SWARM SCIENCE: A MAGNETOSPHERIC PHYSICS PERSPECTIVE

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ABSTRACT/RÉSUMÉ

Nominally an IT and geomagnetic field mission, SWARM has significant potentials to facilitate a major evolution in the treatment of the magnetosphere-ionosphere coupling. We argue that the realization of these potentials is predicated on a change of mindset; that is, the ionosphere is not a two-dimensional surface passively closing magnetospheric currents, but a three-dimensional system with its own electrodynamics. We expect that this changed mindset will sensitize the scientists to look for signs and clues of the 3D ionosphere from the wealth that will come out of the SWARM dataset.

1. INTRODUCTION

The instrument complement and orbital characteristics of SWARM offer exciting potentials for progress in our knowledge of magnetosphere-ionosphere coupling. For the magnetospheric physics community, these potentials will be maximized, if we think proactively and critically of the areas where certain preconceptions need to be changed or challenged. Since SWARM does not probe *in-situ* the magnetosphere, the mission is unlikely to directly contribute to the solution of high-profile "local" problems such as substorm trigger and reconnection. However, a case can be made that ionospheric physics is the greatest unknown factor in magnetospheric physics. This uncertainty stems from the simplified and often unjustified assumption magnetospheric models make about the ionosphere: a 2D conductive surface that closes passively field-aligned currents imposed by the magnetosphere (hereafter referred to as 2D-I). In reality, the ionosphere is a 3D entity capable of its own complicated electrodynamics that is not *a priori* weaker than whatever is imposed by the magnetosphere. Moreover, the ionosphere is known to re-scale the magnetospheric inputs it receives. By revealing the full ionospheric electrodynamics, SWARM can help establish the much needed and more sophisticated view of the ionosphere as a 3D entity responding to magnetospheric driving in independent and highly nonlinear ways. Within this latter context, we can proceed to develop computational models of M-I coupling that moves the state of the art to 3D-3D M-I coupling (3D^{2}MIC).

In this paper, we give argument why 3D^{2}MIC is essential, review some of the existing works already moving in this direction, and outline a strategy where information pertinent to 3D-I can be extracted from SWARM data. This last part will emphasize the crucial role ground-based observations can play in complementing SWARM and achieving theoretical closure.

2. SWARM OBSERVATIONS

The overall mission plan, science objectives, and instrument payloads of SWARM are described elsewhere in this proceeding. In brief, the three SWARM spacecraft will fly in a "scissor formation": the two-paired spacecraft will fly side-by-side in an inclined circular orbit (altitude 450 km, inclination 87.4°), with an inter-spacecraft separation of 1.5° longitude. The third spacecraft will over-fly the twin in a slightly higher circular orbit (altitude 530 km, inclination 86.8°). The nodes of right ascension are equal initially, but SWARM C will drift from the twin over time, with a longitudinal separation of 6 h local time expected at the end of mission.

For the first time, from a stabilized platform, and in a constellation configuration, SWARM will produce the following level-1 data:

- Vector geomagnetic field with accuracy of 0.5 nT (0.15 nT for the magnitude)
- Cross-B electric field with accuracy 1.5 mV/m
- Free electron density with accuracy 0.5×10^{10} m^{-3}
- Air drag acceleration to the accuracy 2.5×10^{-8} m-s^{-2}, from which the thermospheric neutral density and cross-track neutral wind speed can be inferred.

Additionally, the Canadian CEFI will measure electron and ion temperatures, which, though not first-order mission requirements, are important parameters for IT physics.

The altitudes where the SWARM satellites are situated are quite strategic. The satellites will over-fly the conductive layer where most of the ionospheric currents are concentrated, but not too far from these currents so that altitude dependence can be inferred. For example, the Canadian EFI instrument will measure the electric field **E,** which for all intents and purposes can be mapped to the ionosphere F region. This electric field drives the Pedersen and Hall currents situated at different altitudes and flowing in orthogonal directions. The high resolution and constellation formation of SWARM will allow this important three-dimensional distribution to be mapped systematically for the first time. The way to achieve the altitude distinction follows basically the same inversion principle used to retrieve the main and lithospheric fields, although the underlying models will be different.

The SWARM orbit altitude is also ideal for studying nonlinear plasma physics in the topside ionosphere (altitudes from the F_2-maximum to several thousand km). Although SWARM does not have a full plasma wave package, the 16 Hz cadence of the electric and magnetic field instruments cover the entire PC micropulsation spectrum, as well as the precursor to substorms, Pi2. It is known that, above the SWARM altitude, a rich set of nonlinear wave-particle interactions occur which lead to transversely accelerated ions, plasma fountains, and double layers.

SWARM measurements promise a wealth of data to magnetospheric physics. We refer the reader to a companion paper by *Knudsen et al.* [this proceeding], which describes many immediate interests in this area. Our orientation in this paper is more long-term, and the methods to achieve the objectives are less established. In fact, most of the required tools to take advantage of the SWARM data to achieve the advances we envisage have not been developed. For this reason, the first half of this article will present theoretical argument why our current paradigm of MI coupling needs a major overhaul.

3. PROBLEMS OF THE M-I COUPLING PARADIGM

It is generally accepted that the ionosphere can play a very important role in magnetospheric physics. It is an important source to the plasma sheet and ring current; it modulates magnetospheric convection; it is a source and provides closure to field-aligned currents; it is an energy sink both for magnetospheric convection and substorms. It has been suggested that the ionosphere can even be a trigger of substorms [1]. A seldom-mentioned fact is that the ionosphere is much more massive than the magnetosphere in terms of inertia. Using a conservative F-region electron density 10^{11} m^{-3}, and a nominal ionospheric layer thickness 100 km, the ionized mass in the ionosphere is estimated to be 10^4 kg (assuming the predominance of O^+). In contrast, assuming an average plasma sheet density 10^5 m^{-3}, plasma sheet area 40×40 $R_E{}^2$, and plasma sheet thickness 10 R_E, we obtain a typical magnetospheric mass 10^2 kg.

While the mass comparison does not capture all that is important, it does point to the fact that the ionosphere has a larger store of electric charge that can change magnetospheric electrodynamics. Despite the general recognition of the importance of the ionosphere, the treatment of M-I coupling has been quite idealized and inadequate for many problems. For example, the ionospheric mass outflow, known to account for up to 50% of the mass in the plasma sheet and ring current [2, 3] is seldom included as a mass loading term in the transport equations in global magnetospheric models. A more serious example of the unjustified idealization of the ionosphere is the widespread use of the current continuity equation:

$$\nabla \cdot \overleftrightarrow{\Sigma} \cdot \mathbf{E} = j_{\parallel}{}^{(m)} \qquad (1)$$

where $\overleftrightarrow{\Sigma}$ is the height-integrated ionospheric conductivity tensor, **E** is the electric field in the rest frame of atmospheric neutrals, and $j_{\parallel}{}^{(m)}$ is the field-aligned current arising from magnetospheric stresses. The qualifier “magnetospheric stresses” underlies the following assumption. For a magnetospheric plasma of mass density ρ, pressure tensor $\overleftrightarrow{\mathbf{P}}$, and velocity **v**, the cross-field current density in a magnetic field **B** is

$$\mathbf{j}_{\perp} = \frac{\mathbf{B}}{B^2} \times \left[\rho \frac{\partial \mathbf{v}}{\partial t} + \rho \mathbf{v} \cdot \nabla \mathbf{v} + \nabla \cdot \overleftrightarrow{\mathbf{P}} \right] \qquad (2)$$

where the variables on the right-hand side can be computed, in principle, by global MHD models. The magnetosphere-driven field-aligned current is given by

$$j_{\parallel}{}^{(m)} = B_0 \int \frac{\nabla \cdot \mathbf{j}_{\perp} ds}{B} \qquad (3)$$

where the integral is along a field line and B_0 is the largely constant magnetic field in the high-latitude ionosphere. The above procedure is used widely in magnetospheric physics with unquestioning fealty, but is in fact an extreme simplification of the ionospheric behavior. *A priori*, an ionosphere under the magnetospheric driving $j_{\parallel}{}^{(m)}$ will react by generating a field-aligned current of its own, $j_{\parallel}{}^{(i)}$, and the correct version of Eq. 1 is formally

$$\nabla \cdot \ddot{\Sigma} \cdot \mathbf{E} = j_{\|}^{(m)} + j_{\|}^{(i)} \qquad (4)$$

The proposition that $j_{\|}^{(i)} \equiv 0$ is clearly an assumption of *extreme* ionospheric passivity. Even Eq. 4 as written can be argued to be inadequate. The ionosphere E/F region has a thickness of >100 km. The height-integrated formulation is reasonable for phenomena with cross scale size >>100 km, but not *a priori* valid for scale size ≤ 100 km. Yet, interesting high-latitude features such as the auroral arcs have scale sizes ≤ 100 km. Hence it can be argued, simply on dimensional basis, that models of auroral-arc physics based on 2D-I are inadequate.

Consider a rather simple generalization of Eq. 1. It is known that the Pedersen and Hall conductivities peak at different altitudes. A small improvement to Eq. 1 is to use a two-sheet approximation: the Pedersen conductance in a lower-altitude sheet 1 and the Hall conductance in a higher sheet 2. Even such a small improvement could significantly change the form of MI coupling equation. Under the two-sheet approximation, the current continuity equations read,

$$\left(\nabla \Sigma_H \times \hat{\mathbf{b}}\right) \cdot \mathbf{E} = j_{\|}^{(m)} - j_{\|}^{(2)} \qquad (5)$$

$$\nabla \cdot \left(\Sigma_p \mathbf{E}\right) = j_{\|}^{(1)} \qquad (6)$$

where $j_{\|}^{(2)}$ is the FAC going out from the under-side of sheet 2, and $j_{\|}^{(1)}$ is the FAC going into the up-side of sheet 1. If one assumes that the ionosphere has no internal dynamics to alter the flow of field-aligned current, $j_{\|}^{(1)} = j_{\|}^{(2)}$, and adding Eqs. 5 and 6 together yields Eq. 1. However, there is no reasonable ground to make the above supposition, and a slightly more realistic situation is $j_{\|}^{(1)}$ is some (nonlinear) mapping of $j_{\|}^{(2)}$, say, $f\left(j_{\|}^{(2)}\right)$. Under this general premise, one can see that the MI coupling equation would assume a form,

$$\nabla \cdot \left(\Sigma_p \mathbf{E}\right) = f\left(j_{\|}^{(m)} - \left[\nabla \Sigma_H \times \hat{\mathbf{b}}\right] \cdot \mathbf{E}\right) \qquad (7)$$

Eq. 7 dramatizes the point we have been making throughout this paper: So long as the ionosphere is not absolutely passive (i.e., *f* is a non-unitary mapping), the MI coupling can behave quite differently from what has been taken for granted with Eq. 1. In section 5.1, we will discuss a physical model which supports this argument in detail.

The above discussion, though hardly complete, brings to the fore the need for an improved treatment of M-I coupling: Given $\mathbf{F}(m)$ as a distribution of fluxes from the magnetosphere (mass, momentum, energy, and current), what is $\mathbf{F}(i)$, the ionosphere feedback of the same? To answer this question, both the magnetosphere and ionosphere must be treated as full-blown 3D entities, and neither should be presumed to dominate the other.

4. ROI: A COMPLEMENTARY HALF APPROACH TOWARD UNITY OF KNOWLEDGE

The 90's saw the emergence of a suite of 3D global MHD codes. Although there are questions about whether MHD can capture the whole specter of magnetospheric physics (e.g., reconnection), the fact remains that these models have significantly advanced our knowledge of the magnetosphere. Basically all the global MHD models for the magnetosphere use the 2D-I simplification Eq. 1. For computational reasons, most MHD codes do not extend all the way down to the ionosphere, but are terminated on a surface 2-3 R_E above Earth (which we call $\Re$), and then some simplified mapping schemes are implemented to incorporate Eq. 1 to represent the 2D-I M-I coupling.

As a first step toward 3D^{2}MIC, a change in the above approach lies in the following. Instead of mapping the fluxes through $\Re$, we can treat it as a boundary condition, and treat the plasma system below it in a three-dimensional manner. In practice, of course, this step is much easier said than done, as the said system features a wide spread of mass density and complex ion chemistry. Yet, the credo that no problem but hard ones remain applies here – there is no shortcut to circumvent the 2D-I problem.

The proposed paradigm is a mirror image of the simplified approach the magnetospheric physicist uses to treat the ionosphere; that is, given $\mathbf{F}(m)$ on $\Re$, we write, as accurately as we can, the equations governing the plasma physics and plasma-neutral interaction below $\Re$, and solve plasma density, electromagnetic field, currents, and other system variables, pursuant to the boundary condition. The outcome of this model, which can be characterized as the "revenge of the ionosphere" (hence ROI), is effectively the 3D IT response to arbitrary magnetospheric driving (as one can prescribe $\mathbf{F}(m)$).

We emphasize that the proposed approach is a half measure, because strictly, in an efficiently interacting magnetosphere-ionosphere system, there exists no hard 2D boundary on which a boundary condition can be fixed *a priori.* In this case, the IT response will modify the magnetospheric behavior, which in turn will introduce a change in the flux: $\mathbf{F}(m) \to \mathbf{F}(m) + \Delta\mathbf{F}$. This caveat notwithstanding, ROI would be a major step towards a full treatment of MIC.

5. AURORAL PHYSICS IN THE 3D IONOSPHERE

Understanding the formation and dynamics of aurora is a fundamental challenge in our field. Studies of convection and substorms address the problem of the source of auroral generation, and the question of generating mechanisms hinges strongly on how the ionosphere behaves. In this section we review some theoretical works taking place in Canada, which gives a glimpse to how ROI can evolve from an already-existing base.

5.1 Ionospheric electrodynamics associated with thin arcs. At the altitude of F-region, the streams of precipitating electrons undergo a pronounced cascade into structures less than 100 m across [4]. *St-Maurice et al.* [5] argued that, on such small scales, ionospheric transport and electrodynamics couple strongly, and a consequence of this coupling is a thermal current $j_{\|}^{(i)}$ comparable to the nonthermal precipitating electron flux but flowing in the opposite direction. It was also suggested that gradients of ionospheric conductivity formed self-consistently from precipitating electrons can generate thermal currents of several 100 μA/m^2. This idea was followed by *Noël et al.* [6, 7] through a 2D (latitude-altitude) time-dependent model including ion chemistry in the E-F region. The results of the computation show that the ionosphere generates not only strong feedbacks on magnetospheric driving but also distinct field distributions, which, as expectation goes, should leave distinct marks in magnetospheric processes.

5.2. Nonlinear dispersion of field-line resonances

Field-line resonances [8] are magnetospheric standing waves, and their role in auoral physics has received much attention. *Lu et al.* [9] performed a full nonlinear simulation of a field-line resonance in a dipolar field and found that, as FLR approaches the ionosphere, the electron inertial effect does not only cause a dispersion of the wave structure, but also an overall migration of the location of the FLR. The nonlinearity creates strong density cavities, whose trapping effect leads to the change of FLR frequency from the linearly predicted value. This work, and related studies referenced therein give strong indications that energy inputs from magnetospheric waves are re-processed by nonlinear plasma physics above the ionosphere (where the electron inertial effect becomes important).

5.3. Stationary inertial Alfvén waves

Knudsen [10] considered a different case of nonlinear plasma wave dynamics in the topside ionosphere. Instead of relying on magnetospheric oscillation as the driver, *Knudsen* [10] considered the effect of magnetspheric convection, which carries the plasma through a thin current sheet. By solving the steady-state two-fluid equations, *Knudsen* [10] revealed density and electromagnetic field structures on the scale of electron inertial length $\lambda_e = c / \omega_{pe}$. Electron acceleration takes place within these structures, and the cause of this acceleration is a parallel electric field due, again, to the electron inertial effect, just as was the case in 5.2. However, the energy source of the Knudsen theory is different; it is magnetospheric convection, in interacting with the auroral FAC sheet, that imparts energy to electrons. It was found, especially, that the stationary inertial Alfvén waves can accelerate electrons to several times of Alfvén speeds, if its phase velocity is antiparallel to the field-aligned drift of electrons.

The three examples given above are illustrative, and they share a common trait: the vertical variation along the magnetic field lines in the ROI regime is essential for the emergence of new features under discussion, and that the electron inertial length seems a key scale. At the SWARM altitude the electron inertial length is ~$O(10)$ m. For a nominal satellite speed 8 km/s, the 16 Hz cadence of CEFI is not enough to resolve this scale. However, all the models mentioned above indicate that structures are most pronounced in the 100 m – 1 km range, presumably due to the controlling effect of plasma in altitudes higher than ~500 km.

6. LATITUDINAL COUPLING

There is a strong emphasis in magnetospheric physics on the connection and coupling among its various regions. For example, one can trace a particle from the site of dayside reconnection, through the cusp, mantle, lobe, plasma sheet, ring current, and ultimately precipitation into the upper atmosphere. Many magnetospheric problems, such as convection, substorms, and storms, essentially concern themselves with how a region acts on or reacts to another, following largely a high-to-low latitude progression of cause and effect.

The presumption of magnetospheric dominance in MI coupling (namely Eq. 1) makes the integrated conductivity the sole ionospheric factor that can influence the magnetospheric processes. Again, with the extended view of the ionosphere as a three-dimensional entity, new modes of cross-latitude coupling could develop owing to ionospheric physics. *Knudsen et al.* [this proceeding] give a number of ionospheric phenemena that respond to magnetospheric driving but develop locally through ionospheric physics. It is also shown that magnetospheric forcing reaches deep down to the stratospheric altitude [11]. All this requires treating IT as a 3D entity. It is quite possible that, if the mid-latitude ionosphere is activated, initially by enhanced convection perhaps, it could back-react on the high-latitude ionosphere, independently of what the magnetosphere does, since currents can flow across latitudes in the ionosphere more easily than charged particles can move from the plasma sheet to the ring current.

7. COORDINATED DATA ANALYSIS STRATEGY

As noted above, the SWARM satellites will fly in a very strategic altitude, above but near the ionospheric conductivity peaks, and below the region of near-Earth high-latitude magnetosphere where electron inertial effects, plasma density cavities, and a host of outflow acceleration processes are observed. In order to accurately separate the “external” signal, the topside ionospheric physics must be modeled to the accuracy of SWARM measurement, and the ionosphere itself must be considered, *a priori,* as a three-dimensional entity.

The first-order mission requirement of SWARM is the separation of the internal and external magnetic fields. Our discussion in this paper shows that there is a second-order separation that is necessary: the so-called external field contains contributions from multiple sources; without properly isolating these sources, the first-order mission requirement could be compromised, because there is no recipe other than understanding the MIC physics to deduce the external field from SWARM observations. It is often said that SWARM will make an accurate global survey of Poynting flux into the ionosphere. At the SWARM altitudes, the Poyting flux measurement contains an incident part from the magnetospherr and a reactive part from ionospheric back-reaction, i.e., $\mathbf{p} = (\mathbf{E}_m + \mathbf{E}_i) \times (\mathbf{B}_m + \mathbf{B}_i)/\mu_0$. This immediately raises two questions. First, the need to separate the incident flux $\mathbf{E}_m \times \mathbf{B}_m$ and reflection flux $\mathbf{E}_i \times \mathbf{B}_i$. Second, whether the ionospheric reaction to magnetospheric driving is coherent such that $\left\{\mathbf{E}^{(m)} \times \mathbf{B}^{(i)}, \mathbf{E}^{(i)} \times \mathbf{B}^{(m)}\right\} \neq 0$. Therefore, in order to understand the energy coupling between the magnetosphere and ionosphere fully, one needs to develop models which will 1) specify how magnetospherically originated fields $\left\{\mathbf{E}^{(m)}, \mathbf{B}^{(m)}\right\}$ change as a consequence of nonlinear plasma physics (e.g., section 5.2 and 5.3), and 2) specify how the ionosphere reacts to $\left\{\mathbf{E}^{(m)}, \mathbf{B}^{(m)}\right\}$ (e.g., section 5.1). These models will be essential to decompose the SWARM data in accordance with their respective sources. This will not only lead to a deeper understanding of magnetosphere-ionosphere coupling, but also important to the best-possible estimate of the overall external field.

A late attempt to add an electron spectrometer to the SWARM satellites did not materialize. Consequently, despite SWARM’s unique location and configuration, the satellites do not have the capability to determine whether they are in auroral arcs or not. Another shortcoming is that SWARM samples only above the ionosphere. Ground-based observations can significantly address these two problems.

In Canada, Greenland, and Scandinavia, there exist more than 100 ground-based high-latitude magnetometers. These instruments measure magnetic perturbation below the ionosphere. This is important because the magnetic signals of the ionospheric currents reverse in direction above and below the conductivity peaks, and the increased contrast effectively gives a greater signal-to-noise ratio to exploit various differential and inversion techniques. During the mission life time of SWARM, we expect routine availability of the distribution of magnetic field on the ground, $\mathbf{B}(0)$ (over a fixed, but large area in Northern Hemisphere), at the altitude of SWARM A-B, **B**(450), and at the altitude of SWARM C, **B**(530). For the sake of argument, let us assume we have a main and lithospheric field model that is first-order accurate and from which one can arrive at a first-order estimate of the external field (simply by subtraction from the measured **B** over a timescale short compared to the timescales of internal field change). The data can then be compared to the best 3D ionospheric and MIC models at our disposal. The residue of this comparison can be returned as a second-order correction to the internal field model. This iteration can proceed to refine both the internal and external field estimate. There is a need to develop such a model for external-field retrieval.

With the Canadian Geospace Monitoring, Finnish MIRACLE, and THEMIS ground-based ASI array, a large sector of the northern auroral oval will be monitored near-constantly by ground-based auroral imaging. Presently, a virtual observatory called Global Auroral Imaging Access (GAIA; gaia-vxo.com) is being developed to better coordinate auroral observation and data assimilation. It will be valuable to incorporate the GAIA data system into one that is to be developed for SWARM, as this would give the first-order information on whether the satellites are traversing auroral arcs. Also, the Advanced Modular Incoherent Scattering Radar (AMISR) will be operational in high-latitude regions in Alaska and Resolute Bay, Canada, during the SWARM mission. A plan is afoot to complement the AMISR faces in Resolute with a dense local auroral imager array. The combination of these instruments will, over the AMISR FOV, provide an unprecedented view of the 3D ionospheric physics.

During the nominal operational period of SWARM (2010-2014), there will be a number of magnetospheric missions in space (extended THEMIS, RBSP, and MMS). Coordinated data strategy with these missions will be looked at in the high-latitude performance study for SWARM commissioned by the Canadian Space Agency.

8. CONCLUSION

The key argument of the article is that SWARM can do for magnetospheric physics what it promises to do for the geodynamo science community, by better characterizing the physics of the ionosphere. When one discusses the SWARM magnetic-field observation for the internal fields, one uses the plural, and distinguishes the core dynamo field, lithospheric field, ocean circulation signals, etc. The same level of sophistication should apply to the treatment of the external fields. We argued that the ionosphere, as a three-dimensional and active entity, has been idealized for much too long in magnetospheric models, and the most important contribution that SWARM can make is, by taking advantage of its configuration and accuracy, provide crucial information on how the ionosphere and magnetosphere couple as full 3D entities. In conjunction with ground-based instruments, the SWARM mission may well occasion a major breakthrough in how we view magnetospheric physics.

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