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Key Points:

- Electron beams could be used for magnetic field line mapping
- Spacecraft charging problems could be mitigated with a plasma contractor
- Several outstanding issues are identified

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Can an electron gun solve the outstanding problem of magnetosphere-ionosphere connectivity?

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Abstract Determining the magnetic connectivity between magnetospheric phenomena and ionospheric phenomena is an outstanding problem of magnetospheric and ionospheric physics. Accurately establishing this connectivity could answer a variety of long-standing questions. The most viable option to solve this is by means of a high-power electron beam fired from a magnetospheric spacecraft and spotted at its magnetic footpoint in the ionosphere. This has technical difficulties. Progress has been made on mitigating the major issue of spacecraft charging. The remaining physics issues are identified, together with the need for a synergistic effort in modeling, laboratory experiments, and, ultimately, testing in space. The goal of this commentary is to stimulate awareness and interest on the magnetosphere-ionosphere connectivity problem and possibly accelerate progress toward its solution.

1. Introduction

A complex system, like the magnetosphere-ionosphere-thermosphere (M-I-T) system, is a collection of diverse, connected, interacting entities. In the solar-wind-driven M-I-T system, we have not been able to establish many of the fundamental connections and ascertain the mechanisms of the essential couplings. To build system models, we need to determine how critical phenomena in the ionosphere and critical phenomena in the magnetosphere are connected. (Note that here and in the following, we use the term "connection" instead of "coupling" to distinguish the fact that coupling implies interaction, while connection only refers to the link between a certain region of the magnetosphere with the corresponding region of the ionosphere.)

Magnetosphere-ionosphere connections are determined with magnetic-field models or with magnetic-field models constrained by spacecraft measurements [*Tsyganenko and Usmanov*, 1982; *Tsyganenko*, 1989; *Tsyganenko and Sitnov*, 2007]. Accurately connecting magnetospheric phenomena to ionospheric phenomena is difficult because the magnetospheric magnetic field has localized time variations that are not captured in magnetic-field models. The magnetosphere is a high-Reynolds-number system, and, like turbulence, attempting to predict these localized magnetic field perturbations would be ill conceived. Tests of magnetic-field models over the years find 1° accuracy at best for mapping magnetospheric measurements to the ionosphere, with worse accuracy as activity increases [*Weiss et al.*, 1997; *Ober et al.*, 2000; *Shevchenko et al.*, 2010; *Nishimura et al.*, 2011]. Note that 1° in the ionosphere is a substantial fraction of the width of the entire auroral zone [e.g., *Weimer et al.*, 1985; *Feldstein and Galperin*, 1985].

This lack of mapping accuracy holds back magnetospheric research. Not knowing the magnetospheric location of the growth-phase arc prevents us from determining magnetospheric processes that may be key to substorm initiation. More generally, not being able to connect magnetospheric measurements to specific types of aurora prevents us from knowing the various causes and conditions for the various types of aurora and prevents us from discerning how energy is extracted from the magnetosphere to power the aurora. Controversies over the ionospheric signatures of flow structures in the magnetotail prevent us from using the aurora as a diagnostic of magnetospheric dynamics. Uncertainties on the location of the subauroral polarization stream with respect to the plasmapause, the location of substorm subauroral ion drifts with respect to injection fronts, and the location of the Harang discontinuity in the magnetosphere prevent us from gaining full understanding of the physics and impacts of those phenomena. The ionospheric footpoint of the near-Earth neutral line is a tantalizing mystery.

There are other techniques to overcome the magnetosphere-ionosphere connectivity problem, but they are limited in what they can map and when. Matching low-altitude particle distribution functions to equatorial distribution functions works under the rare occasions when there are spacecraft magnetic conjunctions [*Meng et al.*, 1979; *Hones et al.*, 1996; *Weiss et al.*, 1997]. Crossing isotropy boundaries [*Sergeev et al.*, 1993; *Shevchenko et al.*, 2010] or sheet currents [*Motoba et al.*, 2015], both with distinct ionospheric signatures, allows one to constrain the latitudinal (but not longitudinal) mapping of these features. Connecting up time signatures of plasma waves measured in the magnetosphere with time signatures of auroral pulsations allows a spacecraft to be mapped into a pulsating patch [*Jaynes et al.*, 2015] in the pulsating diffuse aurora during substorm recovery times. Of course, conjugate auroral features in the Northern and Southern Hemispheres can be mapped to each other [*Stenbaek-Nielsen et al.*, 1972; *Østgaard et al.*, 2011], with no information about the magnetospheric connection.

A robust, versatile, and definitive solution to the outstanding problem of magnetosphere-ionosphere connectivity is to use a high-power electron beam fired into the atmospheric loss cone from a magnetospheric spacecraft to produce a detectable (optical or radar) beam spot in the atmosphere. A major difficulty of this approach is that the tenuous magnetospheric plasma cannot provide the return current necessary to compensate for the electron beam current. In these conditions, the spacecraft charges to such high levels that the electron beam is electrostatically pulled back. Indeed, fear of catastrophic spacecraft charging is the main reason why this idea has never been realized in practice and remains identified as an outstanding emerging-technology problem in the recent decadal survey of solar and space physics [*National Research Council*, 2012; *MacDonald et al.*, 2012].

2. The Charging Problem and a Promising Solution

In order to put the spacecraft-charging problem in perspective, let us consider a 4 kW electron beam with current $I = 0.1$ A and energy $E = 40$ keV emitted by a spacecraft at geosynchronous orbit. Representative local plasma conditions are the plasma density $n = 1$ cm^{-3} and temperature $T = 1$ keV. One can easily calculate the equilibrium spacecraft potential by balancing the beam current with the current collected by the spacecraft from the background magnetized plasma [*Hastings and Garrett*, 1996]. Assuming spherical symmetry, the framework of the orbital-motion-limited theory [*Mott-Smith and Langmuir*, 1926] predicts that the spacecraft would charge to about 10^7 V, significantly higher than the beam energy, implying that beam emission would not be possible [*Delzanno et al.*, 2015b].

A possible charging mitigation strategy, often used onboard spacecraft or on the International Space Station, involves a high-density charge-neutral plasma fired prior to and during the electron beam. This plasma is normally referred to as the *contactor plasma*, since its purpose is to "make contact" with the background and effectively increase the collection area of the spacecraft [*Olsen*, 1985; *Schmidt et al.*, 1995; *Comfort et al.*, 1998; *Torkar et al.*, 2001]. Assume that the contactor is operated prior to the beam to create a plume of 5 km diameter contacting the spacecraft and that the $I = 0.1$ A beam is fired for 1 s leaving 0.1 C on the spacecraft. (For reference, 1 C is a lightning-bolt worth of charge [cf. *Krehbiel et al.*, 1979; *Uman*, 1987, Table 7.2].) If this charge is passed to the spacecraft-contactor system, a straightforward application of Coulomb's law with a radius of 2.5 km gives a potential of 400 kV. Such Coulomb's law arguments imply that the residual charge from the beam must be rapidly moved far from the spacecraft (i.e., to very large radius) and not simply into the contactor plume.

In order to shed light on the feasibility of using a contactor charging mitigation scheme for this experiment, *Delzanno et al.* [2015a, 2015b] performed an extensive simulation campaign of the beam-spacecraft-contactor-background plasma system. They found that the contactor cannot really be used in an electron collection mode since the collisionless contactor plume is essentially transparent to any ambient electron that might be collected and fails to deliver a significantly larger current to the spacecraft. However, if the contactor current is larger than the beam current, the contactor can be used as an emitter of net positive charge (referred to as "ion emission"). Physically, this is because the contactor enables ion emission off its quasi-spherical surface, where the Child-Langmuir space charge limit (that is well known to strongly reduce the emission of an ion beam in planar geometry) is not a problem [*Delzanno et al.*, 2015a]. Although the simulations were only describing the early evolution of a real experiment, the end result is that the transient of the spacecraft potential can be effectively mitigated by the ion emission from the contactor plume.

3. Open Issues

While the results of *Delzanno et al.* [2015a, 2015b] might provide a pathway for high-power electron beam experiments to operate in the low-density magnetosphere, several open issues, discussed below, must be resolved to establish these ideas conclusively.

3.1. Spacecraft and Plume Charging for a Long Beam Pulse

The simulation results discussed above describe the early evolution of a real experiment. Simple algebraic estimates for a long (1 s) beam pulse for a spacecraft-plume system in vacuum indicate that the system will charge to several tens of kV. Indications are that the presence of ambient magnetospheric protons will greatly aid in the transport of positive charge away from the spacecraft-plume system, reducing the long-beam-pulse potentials. Simulations of the long-time evolution of the system are needed.

3.2. Geometrical Shape of Kilometer-Sized Contactor Plumes

One unknown for such long-beam-pulse simulations is the geometrical shape of the kilometer-sized plasma-contactor plume. All simulations [e.g., *Roy et al*., 1996; *Wang et al*., 2001; *Boyd,* 2006], laboratory measurements [e.g., *Ohler et al*., 1995; *Gallimore,* 2001; *Walker and Gallimore*, 2005; *Beal et al*., 2005], and space measurements [e.g., *Boyd*, 2002; *Gabdullin et al*., 2008] of plumes deal only with the near-spacecraft morphology and dynamics. There are outstanding questions about the evolution of the collisionless plume propagating both parallel to and across the magnetospheric magnetic field. To investigate all of the collisionless plasma phenomena that govern the plume evolution (e.g., charge polarization, Alfven wings, and structuring) almost certainly will require three-dimensional particle simulations with very large dynamic ranges.

3.3. Beam Energy

Major trade-offs for a magnetospheric experiment involve the choice of a few MeV electron beam versus a tens-of-keV electron beam. A major advantage to the MeV choice is that for the same beam power, much less charge is removed from the spacecraft by an MeV beam than by a keV beam. This reduces spacecraft-charging risk and simplifies the beam-contactor operations. Further, if uncontrolled spacecraft-plume charging does occur, the aiming of an MeV beam is less perturbed by the electrical potentials than is the aiming of a keV beam. The MeV-versus-keV choice results in very different gun designs and power-conversion methodologies, with keV designs having some spaceflight heritage. Because energy storage for such a magnetospheric experiment will dominate the payload mass, energy efficiency (from stored energy to energy deposited in the atmosphere) of the gun/power-conversion design is an important consideration. MeV guns can be designed to produce electron beams with less beam divergence than keV guns can, making it easier to inject the full beam power into the atmospheric loss cone to prevent wasting beam power. The keV guns have an advantage that the beam can be electrostatically steered; beam pointing is trickier for MeV guns although magnetic steerage is promising. For MeV electron beams, relativistic effects displace the loss cone away from the magnetic-field-line direction and must be accounted for to maximize beam aiming to hit the atmosphere [*Porazik et al*., 2014]. This can be accomplished once the *B*-field orientation (as in the traditional loss cone calculation) and its curvature are known. For equatorial distances less than about 5 R_E (R_E is the Earth radius) one could safely use the dipole-field approximation but for larger distances the effect of a more realistic magnetic-field configuration can become important. Empirical magnetic-field models and magnetic-field configurations obtained from global/ring-current simulations of the near-Earth environment should be used to assess the loss-cone variation for particles of different energies injected at various equatorial distances.

3.4. Beam Propagation

Beam scattering by instabilities could prevent the beam electrons from reaching the atmosphere. Early work on the propagation of cylindrical-shaped nonrelativistic electron beams through plasmas indicated that the growth lengths for instabilities were larger than the magnetosphere [*Galvez and Borovsky*, 1988]: indeed rocket-fired keV beams have been detected after making transits along the magnetic field through the magnetosphere [*Hallinan et al*., 1978; *Pellat and Sagdeev*, 1980; *Lavergnat*, 1982; *Winckler*, 1992; *Oraevsky and Tríska*, 1993; *Choueri et al*., 2001]. Theoretical instability assessment of MeV-energy electron beams in the magnetosphere has not yet been performed. A related issue to be studied is the scattering of keV and MeV electron beams by the natural plasma-wave environments of the magnetosphere.

3.5. Beam Detection

Locating the beam spot in the nighttime atmosphere with the use of ground-based optical equipment is straightforward [*Borovsky*, 2002; *Marshall et al.*, 2014], providing that sufficient beam power (~10 kW) is deposited in the atmosphere. Using prompt (unquenched) airglow emission lines, a blink technique (a beam-on beam-off sequence synchronized between the gun and the ground-based cameras) can be used to discern the beam spot in an auroral emission background. The possibility of detection of the ionization of the beam spot with ground-based radars [e.g., *Zhulin et al.*, 1980; *Uspensky et al.*, 1980; *Izhovkina et al.*, 1980] may allow the detection of beams fired from the dayside magnetosphere; for radar detection an MeV-versus-keV energy trade-off is involved [*Marshall et al.*, 2014].

4. Conclusions

The ability to connect unambiguously phenomena occurring over vast regions of near-Earth space could solve a variety of long-standing problems in magnetospheric/ionospheric physics and open a new field of experimental space plasma physics. In principle, it could be accomplished by a high-power electron beam fired from a magnetospheric spacecraft and traveling along the magnetic field line to its ionospheric footpoint. Recent progress demonstrates that the once-overwhelming problem of catastrophic spacecraft charging can be mitigated by a plasma contactor operating in an ion emission mode. As called for in the decadal survey [*National Research Council*, 2012], a lot of preparatory science is still necessary to establish this mission concept conclusively. This paper attempts to provide a roadmap for the resolution of the most important issues, emphasizing that a synergistic effort of theoretical/computational modeling and laboratory experiments is needed to achieve risk mitigation. Still, the ultimate proof of the feasibility of these ideas will have to come from space experiments.

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