In-situ Investigations of the Structure of Ionospheric Closure Currents

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Science Background

The transfer of energy and momentum between the terrestrial magnetosphere and ionosphere is substantially mediated by large-scale field-aligned currents (FACs), which are driven by magnetopause dynamics and magnetospheric pressures and close through the ionosphere where the dissipation and drag are governed. While significant insight into ionospheric electrodynamics and the nature of magnetosphere-ionosphere (M-I) coupling (e.g., Lysak, 1990) have been gained by rocket and satellite measurements, in-situ measurements of these ionospheric closure currents remain elusive. The only firm estimates of ionospheric current densities come from inferences drawn from ground-based radar observations combining electric field observations with conductivities derived from density measurements (e.g., de la Beaujardiere et al., 1977; Kamide & Brekke, 1993; Richmond & Thayer, 2000). The *RICCI* mission aims to make key new observations of the structure of the ionospheric currents to determine how the altitude structure of these currents and the ionospheric conductivity is related to auroral precipitation and variations in ionospheric density. Early understanding of auroral electrodynamics was provided by Evans et al. (1977), who calculated Hall and Pedersen conductivities from observed electron densities and found that both conductivities significantly increased as the payload traversed a stable auroral arc. Their observations found that conductivities and the electric field are anti-correlated, which was later confirmed by additional rocket missions (e.g., Mallinckrodt & Carlson, 1985; Marklund et al., 1982; Kletzing et al., 1996). The *JOULE II* sounding rocket experiment derived height-integrated Hall and Pedersen conductivities (Σ_{H} and Σ_{P}, respectively) from in-situ measurements of ion flow velocities, $\vec{E} \times \vec{B}$ drift, and electron densities (Sangalli et al., 2009). These results revealed that that from 110-128 km Σ_{P} decreased, but Σ_{H} increased, when neutral wind effects were included. Mallinckrodt (1985) modeled the current density structure within the auroral ionosphere from 80 to 250 km, using two different auroral electrodynamics configurations proposed by Marklund (1984). The results suggested that the current closure geometries depend strongly on the input energy and auroral configuration and concluded that observations of the magnetospheric inputs, as well as observations within the closure region, would be required to understand the dynamics of the current closure region. Importantly, the contrast in auroral precipitation between upward and downward FAC has many implications for dissipation, atmospheric heating, and electromagnetic feedback processes.

The *Auroral Current and Electrodynamics Structure* (*ACES*) rocket mission addressed the auroral current structure using two payloads at different altitudes. The *ACES* mission was not targeted to directly measure the current or calculate the intensity/direction of the closure currents since a single payload was used at each altitude. The analysis was therefore subject to inherent assumptions necessary to infer the ionospheric currents from single-point measurements. While the *ACES*-Low rocket did obtain in-situ magnetic field measurements consistent with the closure current, Kaeppler et al. (2012) concluded that the direction and the geometry of the closure current could not be directly determined from the measurements. A future mission could solve this problem by employing the curlometer technique (Dunlop et al., 1988, 2002; Robert et al., 1998) via a configuration of sub-payloads to directly measure the current density within the ionosphere, and in concert with the *in-situ* electric field to resolve the Pedersen and Hall currents in the ~110 to ~160 km altitude range. A complete understanding of the auroral current system requires measurement of both the ionospheric currents together with the input energy, currents, and electric fields at higher altitudes (>200 km). The former, the first direct, *in-situ* observation of the ionospheric currents, could be obtained by a breakthrough pathfinder mission that would provide the basis for a more comprehensive and ambitious future investigation combining low and high-altitude observations in a single mission.

Outstanding Measurement Gap

Despite the vast knowledge obtained from previous sounding rocket missions, it remains unclear how the ionospheric closure currents are structured and how such structuring might affect multiple aspects of magnetosphere-ionosphere coupling. In particular, it remains unknown *whether the ionospheric currents flow in limited altitude ranges that depend on auroral precipitation* and *how ionospheric conductivity is organized relative to the energy and flux of precipitating electrons and local changes in ionospheric density.*

Understanding the structure of ionospheric closure currents is relevant to the overall Heliophysics Program and addresses multiple goals outlined in the 2013 Decadal Survey. In particular, discussion of Science Challenge AIMI-2 (*"Understand the plasma-neutral coupling processes that give rise to local, regional, and global-scale structures and dynamics in the AIM system"*) motivates the need to better characterize ionospheric closure currents, stating that "...the dynamics of ionospheric conductivity are among the most poorly quantified parameters of the IT system." A rocket mission is needed that specifically targets aspects of the structuring of closure currents, their relationship to conductivity structures, and the auroral arc electrodynamics.

Unfortunately, previous attempts to use multipoint *in-situ* measurements of the ionospheric magnetic field to derive ionospheric currents have been limited by attitude knowledge uncertainty (Cohen et al., 2019). Existing commercial off-the-shelf (COTS) attitude determination systems with sufficient accuracy to meet the attitude knowledge requirement use star trackers that cannot accommodate high rates of payload motion/spin. However, rocket sub-payload technologies currently available at NASA Wallops Flight Facility (NASA/WFF) use high rates of spin for stabilization. In discussions with NASA/WFF it was determined that **the technology to obtain high-precision attitude knowledge on miniature sub-payloads deployed from a sounding rocket platform does not exist within the current capabilities of the NASA Sounding Rockets Program Office (SRPO**; Cathy Hesh, SRPO, private communication)**.** Development of a "Constellation Magnetometer" through the novel use of CubeSats as miniature sub-payloads deployed from a suborbital rocket platform would supports goals with broad impact across NASA: 1) a candidate technology identified in the 2015 NASA Technology Roadmap; 2) a priority in the 2014 NASA Heliophysics Roadmap to develop and use CubeSats; and 3) the SRPO strategic initiative to provide infrastructure to regularly support CubeSats as deployable miniature sub-payloads for future LCAS rocket investigations.

A sounding rocket mission is needed to obtain the first direct measurement of the ionospheric currents associated with an auroral arc and investigate the structure of ionospheric closure (Hall and Pedersen) currents (Cohen et al., 2019). Such a mission could include technology development of a Constellation Magnetometer, achieved through the novel release of CubeSat miniature sub-payloads from the sounding rocket platform as part of the funded payload suite.

Technical Challenges

Prior experiments have been conducted to use in-situ multi-point measurements of the ionospheric magnetic field (e.g., Zheng et al., 2003; Martineau et al., 2015) to derive ionospheric currents. These attempts have been limited by uncertainties in attitude knowledge (Cohen et al., 2019). At auroral altitudes, the background magnetic field is ~45,000 nT and even a slight uncertainty in attitude knowledge can yield a significant error in the measured magnetic field (and thus the differences between the magnetic field measurements required to apply the curlometer technique (Dunlop et al., 1988, 2002; Robert et al., 1998). Obtaining high-precision attitude knowledge is made even more challenging because COTS attitude determination systems and components with sufficient accuracy to meet the knowledge requirement cannot accommodate high rates of payload motion/spin. Currently, the technology necessary to obtain the required high-precision attitude knowledge on miniature sub-payloads deployed from a sounding rocket does not exist within the capabilities available at NASA/WFF.

The centerpiece of such a future mission would be a significant technology development: adapting CubeSats as miniature sub-payloads from a sounding rocket platform to provide a distributed constellation for precise magnetic field observations. This development is essential to enable a direct measurement of the ionospheric current density. Such a "Constellation Magnetometer" is highlighted as a Technology Candidate for TA 8.3.1 (Field and Particle Detectors) in the 2015 NASA Technology Roadmap. Specifically, the integration of science-grade magnetometers and high-precision star cameras into the CubeSat platform addresses the technology focus on "*increasing sensor sensitivity and developing robust and efficient deployment mechanisms and platforms. The magnetic and electric isolation required are critical for the sensors and spatial locations.*"

Close consultation with NASA/WFF has led to the conclusion that **the technology necessary to meet the requirements to obtain the high-precision magnetic field measurements critical to obtain science closure for such a mission do not exist within the current deployed sub-payload capabilities of NASA/WFF.** Although miniature sub-payloads have been developed for previous missions, none of these have imposed or achieved the stringent attitude knowledge requirements necessary to apply the curlometer technique (Cohen et al., 2019). The form factor of these previous miniature sub-payloads varied and a reliable, magnetically-quiet solution for data communications has yet to be developed. Recently, the *ISINGLASS* rocket mission attempted to relay data from miniature sub-payloads to the main payload using high frequency (HF) transmitters. Unfortunately, HF transmission was extremely noisy and the resulting magnetic contamination seriously compromised the quality of the distributed magnetic field observations. Finally, NASA/WFF does not currently have a magnetically clean ACS system suited for miniature sub-payloads that could achieve the low spin rates necessary for high-precision star trackers. It is expected that NASA/WFF could address and meet these challenges, but only after a considerable development effort. To address these challenges, a future mission would need to use a CubeSat solution for the miniature sub-payloads. Although CubeSats have yet to be deployed from the suborbital sounding rocket platform, COTS subsystems and components available for the CubeSat platform address the technical challenges outlined above and can be adapted for a sounding rocket.

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