A Concept to Unambiguously Establish Magnetosphere-Ionosphere Connections and to Determine the Magnetospheric Causes of Aurora

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Insufficiently accurate magnetic-field-line mapping between the aurora and the equatorial magnetosphere prevents us from determining the cause of many types of aurora. An important example is the longstanding question of how the magnetosphere drives low-latitude (growth-phase) auroral arcs: a large number of diverse generator mechanisms have been hypothesized but equatorial magnetospheric measurements have not been unambiguously connected to arcs in the ionosphere, preventing scientists from identifying the correct generator mechanisms. The auroral community understands the near-Earth acceleration processes quite well (e.g. field-aligned potentials and Alfven-wave acceleration) but does not understand the equatorial energy-conversion processes driving these near-Earth processes; nor does the community understand the origin of the Alfvenic energy. With very few, and just momentary at that, exceptions, unambiguous magnetic mapping between the equatorial magnetosphere and the ionosphere has never been achieved. In the few exceptions (e.g., Nishimura et al. [Science, Vol. 330, Issue 6000, pp. 81-84, DOI:10.1126/science.1193186 2010]), the unambiguous mapping has been achieved using fortuitous simultaneous observations where unmistakable temporal correlations have been observed between periodic ionospheric and magnetospheric phenomena. Although these are only possible in a very special set of circumstances, they have been shown to be of incredible scientific value, with the Nishimura paper being the first-ever unambiguous identification of the *cause* of one type of aurora (patchy pulsating). Such unambiguous mappings, if they could be achieved regularly, would enable a host of unanswered questions to be addressed and closed.

Magnetic-field models are not accurate enough in the dynamic nightside magnetosphere to establish detailed magnetosphere-ionosphere connections and it is unlikely that breakthroughs in these models will be achieved. “Magnetosphere-to-Ionosphere Field-Line Tracing Technology” using an energetic electron beam fired from a magnetospheric spacecraft has been cited in the National Research Council 2013 Solar and Space Physics Decadal Survey (pp. 333-334) as an “instrument development need and emerging technology” that (a) is in need of a technology boost and that (b) could have a substantial impact in solar and space physics.

Besides the aurora, other scientific problems require precise magnetosphere-ionosphere connection and a field-line-tracing experiment could be used to explore a wide variety of problems. The mapping of boundaries and regions between the magnetosphere and the ionosphere could be unambiguously performed with a magnetospheric-electron-beam spacecraft, provided it is instrumented to identify those boundaries and regions. The magnetic connections between magnetospheric and ionospheric processes such as SAPS, SAID, STEVE, convection reversals, bursty bulk flows, and omega bands could be determined with certainty.

Magnetosphere-ionosphere coupling can be studied by comparing temporal onsets of convection in the magnetosphere (via spacecraft flow measurements) with temporal onsets of ionospheric convection at the magnetic footpoint (measured, for example, by the SuperDARN radar network) and could answer questions about when and where the magnetosphere drives ionospheric convection and when and where the ionosphere drives magnetospheric convection. Finally, there is an extensive literature describing how energetic electron beams fired from above could be used to study mesospheric chemistry, atmospheric electricity, atmospheric electron-attachment physics and electrical conductivity, and plasma-wave generation.

With the goal of understanding what magnetospheric processes drive aurora, this white paper presents a research roadmap to 2050 to develop a mission concept to solve this magnetic-connection problem. One clear strategy is for an instrumented spacecraft in the equatorial magnetosphere to carry an electron accelerator, to fire a powerful energetic-electron beam into the atmospheric loss cone resulting in an optical beam spot in the upper atmosphere that can be imaged from the ground, putting the magnetic connection of the equatorial spacecraft into the context of the aurora. If that strategy can be accomplished then it will be unambiguously known that a measurement taken by the magnetospheric spacecraft magnetically corresponds to the location in the ionosphere where the beam spot is imaged.

Multiple technical challenges must be overcome to enable a viable field-line-tracing mission: these include spacecraft charging, beam aiming, beam dynamics and stability, and the detection of the beam spot in the presence of aurora. For decades a multi-institute team of researchers has worked to make progress on these technical challenges. That research team has consisted of auroral observers, plasma physicists, magnetospheric instrument designers, optical physicists, ionospheric physicists, spacecraft systems scientists, and two compact-accelerator design groups.

Mission concepts have been considered that involve either (a) a single magnetospheric spacecraft making measurements and carrying an electron accelerator or (b) a swarm of measuring spacecraft with one member of the swarm carrying the electron accelerator. The spacecraft carrying the accelerator will also carry a power-storage system and a plasma contactor (for spacecraft-charging mitigation). The purpose of a swarm is to measure perpendicular-to-$\underline{\mathbf{B}}$ gradients in the magnetosphere, which are important for diverting perpendicular magnetospheric currents into field-aligned currents, a critical part of the processes of the driving of auroral arcs; the gradients of interest are ion-pressure gradients, electron-pressure gradients, mass-density gradients, temperature gradients, flow shear, gradients in the field strength, and the cross products of the various gradients. Hall effects may be important and so measuring both the perpendicular ion flow and the perpendicular electron flow is desirable; this can be accomplished by measuring both the ion flow and the electric field.

Two orbital concepts have been considered. The first consists of a tight swarm of spacecraft in the equator at geosynchronous orbit (6.6 R_E), with a single ground-based observatory in the vicinity of the swarm's magnetic footpoints. The ground-based observatory would have at least one camera dedicated to beam-spot imaging plus cameras for auroral imaging. In the geosynchronous concept a ground-based radar could be used to help to locate the beam spot. Additionally, the radar could be used for physics studies with the electron beam as an element of upper-atmosphere experiments and radar beamspotting allows the field-line tracing to operate in daylight. Other instrumentation at the observatory could be ionosondes, an ionospheric heater, a wave transmitter, and a magnetometer network. The second orbital concept has a swarm of spacecraft in an eccentric orbit and would take advantage of the Canadian TREx network of auroral cameras. Eccentric orbits can be chosen with periods of 24 hr so that the magnetic footpoint of the swarm wanders over the TREx network in Western Canada with a 24-hr period.

A critical issue for operating a high-power electron beam from an ungrounded spacecraft in the tenuous magnetospheric plasma is spacecraft charging. An electron beam depositing enough power (~10 kW) in the upper atmosphere to be seen in the presence of ongoing aurora will remove a fraction of a Coulomb of negative charge from the spacecraft in a time on the order of 1 s. A substantial computer-simulation-based research effort, supported by laboratory experiments, has demonstrated that the operation of a plasma contactor releasing a high-density charge-neutral plasma plume before and during a beam firing can greatly mitigate the charging of the spacecraft during the beam operation. Contrary to prior discussion of an emitted plasma plume acting to collect charge from the ambient plasma, the research effort demonstrated that the surface of the plasma plume acts as an ion emitter that can emit an ion current equal to the current of the electron beam. An objective of space-flight testing of this charge-mitigation concept will be crucial.

Completion of compact-accelerator and pulsed-power designs and obtaining space-flight heritage for those designs are critical objectives in the development of future missions. Designs for compact space-based relativistic-electron accelerators are underway. Tradeoff studies between relativistic (MeV) and non-relativistic (10's of keV) accelerators need to be performed.

Getting the electron beam from the spacecraft in the magnetospheric equator to the atmosphere involves aiming the beam into the atmospheric loss cone, fitting the beam within the loss cone, ensuring that the propagating beam is stable, and ensuring that the beam electrons are not scattered by magnetospheric plasma waves. Higher-energy electron beams are more desirable for lower beam divergence (fitting into the loss cone) and for spacecraft-charging considerations. Too high of a beam kinetic energy, however, brings loss-cone-shift problems wherein the aiming of the beam into the loss cone becomes ambiguous. Calculating the stability and dynamics of the electron beam propagating through the ambient magnetospheric plasma is an ongoing area of theoretical and experimental research. Fortunately, the powerful two-stream instabilities are greatly weakened by the fact that the beam will have a finite cylindrical cross section.

To produce a beam spot that is optically detectable from the ground in the presence of active aurora, a beam power of ~10 kW or more needs to be deposited into the atmosphere. To identify the beam spot in the presence of aurora, an on-off temporal blink pattern of beam firings must be used along with temporal processing of the camera images to locate the blinking beam streak. This will require the development of smart and rapid optical-data-analysis methods.

Responding to the Decadal Survey, a research roadmap from now to 2050 to bring such a field-line-tracing mission to fruition must include the objectives/milestones: (1) to obtain completed accelerator designs and prototyping (2030); (2) to complete the research on beam stability and beam scattering (2030); (3) to perform tests in space of the spacecraft-charging mitigation scheme (2030); (4) to complete a study of the tradeoffs between relativistic and non-relativistic electron beams including accelerator-design characteristics (2031); (5) to acquire flight heritage for the accelerator and power-system designs (2035); (6) to generate a full mission design with coordination between the magnetospheric, ionospheric, and atmospheric research communities (2036); (7) to launch, optimize the field-line-tracing operations, and begin data analysis (2040); and (8) to design the next-generation field-line-tracing mission (2050).