Kivelson Margaret G., Galland (Orcid ID: 0000-0003-3859-8581)
Jia Xianzhe (Orcid ID: 0000-0002-8685-1484)

Coupled SKR Emissions in Saturn's Northern and Southern Ionospheres

Margaret G. Kivelson[1,2], and Xianzhe Jia[2]

[1] Department of Earth, Planetary, and Space Sciences, UCLA, Los Angeles, CA 90095

[2] Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI 48109

Corresponding author: Xianzhe Jia (xzjia@umich.edu)

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Key Points:

- Describe the generation of coupled north-south SKR emissions observed at Saturn
- The SKR emission in the north at the southern period is interpreted as a secondary effect of the strong field-aligned current system that drives the southern signal
- The signals at the southern period should appear at 270° southern PPO phase in both hemispheres.

Abstract

Kilometric radiation (SKR) emitted above Saturn's auroral ionosphere is modulated in intensity at periods close to the planetary rotation period; SKR periods differ slightly for sources in the north and in the south. Although there is good evidence that the signals are generated independently in the two hemispheres, it is also well established that during southern summer power emitted from the northern hemisphere is modulated in intensity not only at the northern period but also at the southern period, an observation that requires an explanation. We examine the idea that the signal in the north at the southern period is a secondary effect of the strong field-aligned current system centered at 270° that drives the southern signal. Basing our analysis on studies of field-aligned current systems in the terrestrial and jovian magnetospheres, we argue that the parallel electric fields that drive electrons into the southern auroral ionosphere and generate SKR are, at least in part, bi-directional and thus capable of accelerating electrons toward the opposite hemisphere where the secondary signal is detected with intensity lower than that of the locally generated signal. This interpretation implies that the atmospheric process that modulates the periodic responses can operate independently in each hemisphere.

1 Introduction

The periodic variation of field and particle properties at roughly the planetary rotation period is by now a well-established feature of Saturn's magnetosphere (a comprehensive review is given by *Carbary and Mitchell* [2013]). Modulation was first observed in the intensity of Saturn kilometric radiation (SKR) [*Kaiser and Desch*, 1980; *Desch and Kaiser*, 1981; *Galopeau and Lecacheux*, 2000; *Gurnett et al.*, 2005; *Kurth et al.*, 2007*; Zarka et al., 2007;*] and of emissions in other radio frequency bands [*Gurnett et al*., 2007; *Ye et al*., 2009]. Subsequently, small amplitude perturbations of the equatorial magnetic field inside of ~ 15 R_S (R_S = 60,268 km is Saturn's radius) were found to rotate at the SKR period [*Espinosa and Dougherty*, 2000; *Espinosa et al.*, 2003; *Southwood and Kivelson*, 2009; *Andrews et al.*, 2008, 2010a], and properties of energetic particles [*Carbary et al*., 2007] and low energy plasma [*Gurnett et al*., 2007; *Ramer et al*., 2016] were also found to vary at that period.

Nearly continuous records of SKR emissions, available since 2004 when the Cassini spacecraft was approaching Saturn, have revealed additional features of the periodicity. During southern summer the intensity of SKR and other radio emissions originating in the northern hemisphere is modulated at a period of ~ 10.6 hours whereas the higher intensity emissions from the southern hemisphere are modulated at the slightly longer period of ~ 10.8 hours [*Gurnett et al*., 2009a and b; *Lamy*, 2011; *Ye et al*., 2010, 2016; *Fischer et al*., 2015]. Differences in period and intensity consistent with those found in radio emissions, including the presence of dual periods, have been identified in the magnetic perturbations [*Provan et al.*, 2012, 2014; *Andrews et al.*, 2010b; *Southwood*, 2011], oscillations of the auroral oval and variations in its intensity [*Nichols et al.*, 2010a and b], and charged particle fluxes [*Carbary et al*., 2009]. The source region of the SKR falls between 70° and 80° latitude in both hemispheres, with the northern one at slightly higher latitude [*Cecconi et al*., 2009].

2 Northern and Southern SKR Emissions

SKR is emitted mainly in the extraordinary mode and is fully elliptically polarized [e.g., *Lamy et al*., 2008]. The polarization is left-handed for sources in the south, which propagate anti-parallel to the field as they travel from the source to the spacecraft, and right-handed from sources in the north, which propagate parallel to the field *Lamy et al.*, 2008; see also *Kaiser and Desch,* 1982; *Gurnett et al.,* 2010]. This difference in polarization enabled *Lamy* [2011] to obtain a dynamic periodogram, reproduced here as Figure 1, that confirmed the previously identified difference of the dominant periods of northern and southern emissions. Furthermore, in the spectra of northern hemisphere SKR, a new feature appeared. The periodogram revealed a clear signal not only near 10.6 hours as previously demonstrated, but also at the 10.8 hour period that dominates the southern hemisphere spectra. The bursts are intermittent, which may relate to observation latitude or to the generation conditions. The dual frequencies can be seen in the bottom panel of Figure 1. The dual frequencies raise the question: is there a separate source of southern period emissions in the north or is there a different explanation? We do not address the question of varying intensity, but ask only what drives the signals in the opposite hemisphere. In discussing the cause of emissions in the northern hemisphere that vary at the southern period, *Lamy* (2011) observed that a possible inter-hemispheric connection could arise if "auroral electrons accelerated in one hemisphere . . . ultimately reach the other one," noting that such a phenomenon has been proposed as an interpretation of the pattern of Io's auroral footprints by *Bonfond et al.* [2008]. We pursue that concept in the following discussion.

3 Interpretation and Discussion

One possible interpretation can be ruled out. The frequency vs. time plot produced by spectral analysis of the sort used to produce Figure 1 does not distinguish between signals produced by two separate sources closely spaced in frequency (f_1 and f_2) and signals of a wave with a carrier frequency that falls between f_1 and f_2 modulated in amplitude at a low frequency, $f_2 - f_1$ [e.g., *Carbary,* 2015]. If the sources of periodic modulation of intensity were of the latter type, one would expect that the sources would be the same in the north and the south and that dynamic spectra would reveal two frequencies in both hemispheres. That would leave unanswered the question of why only the lower frequency appears in the southern hemisphere. We do not consider this possible interpretation further because the existence of an amplitude modulated signal as a source of the temporal variations near Saturn's rotation period has been ruled out most convincingly by *Cowley et al.* [2016]. They demonstrate that the dominant signals at Saturn are emitted separately from the two hemispheres at different frequencies. If this assertion is accepted, we must find another explanation for the presence of emissions modulated at the southern period in the high latitude northern ionosphere.

Our interpretation of the spectra shown in Figure 1 starts by assuming that sources in the northern ionosphere drive perturbations only at the northern period and sources in the southern hemisphere drive perturbations only at the southern period. The signal in the northern hemisphere at the southern period is interpreted as a secondary manifestation of perturbations driven from the south. Let us consider why there might be a secondary signal of the southern period in the north. Critical to the argument is the fact that during southern summer, the southern signal is on average far more intense than is the northern signal, with a typical intensity ratio of ~3:1 [*Provan et al.*, 2011; *Andrews et al*., 2012].

In both hemispheres, SKR is generated above the ionosphere where intense field-aligned currents (FACs) flow upward. Upward current is carried principally by downward flowing electrons. Assuming singly charged ions, the parallel current ($j_\parallel$) is given by $j_\parallel = ne\left(v_{\parallel,ions} - v_{\parallel,electrons}\right) \approx -ne\, v_{\parallel,electrons}$, where n is is the electron number density, e is the charge on an electron, and $v_{\parallel,electrons}$ and $v_{\parallel,ions}$ are the field-aligned velocities of electrons and ions, respectively. If FACs that couple the ionosphere to the magnetosphere or to the opposite ionosphere pass through regions with low plasma density (n becomes very small), the paucity of current carriers may require field-aligned acceleration of the electrons so that they move fast enough to carry the required current (i.e., $v_{\parallel,electrons}$ becomes very large). The mechanisms that accelerate the electrons are similar for SKR at Saturn, auroral kilometric radiation (AKR) at earth, and decametric radiation (DAM) at Jupiter, the frequencies differing only because of the magnitude of the magnetic field. Field-aligned potential drops, or equivalently parallel electric fields, arise where acceleration is needed. Such parallel electric fields accelerate electrons, providing the free energy required for the electron cyclotron maser instability to operate (e.g., *Wu and Lee* [1979]; for reviews of the theory of this mechanism see *Zarka* [1998] and *Treumann* [2006]).

The properties of the electron acceleration regions of the terrestrial aurora have been elucidated with data acquired by the FAST spacecraft [e.g., *Paschmann et al*., 2003; *Chaston et al*., 2007, 2008]. The FAST data show that the acceleration is achieved by a combination of quasi-steady parallel electric fields and kinetic Alfvén waves. Where kinetic Alfvén waves are present, the parallel component of the electric field is oscillatory. Correspondingly, plasma electrons must be accelerated not only down into the ionosphere (to carry upward FAC) but also upward, away from the ionosphere following a field line through the magnetosphere to the opposite ionosphere. Such electron beams moving upward in the southern hemisphere have been observed in conjunction with intense field-aligned current within and close to the source region of SKR by *Schippers et al.* [2011]. Because the internal magnetic fields of planets are symmetric within a factor of ~2 and bouncing energetic electrons typically conserve the first adiabatic invariant, the parallel velocity of a reflected electron moving into the loss cone plasma distribution present above the opposite ionosphere will be roughly equal to its initial value. Assuming that the phenomenology at Earth applies also to Saturn, such accelerated electrons moving downward into the opposite hemisphere could plausibly excite SKR (Figure 2). Only a fraction of the electrons would be accelerated in the Alfvénic part of the southern acceleration region, so only exceptionally intense FACs, such as those associated with the emissions in the south during southern summer, would produce enough backward-moving electrons to produce a detectable signal in the opposite hemisphere. Because only a fraction of the primary electron flux is reflected, the signal in the opposite hemisphere would be weaker than in the source hemisphere. Indeed, the northern hemisphere emissions at the southern period are significantly weaker than the corresponding southern hemisphere emissions. Furthermore, it is understandable that field-aligned electrons associated with the weaker signals generated in the north do not typically produce a detectable signal in the south. It is possible that isolated intensifications in the south do occur at times when the northern source is anomalously intense. For example, Figure 1 of *Ye et al*. [2016] includes isolated intensifications in the southern hemisphere in 2004 and 2005, some of which are consistent with observing the northern period in the south, although the paper does not comment on them.

The mechanism described above has not been explicitly identified at Saturn, but the concept of reflected electrons in a region of intense auroral emission has been useful in interpreting aspects of auroral signatures linked magnetically to the moon, Io, at Jupiter [*Bonfond et al.*, 2008]. Figure 3 is an extension of Figure 4 of the *Bonfond et al.* paper. The emissions in the auroral ionosphere are driven by FACs (shown schematically as blue lines in the diagram) generated by Io's motion relative to Jupiter's near-equatorial plasma. The FACs flow both north and south away from Io. Near the center of Jupiter's equatorial plasma sheet, the Alfvén wave speed (of order 200 km/s) and the plasma flow speed (74 km/s) [*Kivelson et al.*, 2004] imply wave propagation at an angle of about 20° from the field direction as illustrated in Figure 3b. Once the waves exit the high plasma density region near the equator, the plasma density becomes very low and the Alfvén speed becomes so high that the remaining propagation is nearly field-aligned. When Io is near the center of the plasma sheet, the FACs reach the two ionospheres at locations that are offset in the direction of planetary rotation from Io's position. At the ionospheric foot of the field line carrying current upward from the ionosphere, auroral emissions arise where accelerated electrons interact with the ionosphere [*Gérard et al.*, 2002].

The auroral response changes when Io is located well off the center of the plasma sheet. *Bonfond et al.* [2008] show that when Io's position is above the jovian plasma sheet, the primary auroral excitations do not lag Io's flux tube but, rather, are found close to the ionospheric ends of Io's flux tube both in the north and in the south (see the insets above and below the schematic illustration in Figure 3c). The signal in the north is easy to interpret. The FACs generated at Io are carried by Alfvén waves, and the extremely low plasma density and high Alfvén speed in regions between the upper boundary of the plasma sheet and Jupiter's ionosphere imply that disturbances travel at a large fraction of the speed of light and reach the northern ionosphere without having drifted far from the foot of Io's flux tube. However, a wave-mediated signal propagating southward from an origin just north of the plasma sheet at an Alfvén speed of 200 km/s would require of order 20 minutes to traverse the entire thickness of the equatorial plasma sheet (~ 4 R_J in thickness, where R_J is Jupiter's radius = 71492 km); consequently, the signal in the southern ionosphere would lead (in the sense of planetary rotation) the foot of Io's flux tube by ~ 12° of longitude. This accounts for the brightest spot in the lower bar of Figure 3c, but not for the somewhat dimmer spot near the southern foot of the Io flux tube. *Bonfond et al.* conclude that the auroral emission near the southern foot of Io's flux tube results from precipitation of high energy electrons that have traveled very rapidly from a source near the northern foot of the same flux tube.

4. Additional implications

A link between accelerated field-aligned electron flux and SKR emissions is well established so our model has implications for the rotation phase at which the southern period emissions are most intense in the northern auroral zone. Using the PPO (Planetary Period Oscillation) phase definition adopted for the study of the magnetic signatures of the FACs [as in *Hunt et al*., 2015], our model implies that SKR emissions in the northern auroral regions produced by backscattered electrons of southern periodicity should be centered at 270° southern phase, the phase at which emissions peak in the south. This is 180° from the phase at which the upward current arising in the north from the southern source is located. (Figure 1g of Hunt et al. shows that in the north, the upward PPO current from the southern source flows at 90° southern phase.) One might expect that upward current to be a second source of SKR emission that would intensify as it moved into the morning sector [e.g., *Lamy et al.*, 2009, *Jia et al.*, 2012], thereby introducing a second harmonic into the periodic intensification of SKR.

We are faced with a dilemma that requires further analysis of the link between FACs, accelerated electrons, and the generation of SKR. The backscattered electrons at 270° southern phase carry upward current in the north. If upward currents of southern origin and similar amplitude were present at both 90° and 270° southern phase, the magnetic signatures would vary at the second harmonic of the southern PPO period. Such higher frequency variations have not been identified in the analysis of *Hunt et al.* [2015]. This means that either our model is wrong, or that the FACs carried by the backscattered electrons are not intense despite the fact that the accelerated electrons stimulate SKR emissions. We favor this interpretation because the conditions for generating radio emissions can be satisfied where field-aligned electron flux accelerated by a remote source encounters a loss cone distribution even if it contributes little to local FACs and magnetic perturbations. One can show that the amplitude of the magnetic perturbation driven by precipitating electrons varies inversely with electron energy, ε. Precipitating electrons with density n_e enter the ionosphere with velocity v_e. On average each electron deposits energy ε. The power delivered per unit area to the ionosphere by the precipitating electrons is thus $n_e v_e \varepsilon = -j\,\varepsilon/e$, where j is the current density and e is the charge on the electron. Ion velocities are small and their contribution to the current density has been dropped. If P is the total SKR power and α is the conversion efficiency, then $j = eP/\alpha\varepsilon\ell\delta$, where ℓ is azimuthal length of the SKR source region and δ is latitudinal length. From Ampere's law, $B_\varphi = \mu_o j\delta/2 = \mu_o eP/2\alpha\varepsilon\ell$. The equation above shows that the field perturbations arising from precipitating accelerated electrons may be quite small (B_φ decreases as the energy of the electrons increases). Indeed, using typical values from published results on the properties of the SKR source [e.g., *Lamy et al*., 2013], i.e., a total SKR power P ~ 10^7 W, characteristic electron energy ε ~ 1 keV, conversion efficiency α ~ 1%, local time extent ℓ ~ 2 hours and latitudinal width δ ~ 3° at ~ 70° latitude, one obtains a magnetic perturbation B_φ ~ 6 nT. This is small compared with the ~ 25 nT signature normally used to identify the PPO perturbations by *Hunt et al.* [2015]. Thus the absence of a magnetic signature of the backscattered electrons at 270° southern phase can be understood.

We are left with ambiguity. The upward PPO currents in the north from the southern system could be the dominant source of the northern SKR emissions modulated at the southern period, in which case, the emissions would peak at 90° southern phase and the postulated source from backscattered electrons would be weak. However, it is only when FACs are too large to be carried by the electrons of the ambient plasma that parallel electric fields develop and accelerate electrons along the field. PPO currents weaken as they propagate through the magnetosphere and the currents of the southern system are not intense in the northern hemisphere. This is illustrated in the cartoons of Figure 1g of Hunt et al. It is reasonable to suggest that the return current out of the northern ionosphere can flow without requiring acceleration by a parallel electric field. In this case, the SKR emissions stimulated by the southern source would peak at 270°, the southern phase at which SKR power peaks in the south. This is a conclusion that can be tested.

Both models are consistent with the expectation that in the post-equinox years when the intensity of the northern hemisphere SKR dominated a secondary signal would appear in the south at the northern period. *Lamy* [2017] states that recently updated southern SKR periodograms show “a secondary peak at the northern period after late 2016, a situation similar to the converse presence of the southern period in northern SKR in 2007.”

5. Summary

At Saturn, the electron precipitation that drives SKR is usually described as being driven by quasi-static parallel electric fields that arise in regions of upward FAC, but it seems plausible that, as at Earth and Jupiter, backscattered electrons associated with kinetic Alfvén waves in the opposite hemisphere contribute to the generation of radiation. Either mechanism would explain why a portion of the signal radiated from the northern hemisphere is modulated at the southern period even when sources in the north vary purely at the northern period and would eliminate the awkward need to drive the northern auroral ionosphere at two distinct periods. One of the two mechanisms must dominate the generation of radiation because there are no reports of the second harmonic in the radiation spectra. We think it probable that backscattered electrons dominate the emissions in the north at the southern period, largely based on evidence that backscattered electrons are effective in stimulating auroral emissions at Io’s footprint in Jupiter’s ionosphere.

The last months of the Cassini mission (the Grand Finale) acquired data on orbits that skim the SKR source region, possibly close to the region of the most intense emissions in the north. Without a functioning plasma investigation it may not be possible to identify signatures of field-aligned electrons or kinetic Alfvén waves, but our analysis suggests that it would be desirable to probe available instrumentation for evidence of their presence and of their rotation phase dependence.

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Figure Captions

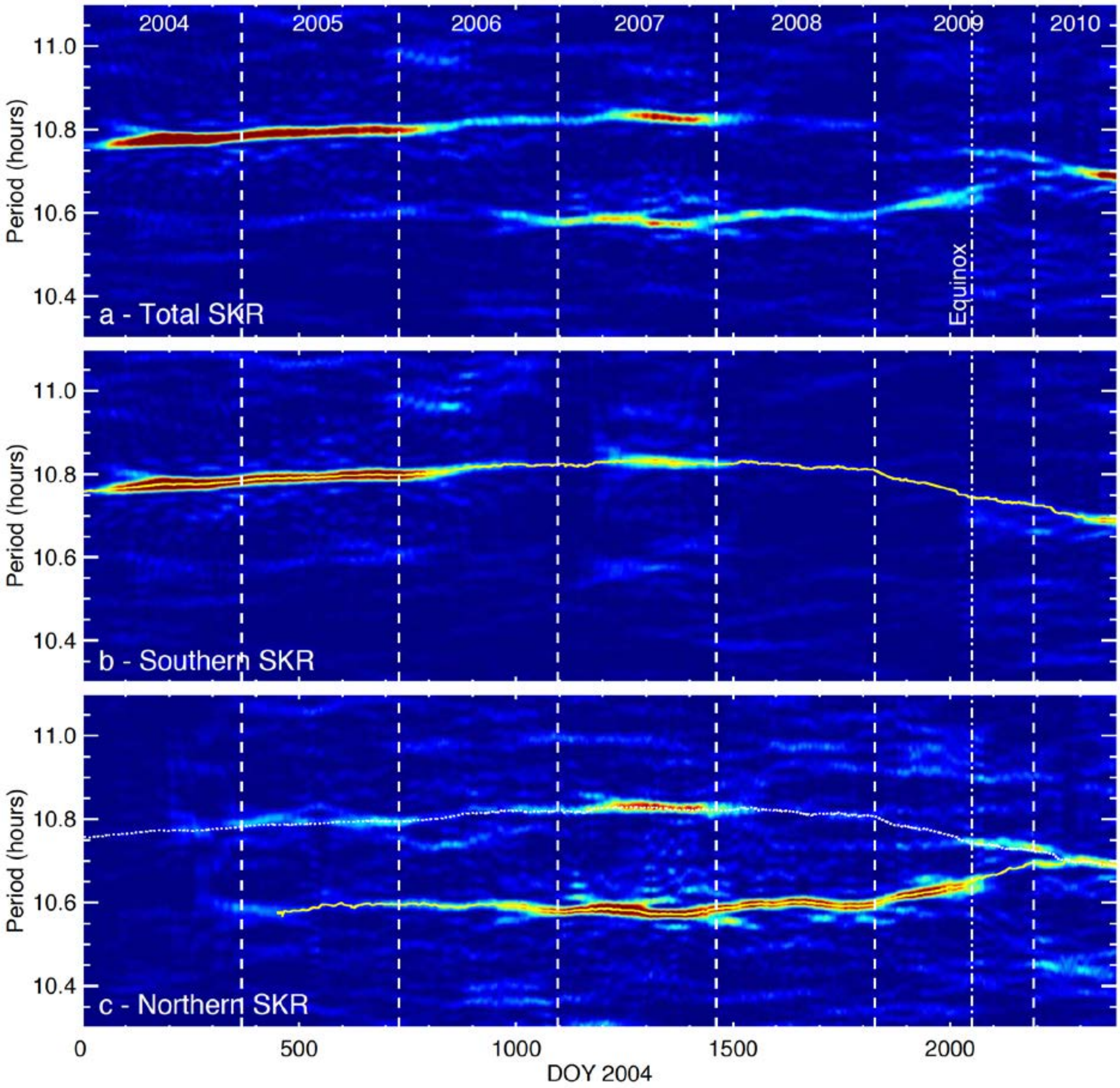

Figure 1. The spectra of SKR emissions from *Lamy* [2011] (their Figure 1). Periodograms of the relative intensity of (a) total, (b) southern and (c) northern SKR power between 40 and 500 kHz vs. time. See *Lamy* [2011] for details. Solid yellow lines were provided in the original publication to represent the inferred periods north and south vs. time. The dotted white line in panel (c) representing emissions in the north was traced from the solid yellow in panel (b) representing the southern period. The secondary emissions are seen to lie close to this line.

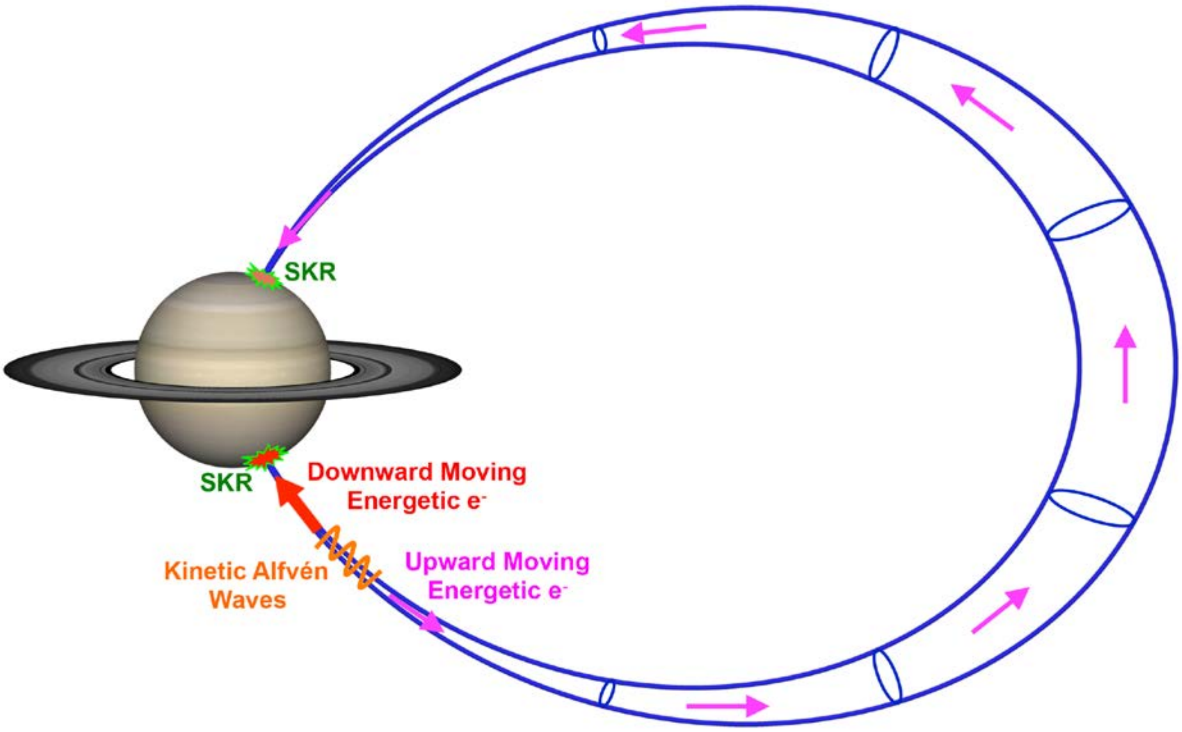

Figure 2. A schematic illustration of our proposed interpretation of the coupled SKR emissions in Saturn's northern and southern ionospheres.

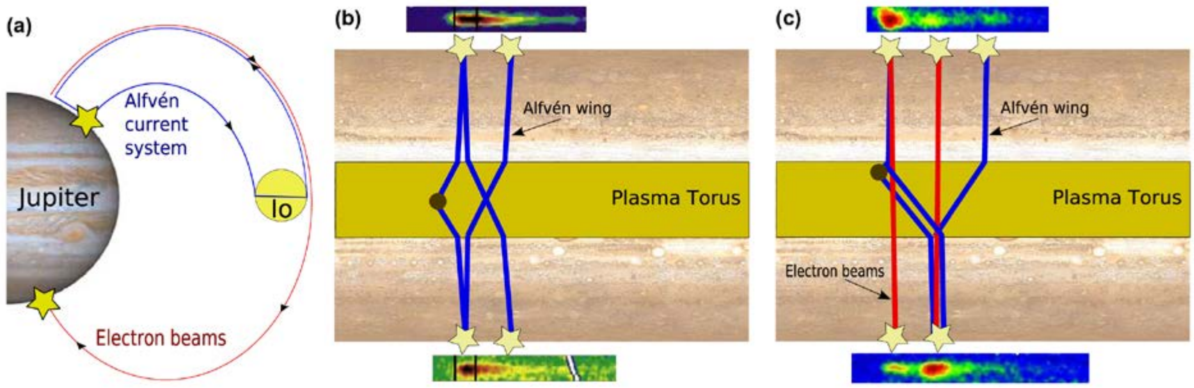

Figure 3. (a) From *Bonfond et al.* [2008], their Figure 4a. A meridional view of FACs flowing to and from the northern ionosphere generated by Io's motion through the jovian plasma sheet (blue lines). In red: reflected accelerated electrons precipitating into the opposite hemisphere. (b) A combination of illustrations from Figures 3 and 4 of *Bonfond et al.* [2008], A flattened L-shell through Io (black circle) showing schematically the paths of current-carrying Alfvén waves (blue lines) generated when Io is near the center of the plasma sheet. Yellow stars show where the FACs excite auroral emissions. Colored bars above and below the figure show the morphology of the auroral emissions observed north (top) and south (bottom) at the ionospheric ends of Io's flux tube when Io is at the center of the plasma sheet. (c) As for (b) but when Io is near the top of the plasma sheet.