A persistent, large-scale, and ordered electrodynamic connection between Saturn and its main rings as revealed by Cassini/RPWS

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Introduction

Auroral hiss emissions are ubiquitous in planetary magnetospheres, particularly in regions where electric current systems are present. They are generally diagnostics of electrodynamic coupling between conductive bodies, thus making auroral and moon-connected (e.g. Enceladus) magnetic field lines prime locations for their detection. Auroral hiss propagates in the same direction as electron beams and are understood to be generated by Landau resonance, i.e., when their parallel phase speeds match the electron beam speed. Cassini's Grand Finale orbits afforded a unique opportunity to directly sample magnetic field lines connected to the main rings. Using plasma wave data, we provide strong evidence for the persistent and organized presence of auroral hiss demonstrably associated with the main rings. Further, we find this phenomenon consistent with plasma wave data during Saturn Orbital Insertion, when Cassini made an equatorial pass over the main rings. This suggests the main rings facilitate the closure of field-aligned currents by the action of radial currents across the rings.

Observations

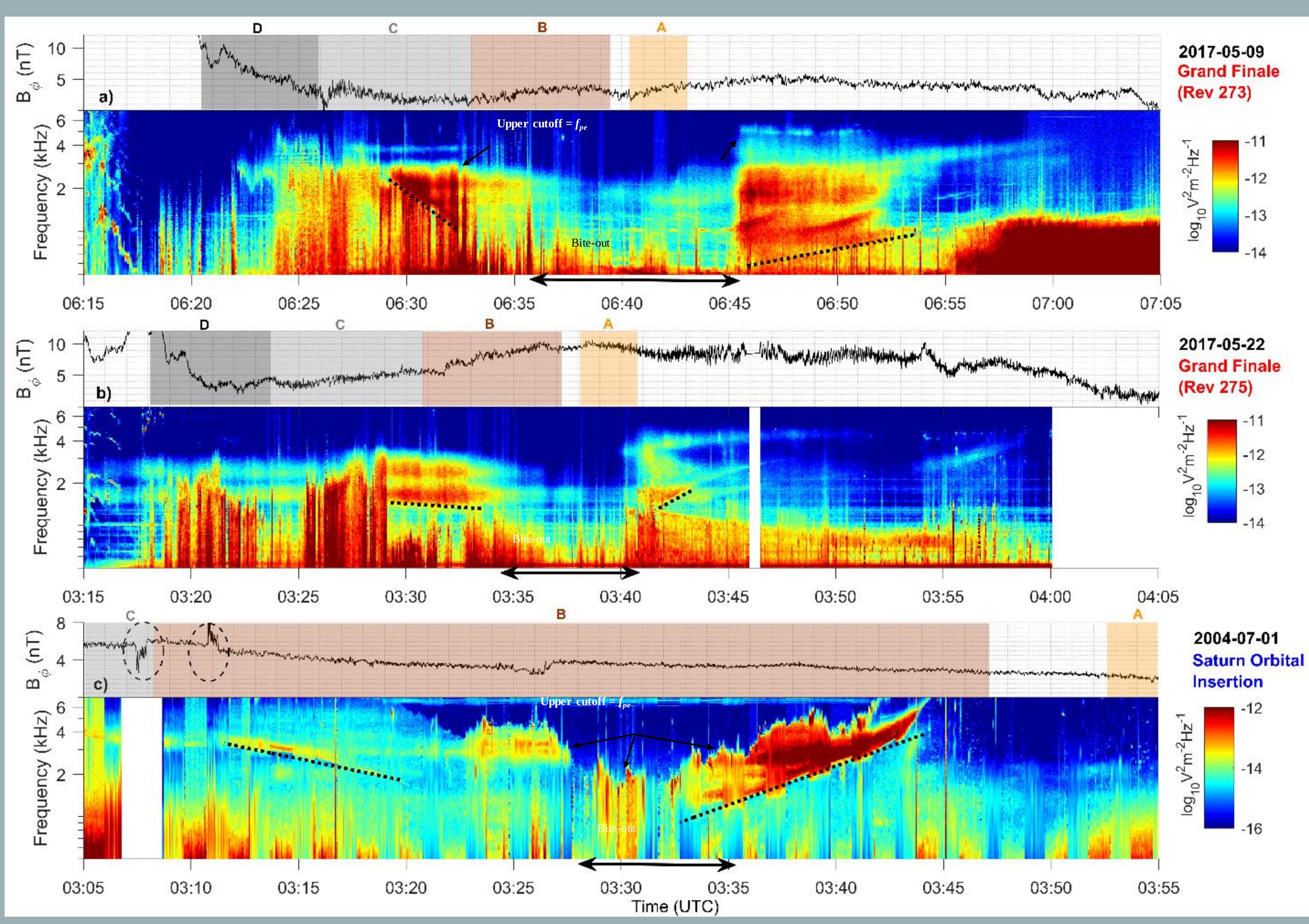

Figure 1 – Electric field frequency-time spectrograms of whistler-mode auroral hiss emissions observed on magnetic field lines connected to the main rings (panels a and b) during the proximal orbits and (panel c) during SOI. Dotted lines show the approximate funnel shape of the emission. The upper frequency cutoff corresponds to the electron plasma frequency, f_{pe}, and the "bite-outs" in the funnel are due to density depletions that exist over the rings. Upper panels are B_ϕ measurements. There is however no clear correspondence between gradients in B_ϕ and the auroral hiss. The dashed ellipses surround artefacts due to spacecraft maneuvering.

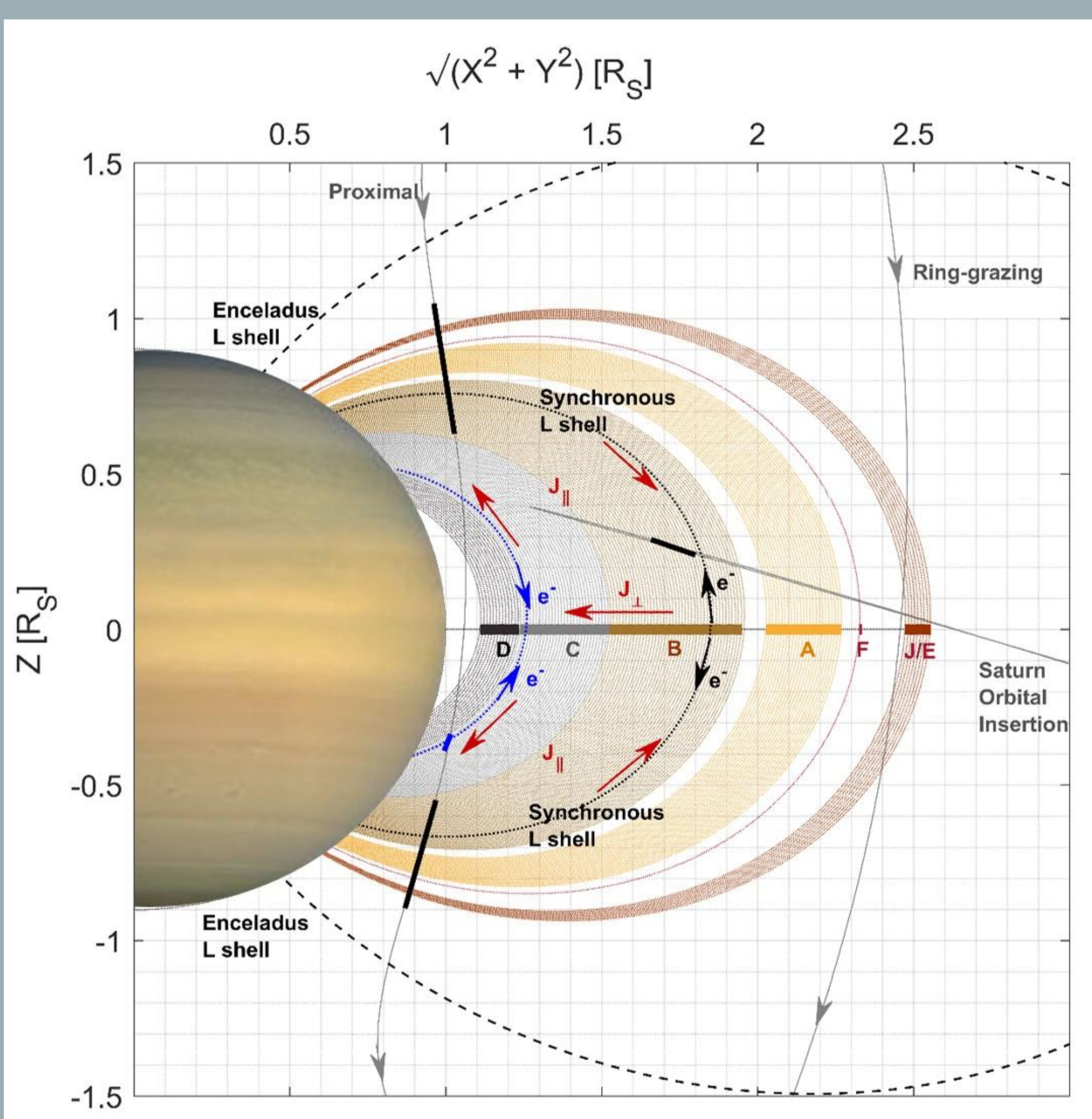

Figure 2 - The thickened segments of the trajectories during SOI and the proximal orbits represent the ranges over which auroral hiss was observed. Black color is where they are believed to originate from the main rings and propagate towards the ionosphere, and blue, is where the reverse direction is believed. To guide the eye, black and blue arrows are added to show the corresponding directions of electron beams inferred from auroral hiss. Red arrows are directions of the current system that is consistent with spatial distribution of the auroral hiss observations.

Theory

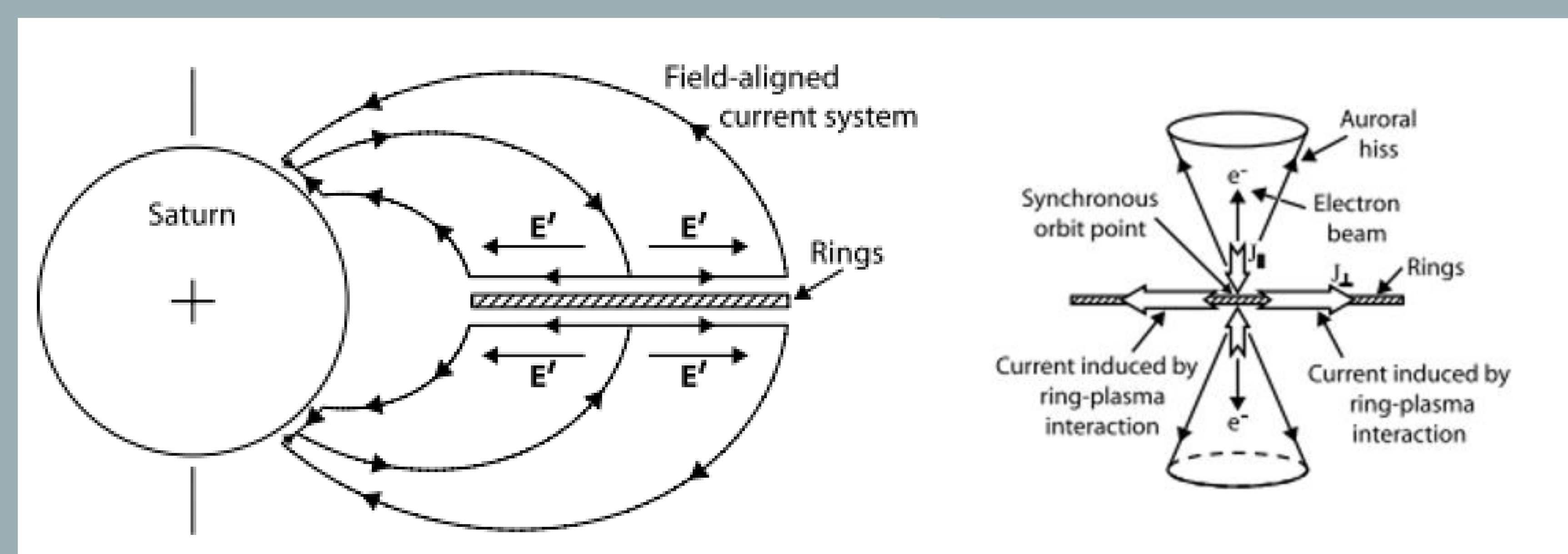

Figure 3 – A working hypothesis for ring-ionosphere coupling. Diagram adapted from Xin et al. (2006).

The distribution of observations in Figure 2 has a striking resemblance to a hypothetical picture put forth by Xin et al. (2006) in Figure 3. Since auroral hiss emissions have been observed symmetrically in the northern and southern hemispheres, this suggests the presence of two electron beams, sourced at the ring plane, and directed symmetrically towards the northern and southern ionospheres. Electron beams are often the charge carriers in a field-aligned current, thus these observations suggest that a field-aligned current is directed into the rings. Figure 2 shows the emissions, from both the proximal orbits and SOI, distributed around the magnetic field line connected to the synchronous point (black dashed line). The synchronous point, at 1.86 R_S, represents the radial distance along the kronographic equator where the ring particles match the corotational velocity of Saturn's magnetosphere. The proximity of the observations to L = 1.86 suggests a compelling possibility that the current is produced by an interaction between the rings and the corotating magnetospheric plasma [Xin et al., 2006].

Figure 3 illustrates how the differential motion between the ring particles and magnetospheric plasma can give rise to a current. Consider the motions of ring particles (with any associated neutral gas) and plasma in Keplerian and corotational speeds, respectively. In the rest frame of the rings, a differential speed, $\Delta V = V_{plasma} - V_{ring}$, sets up a motional electric field, $E' = -\Delta V \times B$ that drives radial currents across the rings. The synchronous point, where $\Delta V = 0$ would therefore represent the dividing point in the radial currents. Inward of the synchronous point, where $V_{ring} > V_{plasma}$ (i.e., Keplerian speed is greater than corotational speed), the electric field is set up in a direction towards the planet. Conversely, outward of the synchronous point, where $V_{plasma} > V_{ring}$, the electric field is directed away from the planet. This system of radial electric fields will drive radial currents, $J_\perp$, across the rings by the action ring-plasma collisions. This would be possible if the collision frequency is sufficiently large to produce a finite transverse conductivity.

Discussion

The auroral hiss emissions are quasi-electrostatic in nature. Such whistler-mode waves are characterized by the lowest phase speeds, and since the Landau resonance condition requires $v_{beam}/c = v_{ph\|}/c$, the beam energies required for their growth are small. Using the whistler-mode dispersion relation, a beam energy of 10 eV yields a parallel phase velocity that is well within the quasi-electrostatic range, and therefore in excellent agreement with the observations. The lack of a correspondence between a gradient in B_ϕ and the auroral hiss is likely due to the following combination of factors: (i) assuming electrons are the primary charge carriers, the field-aligned current desnity, $j_\| \approx -en_e v_\|$, where e is the electron charge, $v_\|$ is very low for quasi-electrostatic whistler-mode waves, and n_e over (but not in) the B ring is ~0.2 cm^{-3}, orders of magnitude lower than measured in the ionosphere [Coates et al. 2005; Persoon et al., 2018], yielding a very weak field-aligned current density (ii) the presence of magnetic field variability over the main rings, and (iii) digitization noise and the magnetometer operating at a high range (low sensitivity). Altogether, it is very plausible these can mask a weak field-aligned current associated with the auroral hiss. While the MAG data is inconclusive for unique signatures of the associated currents, it is worth noting that a net positive deflection of B_ϕ in the southern hemisphere has been reported [Ogiwal et al., 2021], i.e., corresponding to field-aligned currents flowing into the ring plane, and is consistent with the direction of auroral hiss (and associated electron flow).

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