leave significant measurement gaps in space and time. At high latitudes, these can be filled to a degree with the SuperDARN radar network, coupled with a large-scale semi-empirical convection model, as illustrated in the top panel of Figure 3. Two-dimensional convection patters such as these can then be used to generate large-scale FAC patterns (Figure 3, bottom panel), but require a separate estimate of the height-integrated Pedersen conductivity Σ_P [14,15,16]. Together, the combined techniques will provide an unprecedented view of the

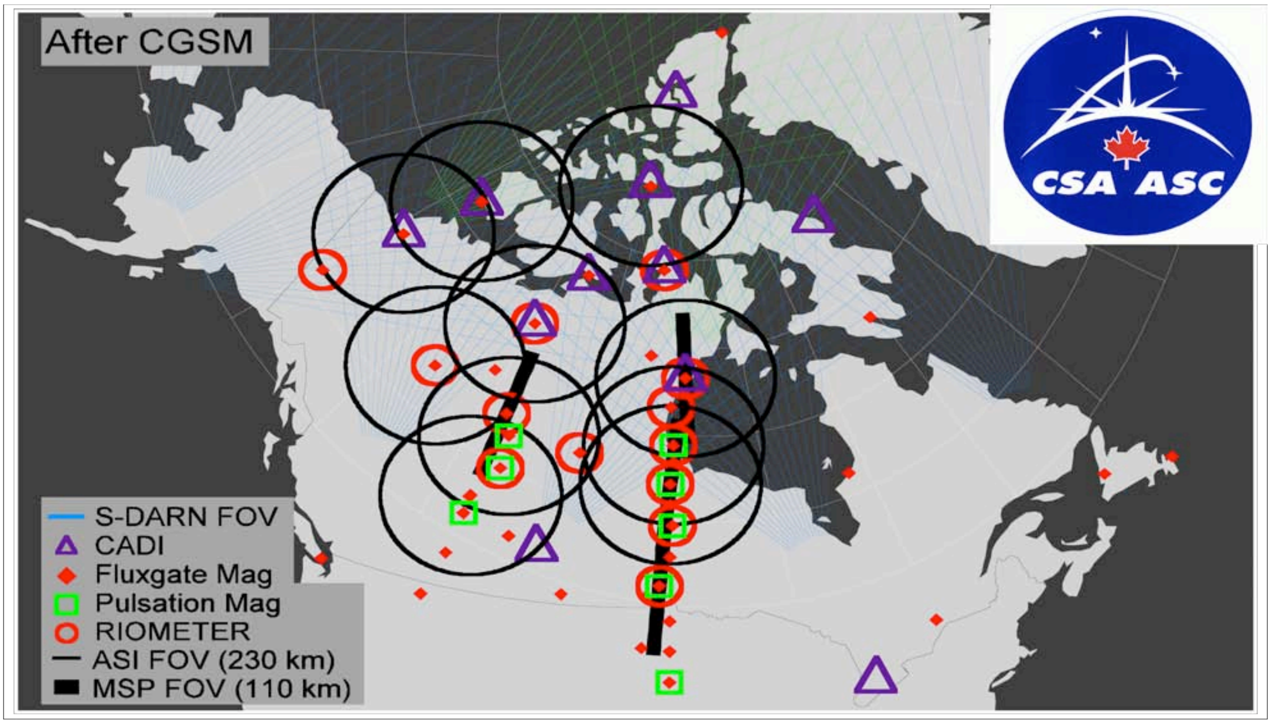

Figure 1. The Canadian GeoSpace Monitoring (CGSM) network of magnetometers, cameras, meridian-scanning photometers, radars, digital ionosondes, and riometers. Figure: Eric Donovan.

structure and evolution of FAC systems, and of the energy dissipated within them.

1.3. Synergies: Swarm, CGSM, and THEMIS

CGSM (Canadian GeoSpace Monitoring) is a continuation and significant enhancement of the earlier CANOPUS ground-based observing network distributed through Canada. CGSM includes the CARISMA and CANMOS magnetometer arrays, the NORSTAR all-sky camera, MSP, and riometer arrays, the two SuperDARN Canada HF-radars, the CADI digital ionosonde network, and the F10.7 Solar Radio Flux monitor. There is a significant modeling and data assimilation component to CGSM, which will be carried out at the Facility for Data Assimilation and Modeling (FDAM) at the University of Alberta. CGSM is an ongoing national program, organized around five grand-challenge science themes: 1) magnetospheric convection within and energy injection into the magnetosphere; 2) the triggering and development of magnetotail instabilities and flows; 3) the generation, modulation, and multi-scale structure of auroral arcs and auroral particle acceleration; 4) the role of wave-particle interactions in the acceleration and loss of energetic particles in the magnetosphere; 5) cold plasma injection, transport, and loss in the global magnetosphere. CGSM data will be available in real-time via the web. Summary and archive data will be available directly from the research groups, and through the Canadian Space Sciences Data Portal.

CGSM will be augmented further by the THEMIS ground-based array of magnetometers and cameras (see Figure 6), and in conjunction with Swarm will provide excellent opportunities to study the relation between optical auroral forms, auroral electrojets, field-aligned currents, and convection. The optical aurora is a visual map that is affected by all of these features, but the relationship among them remains poorly understood. Establishing a sound physics-based understanding of these relationships is a central focus of Canadian space science, and a primary driver of our involvement in synergistic programs such as CGSM, THEMIS, and Swarm. The scientific benefit is advancement of our understanding of the plasma physics at play in geospace. The operational benefit will be derived from the fact that a deeper understanding of these relationships will allow the visible aurora to be used as a diagnostic map of the state and configuration of the magnetosphere.

SuperDARN. Swarm's high-spatial-resolution plasma convection measurements will be able to help resolve several aspects of the SuperDARN radar measurements. For example, the cause of certain features of coherent echoes, such as double-humped spectra, remain unexplained. This is due in part to poor knowledge of the electric field microstructure of the scattering volume. Recent SuperDARN observations suggest that small-scale vortices (~1-10 km in size) exist in the cusp-cleft F region, and these vortices are responsible for the multi-peak spectra of the F-region echoes. However, no definitive conclusion can be made with the currently available radar resolution of 45-km [33]. Similar convection structures at E-region heights can be responsible for double-peaked echoes [34]. On the other hand, it might be that multi-peak radar spectra result from the plasma physics of irregularity formation. Swarm's superior resolution will open up new opportunities for studies of the production mechanisms of wave-like irregularities.

THEMIS (Time History of Events and Macroscale Interactions during Substorms) is a NASA Midex mission that will combine, beginning in 2006, five satellites with an extensive network of white-light all-sky imagers and magnetometers. THEMIS will determine the substorm onset location and mechanism, one of the central outstanding questions in space physics. The THEMIS ground-based array will extend the CGSM network eastward and westward, and will collect data at higher rates.

The ground-based THEMIS array will remain in place and operate after the in-situ portion of the THEMIS mission is complete. If the in-situ mission extends to overlap with Swarm, it will benefit from Swarm's accurate determination of the global convection patterns and FAC systems that form the context in which substorms occur. Swarm will also characterize the ionospheric conductivity distribution, which constitutes an important boundary condition for substorm studies.

1.4. Ionospheric Instabilities

What is the nature of the Global Ionospheric Electrodynamic Circuit (GIEC)? What conditions lead to ionospheric disturbances and turbulence? How are regional disturbances related to the GIEC?

Solar wind energy couples through the magnetosphere and into the ionosphere and upper atmosphere via electric currents. While this coupling predominates at high latitudes, it is increasingly clear that its consequences extend even to equatorial latitudes [17,18,19], although the specific coupling mechanisms remain poorly understood. The low-latitude signatures of global disturbances include changes in the circulation and composition of the ionosphere and thermosphere, and, often, ionospheric irregularities that can affect communications and navigation at all latitudes. Swarm will be able to establish, simultaneously, the local properties of ionospheric instabilities – density, electric and magnetic fluctuations – and the global geoelectric and geomagnetic context in which they form, providing a powerful tool with which to explore causal connections.

Equatorial latitudes. Subtle changes in the space environment can lead to sudden and drastic events. A spectacular example is the (up to) 1000-km-high plumes of 3-meter-scale plasma bubbles erupting in the lower ionosphere and exploding to altitudes of 1000 km and beyond. The basic cause of equatorial spread-F is the Rayleigh-Taylor instability, in which a "heavier", unstable F region is suspended above lower-density plasma by the combined effects of recombination at lower altitudes and vertical plasma drift. Although the basic spread-F instability mechanism is thought to be understood, it is unclear what causes some days to remain relatively undisturbed, and others to produce exceptional events such as the one shown here. Interestingly, there is recent evidence that equatorial instabilities are affected by magnetospheric disturbances associated more commonly with high latitudes [20]. For example, the low-latitude *Sq* current system, thought to drive the equatorial electrojet, recently has been reported to exhibit signs of coupling to higher-latitude current systems [18].

Equatorial current systems and plasma drifts are quite weak compared to their high-latitude counterparts. Typical magnetic perturbations are of the order of a few nT, with plasma drifts of several m/s. Swarm will be able to resolve them, bringing new information to the study these and related phenomena, while allowing magnetic field models to be compensated for their effects.

Middle latitudes. Mid-latitude irregularities can arise specifically from the oblique-field geometry (e.g. in sporadic E layers), or through coupling to equatorial or high-latitude phenomena. Equatorial spread-F plumes can extend as far north as Hawaii, for example, where they manifest as irregularities in airglow and in GPS errors [21]. It remains unclear the degree to which mid-latitude spread F initiates locally, as opposed to coupling magnetically from the equator.

A clear example of cross-regional coupling is the well-known equatorial ionization (Appleton) anomaly, in which plasma lifted by vertical plasma flows at the equator (the equatorial fountain) diffuses down field lines, enhancing plasma density to the north and south, and leaving a depleted region at the equator itself. The density enhancements depend directly on vertical flows at the equator, but also, interestingly, on the intensity of the equatorial electrojet [22,23]. Cross-regional coupling mechanisms such as these must be studied with quasi-simultaneous electrodynamics measurements in each of the coupled regions, which Swarm is ideally suited to provide.

The Appleton anomaly is a persistent feature that can, if not accounted for properly, cause systematic errors in geomagnetic field models. This has been demonstrated with the CHAMP satellite to show systematic depressions in B of several nT within the Appleton anomaly, where the higher plasma densities expel magnetic fields via the diamagnetic effect [24]. This effect is an important scientific driver for the inclusion of a Langmuir probe measurement (provided by the Swedish Institute for Space Physics as part of the EFI) on Swarm.

SAPS. At northern mid-latitudes, equatorward of the high-latitude Region I/II current systems, is a region characterized by depleted plasma densities (the trough) and high-speed (> 1 km/s) westward plasma flows, or sub-auroral polarization streams (SAPS). SAPS are thought to be the ionospheric signature of the low-latitude boundary of the Region II current system, and are related to the storm-time ring current [25]. By the time Swarm flies, the high-speed SAPS drifts will be monitored simultaneously by "StormDARN", the mid-latitude extension of SuperDARN, as well as by the mid-latitude incoherent scatter radar at Millstone Hill and the CADI digital ionosonde in London, Ontario.

High latitudes. The interaction of field-aligned current systems with the high-latitude ionosphere generates strong density irregularities. These include depletions, such as in the deep auroral density cavities associated with auroral arcs, and enhancements, from electron precipitation within the auroral oval and polar cap. Density irregularities can result from local ionospheric instabilities driven, for example, by high-speed plasma flows such as the eastward convection jet found at the high-latitude boundary of the auroral zone [26].

At still higher latitudes, one finds large-scale (>500 km) regions of enhanced plasma density known as polar cap patches. Typically, patches convect in the anti-sunward direction, appearing in all-sky cameras [27, 28] and digital ionosondes [29]. The walls of these patches are often unstable to smaller-scale irregularities, down to meter scales. Any electric currents associated with these features are much weaker than those found within the auroral oval, and so far have not been reported in the literature. Swarm offers a possibility to reveal the electrodynamic structure and origin of weak arcs and density structures, as well as their stronger, auroral-zone counterparts.

1.5. Ionospheric heating and ion outflow

Where and how does our atmosphere escape to space? What is the relation between ionospheric outflow and field-aligned current systems, convection systems, and their boundaries?

While electric convection fields are the main goal of the Swarm ion drift measurements, the distribution functions from which they are derived are a valuable by-product, as are second moments (temperatures) and field-aligned drift components. Two-dimensional ion distribution functions such as that shown in Figure 5 comprise the raw data output from the Electric Field Instrument. On Swarm, limited telemetry bandwidth will allow only moments to be telemetered at the full time resolution (16 per second). However, full distributions can be

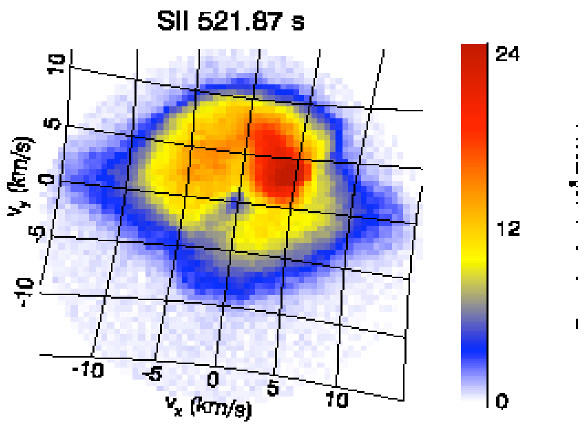

*Figure 2: SII image showing rammed and heated atomic oxygen (O^+) in the nightside auroral ionosphere near 900 km altitude. The bright red region represents ~2,000 K ambient ions; blue "wings" show heating to 100,000 K in the direction transverse to **B**. This sub-orbital example was taken on the GEODESIC sounding rocket [30].*

telemetered at a slower rate - perhaps one every several minutes. Periodic samples of full ion distributions will be necessary to test the integrity of the detector and moment-calculating schemes, but will provide a valuable scientific bonus as well. With dozens of high-resolution distribution snapshots each day, multiplied by four spacecraft, these data will accumulate to form a survey of ambient and heated ion distributions over a broad range of geophysical conditions.

The bulk of the oxygen ions represented in Figure 5 have a temperature of 0.2 eV, and are gravitationally bound to Earth. The heated features (right and left), on the other hand, approach the oxygen escape energy of 12 eV, and are therefore destined to escape to space. While this type of heating, driven by plasma waves, is thought to be relatively rare at Swarm's 500-km altitude, there has been no satellite survey at these altitudes with sufficient resolution to quantify its occurrence rate. This is because detection of these heating features requires a high-resolution imaging thermal ion detector such as the SII; integral or moment measurements would not be able to separate such weak features (in this case) from the ambient background.

Well below 500 km, ion-neutral collisions lead to bulk ion heating. This type of heating generally is not strong enough to impart escape energy to ions. However, global surveys of field-aligned ion drifts [31] have shown that frictional heating in the ionosphere can drive ion upwelling that feeds ions into more intense, plasma wave-driven heating regions at higher altitudes, thereby fuelling loss of atmospheric particles to space [see review in reference 32]. SII temperature moments and field-aligned drift measurements will be able to monitor frictional heating and upwelling, while occasional, complete distributions will identify examples when plasma wave heating transverse to **B** extends down to Swarm altitudes. The Swarm EFI on-board processor will be able to select interesting distributions for transmission, chosen for example according to their 2nd moment.

2. CONCLUSION

Swarm electric and magnetic field measurements will be unprecedented by virtue of their combined precision, temporal resolution, and multi-point nature. However, without an electron spectrometer on board, ground-based instrumentation arrays will be essential for determining the ionospheric context in which Swarm measurements will be taken. This is particularly true in the case of studies of the auroral ionosphere, which is frequently and exceedingly structured and dynamic. We have described Canadian instrument arrays here; complementary chains in Greenland, Scandinavia and at lower latitudes will ensure that a high percentage of Swarm passes will benefit from contextual information from the ground. Making the most of space-ground conjunctions will require planning. Toward this end, a first study is being commissioned by the Canadian Space Agency to begin in late 2006.

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