Clues on Ionospheric Electrodynamics From IR Aurora at Jupiter and Saturn

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Ionospheric flows within the upper atmospheres of the gas giants provide a valuable tool with which to understand the currents flowing through the ionospheres of these planets, as well as the magnetospheric origin of these currents. These flows are measured using high-resolution long-slit spectroscopy from ground-based telescopes, producing both intensity and velocity profiles that allow us to understand the flows and see how they are associated with the aurorae. Thus, it is possible to compare and contrast both morphology and flow speeds of H_3^+ in the ionospheres of Jupiter and Saturn, revealing a number of significant similarities suggesting comparable origins for ionospheric features created by currents that are associated with both internal circuits and the influence of the solar wind. There remains much controversy about the way the solar wind affects these planets, particularly at Jupiter. Only with more detailed observations will this controversy be resolved.

1. INTRODUCTION

While much of what we know about the morphology of the aurora of the gas giants (Jupiter and Saturn) comes from the detailed long-term UV observations made by the Hubble Space Telescope [*Clarke et al.*, 1996; *Grodent et al.*, 2008], IR observations have not only given us detailed information about the aurorae [*Badman et al.*, 2011; *Melin et al.*, 2011] but have also provided a depth of understanding about the physical conditions in the ionospheres of these planets [*Miller et al.*, 2006; *Stallard et al.*, 2012a].

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Bright auroral emissions are created on both planets by energetic electrons that stream into the atmosphere from the surrounding magnetosphere along Birkeland field-aligned currents. These currents close via a Pedersen current that typically flows equatorward through the ionosphere, in turn driving a Hall drift that forces the ions to subrotate [*Hill*, 1979; *Stallard et al.*, 2001]. Auroral emissions are also produced at the magnetic footprints of some moons [*Connerney et al.*, 1993; *Pryor et al.*, 2011] and as the result of pitch angle scattering from hot plasma within the magnetosphere [*Grodent et al.*, 2010], though no ionospheric flows have been found that are associated with these aurorae.

Emission from the ionic molecule H_3^+ has been studied using ground-based telescopes, providing both images and spectra that have yielded a number of significant scientific advances. One of the most important aspects of these studies comes from high-resolution spectroscopy, allowing us to measure the line-of-sight velocity of H_3^+ in the ionosphere and, from this, to understand the current systems flowing through the upper atmospheres of these planets [*Stallard et al.*, 2001].

H_3^+ is formed through a fast chain reaction process beginning with the ionization of molecular hydrogen into H_2^+. The H_2^+ ion is then rapidly converted to H_3^+ by a strongly exothermic reaction [*Yelle and Miller*, 2004]. On both planets, the majority of ionization is in the auroral region by precipitating energetic electrons, but also occurs, globally, by solar extreme ultraviolet (EUV) radiation ionizing molecular hydrogen.

H_3^+ is, under most conditions, a highly reactive molecule, and is quickly destroyed in the presence of any species other than hydrogen or helium (since He has a lower proton affinity than H_2). However, in the upper atmosphere of Jupiter and Saturn, species concentrations are controlled by diffusion, such that they each settle out with their own scale height. In a hydrogen-rich atmosphere, this means that heavier species settle out, and at higher altitudes, H_3^+ protonating reactions cannot take place [*Yelle and Miller*, 2004]. As a result, the lifetime of the H_3^+ molecule is directly controlled by dissociative recombination, which occurs at a rate given by *McCall et al.* [2005] as 2.6×10^{-13} m^3 s^{-1}. This means that H_3^+ lifetimes are typically between a few and a few thousand seconds, for electron densities between 10^{12} and 10^9 m^{-3}, respectively. These lifetimes are a factor of 500 and 500,000 times longer than the typical radiation lifetime of a rovibrationally excited H_3^+ molecule, for which Einstein A_{if} coefficients range between ~10 and 100 s^{-1} [*Neale et al.*, 1996].

However, the IR auroral emission of H_3^+ is a thermal emission, directly affected by the conditions within the upper atmosphere [*Miller et al.*, 1990]. Simultaneous observations of the auroral region in both wavelengths have been made from Earth for Jupiter [*Clarke et al.*, 2004] and using in situ images at Saturn [*Melin et al.*, 2011]. While these show that the general morphology of the H_3^+ and UV auroral emission matches, there are still significant variations caused by the ionospheric conditions, as well as altitudinal differences, with H_3^+ brightness being enhanced with increasing altitude at Jupiter due to increases in temperature [*Lystrup et al.*, 2008]; interestingly, it appears that H_3^+ emission appears to be relatively weaker than the UV emission at higher altitudes above Saturn [*Stallard et al.*, 2012b].

Since H_3^+ has an approximate lifetime of 10 min in the upper atmosphere of the gas giants, the molecule can interact with the surrounding neutral atmosphere through collisions. H_3^+ then takes on the thermal characteristics of the surrounding neutral atmosphere, with auroral brightness strongly controlled by temperature, especially at Saturn. This interaction also strongly affects ionospheric velocities, as a continual accelerating force moving ions back into corotation with the planet. As such, the measurement of ion flows within the ionosphere, moving against this background neutral atmosphere, provides a direct measure of the electric currents that cross the ionosphere.

2. VELOCITY MEASUREMENTS

While, at first appearance, there are notable brightness and morphological differences between the aurora of Jupiter and Saturn, the flow speeds of H_3^+ in the ionospheres can be directly compared and contrasted. In looking at the phenomenology of H_3^+ at each planet, a number of significant similarities have been shown to exist, so that apparently, contrasting features can be shown to have similar origins. Equally, there are also some features of intensity and velocity that may be unique to each of these planets.

Using high-resolution long-slit spectroscopy, it is possible to measure the H_3^+ velocity in the line of sight. The peak intensity and position of a particular line of H_3^+ emission can be calculated by fitting the line with a Gaussian in the wavelength direction; by repeating this process across all the spatial rows of the spectral slit, a profile of intensity and ion wind velocity can be produced (for more details of this process, including the instrumental corrections required, in the case of Jupiter, see *Stallard et al.* [2001], and of Saturn, see *Stallard et al.* [2007a]).

Figure 1 shows the intensity and velocity profiles of the auroral regions of both Jupiter and Saturn during "typical" auroral conditions, with a long-slit spectrometer aligned perpendicular to the rotational axis, cutting through the center of the main auroral oval. The ion winds that flow through the upper atmosphere of gas giants are produced by currents that connect the atmosphere with the magnetosphere, and the neutral atmosphere acts to accelerate the ionosphere into corotation with the planet where such currents do not exist. As a result, using this perpendicular cut across the planet allows the measurement of the ion flows relative to the background rotation rate of the planet.

These 1-D cuts through the auroral region can be extrapolated into 2-D maps of the ion flows across the region, as shown in Figure 2. At Jupiter, the spectral slit was scanned across the auroral region [*Stallard et al.*, 2003], while at Saturn, these can only be defined more loosely and are largely based on perpendicular cuts through the rotational pole, extrapolating from the varying positions of the slit on different nights, and the associated intensity structure measured when the slit is aligned with the rotational axis.

Using these observations, we can categorize the ion winds seen at the gas giants into six main velocity regimes:

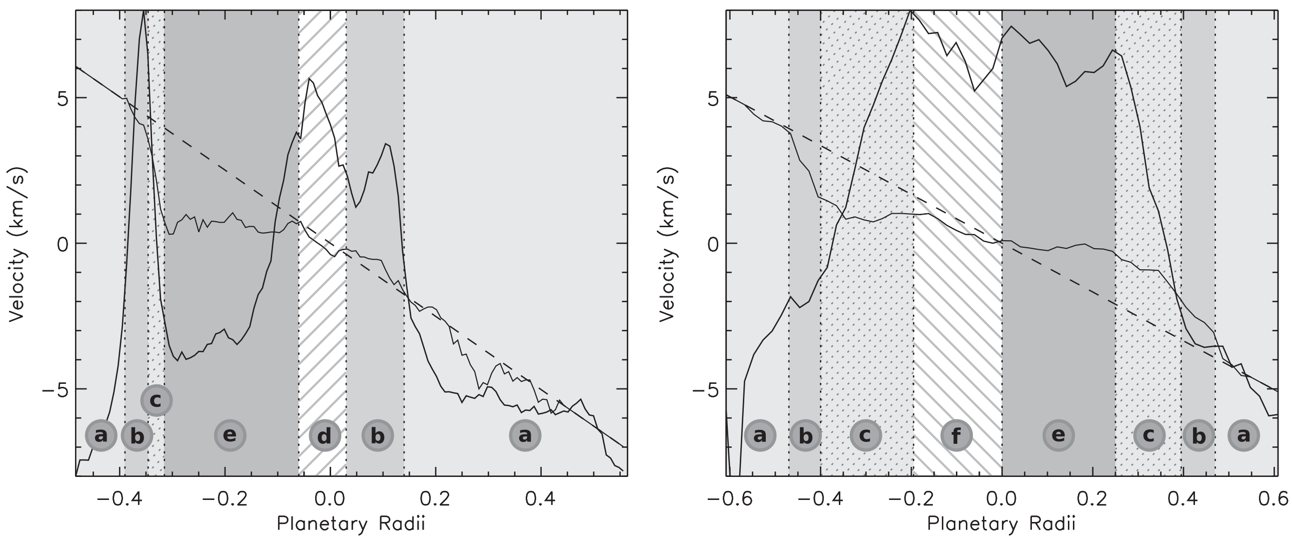

Figure 1. The typical H_3^+ line-of-sight velocity (bold line) and normalized intensity (thin line) for (left) Jupiter and (right) Saturn plotted against the rotational rate for each planet (dashed line). Each velocity profile is divided into regions demarcated by patterned backgrounds and lettering, directly relating to the lettered sections included within the text and Figures 2–4. Both intensity and velocity were calculated by fitting the spectra with a Gaussian; Jupiter data were measured on a pixel-by-pixel basis, while the Saturn data were smoothed with a 5-pixel box car function.

2.1. Region a: Equatorial Regions

This region is equatorward of the region of strong auroral emission and away from any significant currents, in which ions corotate with the planet.

2.1.1. Jupiter. EUV ionization produces enough H_3^+ emission that the ion flow can be measured in regions without any auroral component. In addition, there are also middle-latitude to low-latitude emissions that are higher than can be explained by EUV ionization alone [*Miller et al.*, 1997].

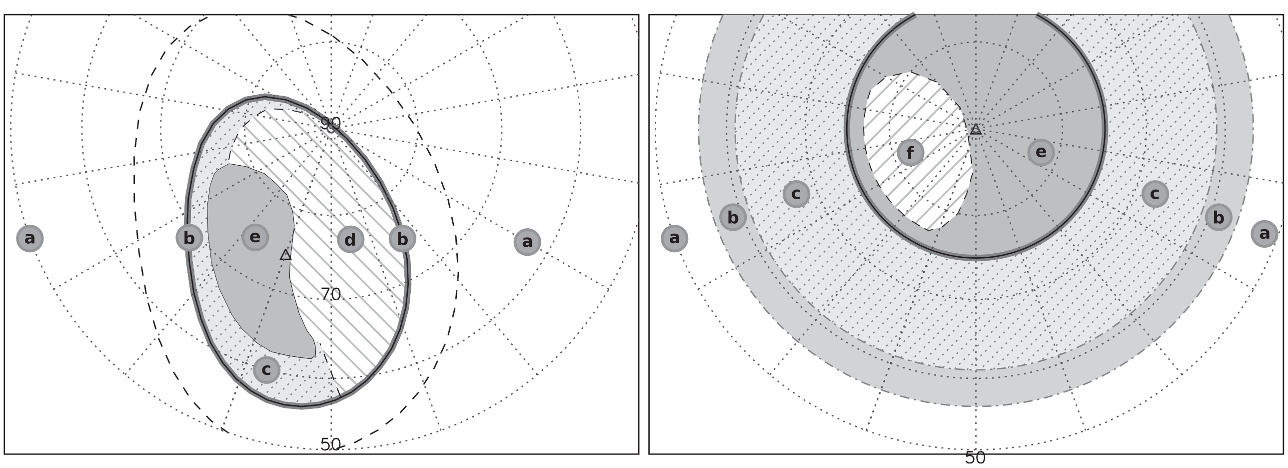

Figure 2. Maps of ion flow in the northern auroral regions of (left) Jupiter (at a central meridian longitude of 160) and (right) Saturn. The various flow regions are demarcated by patterned backgrounds and lettering, matching Figures 1, 3, and 4. In addition, the main (brightest) auroral oval for each planet is delineated (thick gray and black line), as well as the path of the magnetic mapping to Io across Jupiter (dashed line) and the mid-latitude auroral oval at Saturn (the region within the dash-dotted lines). Lines of latitude and longitude are shown (dotted lines) in steps of 10° and 20°, respectively, with noon at the bottom of each map. The magnetic pole is also shown (triangle). The area covered by region f is highly variable, and so its location here is illustrative.

Measurements have shown that Jupiter does not have any significant velocity flow (>0.2 km s^{-1}) within either of these regions [*Stallard et al.*, 2001].

2.1.2. Saturn. Equatorial H_3^+ emission has only been measured recently, and no velocity measurements exist in this region [*Stallard et al.*, 2012a]. However, at the edge of the auroral region, the ions can be seen to return to corotation, before the emission becomes too weak to detect.

2.2. Region b: Breakdown in Corotation

The initial breakdown in corotation poleward of equatorial corotating ions occurs. This region is directly associated with a continuous auroral oval of H_3^+ emission.

2.2.1. Jupiter. The breakdown region is directly associated with the main auroral oval, which maps from at least 15 to several tens of R_J in the magnetospheric equatorial region [*Grodent et al.*, 2003a], with subrotating flows typically of the order 0.5–1.5 km s^{-1} once adjusted to take the line of sight into account. The upper limits to this velocity are measured during periods of enhanced auroral activity [*Melin et al.*, 2006], with the measured speed appearing to vary with auroral brightness [*Stallard et al.*, 2001].

2.2.2. Saturn. The initial breakdown in corotation is associated with the mid-latitude auroral oval significantly weaker than the main auroral oval [*Stallard et al.*, 2008a], at a latitude that maps to 3–4 R_S [*Stallard et al.*, 2010], close to the location of Enceladus.

2.3. Region c: Boundary Subrotation

A region of subrotating ions that is poleward of the breakdown in corotation and equatorward of the region is associated with the solar wind but not associated with any significant auroral emission. For both planets, it is difficult to assess the extent to which this is a true velocity flow, rather than the effect of seeing blurring the boundary between two regions moving with very different velocities, with velocities scaling between those measured in the surrounding regions.

2.3.1. Jupiter. The area covered by this region, along the dawn flank of the zero-rotation polar region, aligns this region closely to the Dark Auroral Region within the UV. However, apart from, at the most, equatorward extent, the region itself is often only a few pixels across [*Stallard et al.*, 2003].

2.3.2. Saturn. This region, typically seen on both the dawnside and duskside of the auroral region, extends from the main auroral oval equatorward, subrotating at less than one-third corotation velocity. This region often extends to significant distances, so that the flows seen cannot be produced by a seeing-smeared boundary between the corotation breakdown and the main auroral oval and must therefore be real. It could, however, conceal significant ion flow variability that simply cannot be detected once the measurements have been affected by the Earth's atmospheric turbulence [*Stallard et al.*, 2007a].

2.4. Region d: Bright Corotation

This is a region of near corotating ions, poleward from the initial breakdown in corotation and associated with significant auroral emission.

2.4.1. Jupiter. This velocity region is directly correlated with the auroral region known as the Bright Polar Region in H_3^+ emission and the Active Region in UV observations; these emission regions are associated with bright auroral arcs, on top of a moderately bright background of emission [*Grodent et al.*, 2003b]. The ion flow measured in this region appears to vary in strength, often appearing to corotate completely, while at other times subrotating at wind speeds up to 1 km s^{-1}, though the ion flows are never larger than those on the main oval [*Stallard et al.*, 2001].

2.4.2. Saturn. Such regions of close-to-corotating ions are not measured at Saturn. However, since H_3^+ auroral arcs are measured at Saturn but cannot be discerned within ground-based data [*Melin et al.*, 2011], observing constraints appear to prevent the detection of any such flow regions.

2.5. Region e: Dim Subrotation

These are regions of strong subrotation or even zero rotation within the auroral polar regions.

2.5.1. Jupiter. This region is limited to the dawnside of the polar regions, where the polar aurora is weakest, and the ionosphere appears to be stagnant within the inertial frame, producing, in the planetary frame, wind speeds of >4 km s^{-1} [*Stallard et al.*, 2001], so that the region is clearly affected by the influence of the solar wind [*Stallard et al.*, 2003; *Cowley et al.*, 2003].

2.5.2. Saturn. This region, poleward of the main oval, cannot be directly discerned from ion flows alone, with the same subrotation of less than one-third corotation as is measured in region c [*Stallard et al.*, 2003]. However, this region sits inside the main auroral oval at Saturn, directly associating it with a region controlled by the solar wind, as described in the next section.

2.6. Region f: Polar Corotation

This is a region of corotation entirely enclosed by the surrounding subrotating ionosphere, close to the magnetic pole.

2.6.1. Jupiter. While the Jovian polar region appears to be held at zero in the inertial plane, there are some examples of subrotation within this region; however, the spatial accuracy of the data is too weak to properly detect such a region of flow [*Stallard et al.*, 2001].

2.6.2. Saturn. This region lies poleward of the main auroral oval and is not associated with any obvious auroral features. The size of this region appears to vary considerably, at times crossing the entire region inside the main auroral oval. However, it is usually concentrated on the dawnside of the polar region, with the duskside subrotating [*Stallard et al.*, 2007a]. However, during periods of major compression, associated with dawn brightening, this region cannot be observed [*Stallard et al.*, 2007a].

3. MAGNETOSPHERIC AND SOLAR WIND ORIGINS FOR ION WINDS

Since the ionospheres of the gas giants tend to be accelerated up to corotation with the planet by the surrounding neutral atmosphere, any subrotational ion flows in the ionosphere are driven by external currents. As such, the ion flows we observe, when combined with auroral emission, provide direct information about the current systems that link the ionosphere with the magnetosphere. We can also use what we know from in situ measurements of the magnetospheric configuration in order to explain the link between auroral emission and their related ion flows.

Our current understanding of the magnetospheric and solar wind origins for the different flows described in the previous section are shown schematically in Figures 3 and 4. A more detailed description of how the magnetosphere of each planet is linked to the ionosphere is given here.

3.1. Region a

The ionospheric equatorial regions of both planets are generally thought to be relatively free of currents, and so the ions in these regions are expected to corotate with the planet.

3.2. Region b

The breakdown in corotation in the ionosphere is directly associated with the breakdown in corotation in the magnetosphere, as explained by the *Hill* [1979] model. Though the cause for this magnetospheric breakdown is different for Jupiter and Saturn, and happens at very different radial distances, the way this process drives ion flows on the planet is the same. The subrotating plasma in the magnetosphere acts as a charge moving through a magnetic field, setting up a continuous current that closes through the planet, driving particle precipitation into the atmosphere.

3.2.1. Jupiter. The magnetic field at Jupiter is strong enough that ions from Io are forced into corotation with the planet, drifting outward under centrifugal force to form a corotating plasma sheet. Angular momentum is supplied from the planet's upper atmosphere by the collision between the ionosphere and neutral thermosphere, maintaining this corotation through a "push me-pull you" effect; in the magnetosphere, as the plasma lags behind the Jovian field, it generates a current and is "instantaneously" brought back into corotation, thus switching the current off again.

As the plasma sheet moves to greater distances, its momentum increases, while the magnetic field strength driving the corotation decreases, until the mechanism breaks down catastrophically at radial distances ~20 R_J [*Hill*, 1979; *McNutt et al.*, 1981], where the magnetic field strength is too low, and the required velocity too great, for full corotation to be maintained.

This results in a very stable auroral emission, produced by the continuous particle precipitation from the current system, as well as steady ion flows in the ionosphere stable at timescales as short as a minute [*Lystrup et al.*, 2007], though they can vary over several Jovian rotations [*Stallard et al.*, 2001].

3.2.2. Saturn. The magnetosphere at Saturn is mass loaded by icy volcanic output from Enceladus. While the eruption rates of Enceladus are much lower than that of Io because the magnetic field at Saturn is weaker, the magnetosphere becomes intrinsically more heavily mass loaded than the magnetosphere of Jupiter [*Vasyliūnas*, 2008].

This means that ions produced from the torus of Enceladus never attain corotation; the neutral torus spreads inward to ~3 R_S, and any ion produced from the torus at this point, or any point further out, cannot be forced into corotation by the magnetic field. As a result, the velocity of ions in the magnetosphere break with corotation at ~3 R_S [*Wilson et al.*, 2009], the inner edge of the torus, producing Hall drift and an auroral oval within the ionosphere at the latitudes mapping between 3 and 4 R_S [*Stallard et al.*, 2010].

This current system can be compared with both the breakdown in corotation at Jupiter, at ~20 R_J, and with the formation of the Io spot's trailing tail, formed by mass loading from Io; Enceladus dominates Saturn's magnetic field, while ions from Io's torus are quickly forced to corotate, preventing

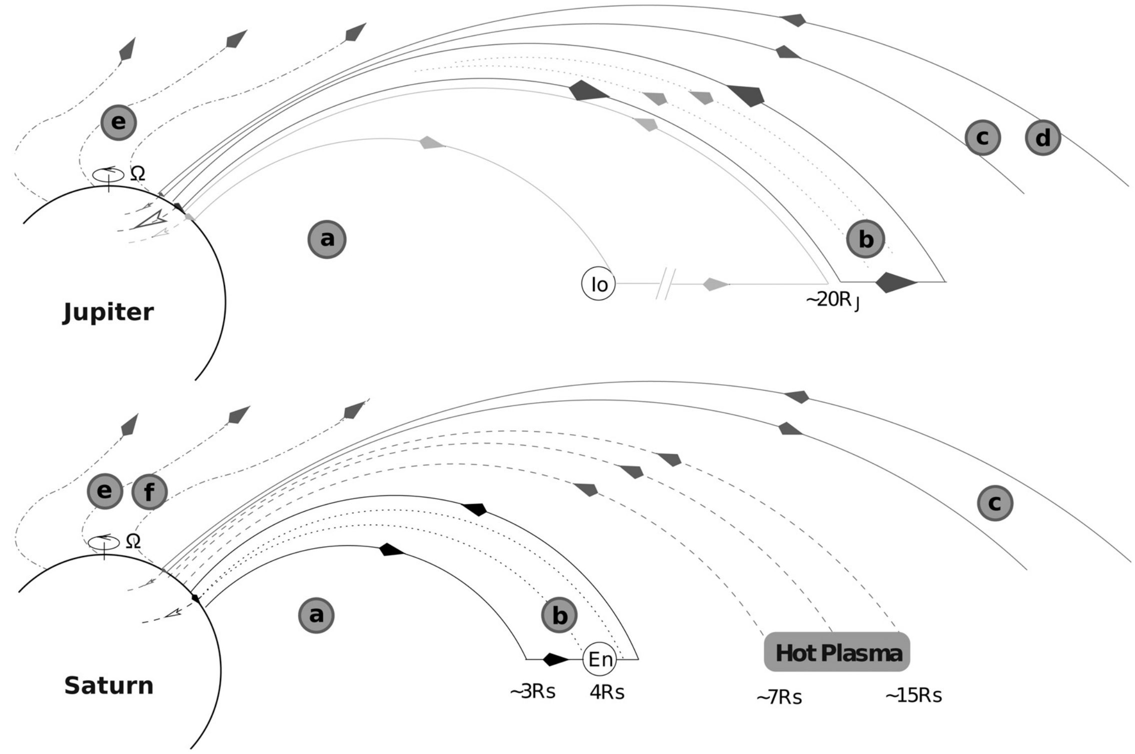

Figure 3. An illustrated representation of magnetosphere-ionosphere interconnection along magnetic field lines at Jupiter and Saturn. Currents flowing along field lines controlled by internal processes (solid lines) [*Hill*, 1979] and magnetic field lines either directly or indirectly connected with the solar wind [*Cowley et al.*, 2003, 2004; *Delamere and Bagenal*, 2010] (dash-dotted lines) are shown. In addition, for Saturn, pitch angle scattering from the hot plasma region is also represented (dashed lines) [*Grodent et al.*, 2010].

the formation of an oval of emission that completely encircles Jupiter.

3.3. Region c

This region, defined on both planets by regions of sub-rotation and relatively dark aurora, has been associated with the return flow of empty flux tubes from the *Vasyliūnas* [1983] and, possibly, Dungey cycles, once plasmoids have escaped down the tail, as explained for region d (section 3.4). These are concentrated on the dawn flank, especially for Jupiter, due to the rotational energy of the planet pushing them to this side from midnight [*Cowley et al.*, 2003].

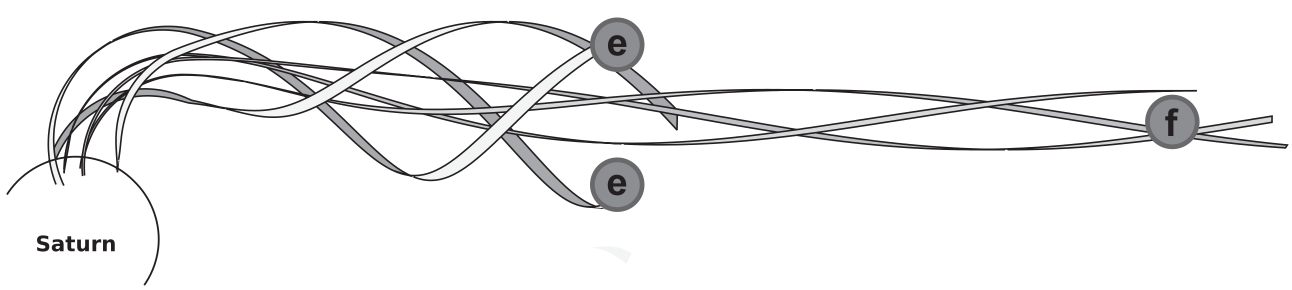

Figure 4. The *Stallard et al.* [2007b] explanation of how open field lines connect with Saturn's auroral region. Field lines connected with the solar wind subrotate and become twisted, resulting in a "core" of field lines [*Milan et al.*, 2005] that are sustained so long that they cannot effectively transfer information back to the planet, resulting in regions of corotation (labeled f) inside the open field line region (labeled e).

3.4. Region d

This region of close to corotation must map to a mid-to-far magnetospheric processes, beyond the breakdown in corotation, but remaining on closed magnetic field lines.

3.4.1. Jupiter. There remains considerable debate about the origin of the "active" region of the UV emission, with which this region of ionospheric flow is associated. *Pallier and Prangé* [2001] have suggested that this feature may be related to the cusp, an analog to what is observed in the Earth's dayside aurora, with auroral arcs mapping to dayside reconnection of the Jovian magnetic field lines with the interplanetary magnetic field. The *Cowley et al.* [2003] model produces a polar asymmetry as, in the magnetosphere, the Vasyliūnas cycle outflow of iogenic plasma flows down the dusk and midnight tails. In this case, the dusk sector of the polar ionosphere then corresponds to closed field lines, which map to the near corotating tail duskward of the outer boundary of the plasmoid.

3.4.2. Saturn. There is no observational evidence of this ion flow region at Saturn, though such flow regions could remain undetected in the region c dusk ionosphere. Indeed, *Jackman and Cowley* [2006] have theorized the existence of such flow regions, associated with the Vasyliūnas cycle, on the duskside of the aurora. Direct evidence of the Vasyliūnas cycle has now been detected within the Saturnian magnetosphere [*Masters et al.*, 2011].

3.5. Region e

On Earth, the Dungey cycle acts to produce a strong antisunward ionospheric flow, as magnetic field lines are effectively dragged across the pole by the solar wind [*Dungey*, 1961]. Since it only takes a few hours for the solar wind to pass the Earth's magnetosphere, the velocity of the flow is significantly higher than the rotation rate of the planet. However, at both Jupiter and Saturn, which have much larger magnetospheres and significantly faster rotational spin, the opposite is true. As a result, the solar wind takes many days to cross the magnetosphere. This is so slow that, to the ionosphere, the field lines affected by the solar wind appear to be stagnant, with an antisunward velocity below the observational detection limit.

3.5.1. Jupiter. Regions of zero-rotation ionospheric flow in the inertial frame of reference can only be produced through an interaction with the solar wind. The most broadly accepted theory of how the Sun controls Jupiter's upper atmosphere, first proposed by *Cowley et al.* [2003] and by the Vogt model [*Vogt et al.*, 2010; *Vogt and Kivelson*, this volume], is that magnetic field lines in the pole are open to the solar wind, in the same way as that of the Earth's and Saturn's magnetic field lines. In this model, the polar cap region is dominated by an asymmetric Dungey cycle, similar to that of the Earth but pushed onto the dawnside of the planet by the outflow of iogenic plasma down the duskside of the magnetosphere, the effects of which are possibly seen in region d.

However, one potential problem with this theory is the significant levels of auroral emission seen in the polar regions [*Grodent et al.*, 2003b; *Stallard et al.*, 2008b], in particular the "Swirl" emission seen in the UV, short timescale apparently random bursts of emission across the region where zero-rotation ion flow is seen. This emission lies on what would be open field lines; these field lines, however, should be empty of plasma, and so this model cannot explain such emission.

A second solar wind interaction model, proposed by *Delamere and Bagenal* [2010] and discussed by *Delamere* [this volume] is that the solar wind interacts with the magnetosphere through small-scale, intermittent structures at the magnetopause boundary. This plasma-on-plasma interaction generates solar wind–imposed magnetic stresses on the magnetosphere. As a result, the solar wind interacts indirectly with the ionosphere, with "Swirl" emission produced by small clumps of closed field lines associated with Kelvin-Helmholtz instability along the boundary of the magnetosphere.

3.5.2. Saturn. Ionospheric flows match well with a Dungey cycle distorted by rotational effects as proposed by *Cowley et al.* [2004], once the effects of seeing have been accounted for [*Stallard et al.*, 2007b], but the spatial detail is not sharp enough to use ion flows to delineate this region. However, synchronous observations by the Hubble Space Telescope and Cassini have mapped the main auroral oval of Saturn to the boundary of magnetic field lines open to the solar wind, suggesting that the entire region poleward of the main auroral oval is open to the solar wind [*Bunce et al.*, 2008; *Bunce*, this volume].

3.6. Region f

When a planet's magnetic field lines are open to the solar wind, they are constrained at the solar wind end, moving steadily antisunward, while at the planetary end, they subrotate with the planet. This results in the field lines becoming twisted and producing a "core" of field lines, at the center of each of the magnetotail lobes, shielded from tail reconnection by the surrounding field lines [*Milan et al.*, 2005]. These "core" open field lines are sustained so long that they cannot effectively transfer information back to the planet, so that the ionospheric region these lines map to is dominated by the neutral atmosphere and corotates with the planet, while the newer field lines surrounding them continue to subrotate [*Stallard et al.*, 2007b].

3.6.1. Jupiter. As discussed above, there remains much debate about the mechanism of solar wind control within Jupiter's ionosphere. However, even if this region is controlled by a form of Dungey cycle, it is possible to explain the lack of any corotation in comparison with Saturn; Jupiter's solar wind–controlled region is held at a near zero rotation, with a maximum subrotation of ~10%. This could significantly inhibit the formation of a twisted tail and thus prevent an old "core" of field lines from forming.

3.6.2. Saturn. This process is able to explain the apparently contradictory presence of corotating ions inside the main auroral oval, which has been shown to mark the open-closed field line boundary. The twisting of the field lines results in an older "core" of magnetic field lines that are shielded from reconnection by smaller solar wind compressions. However, when a major solar wind compression occurs, even these shielded field lines should reconnect.

This theory has been used to explain the massive dawn brightening seen when major compressions in the solar wind impact Saturn's magnetosphere [*Cowley et al.*, 2005], as this "core" is reconnected on the nightside and rotates around, swathing the dawn polar region in emission. Here ion flow measurements are in agreement with the theory: During periods when the auroral morphology is strongly asymmetric, with a bright dawn indicating that a strong solar wind compression has occurred, the region of corotation in the pole cannot be seen; the entire auroral region subrotates [*Stallard et al.*, 2007a].

4. CONCLUSIONS

H_3^+ is an excellent diagnostic tool in helping to understand the upper atmospheres of the gas giants. In the past, it has been used as a probe of the energy distribution within the upper atmosphere, showing the temperature and cooling from the thermosphere [*Miller et al.*, 2006; *Stallard et al.*, 2012a]. Here we have described the major diagnostic tool it can be used for, measuring the ion flows within the ionosphere and how these flows are driven through interactions with the surrounding magnetosphere.

What these observations have shown is that the auroral regions of Jupiter and Saturn are far more alike than previously thought. The same magnetospheric interactions appear to occur on both planets, to a greater or lesser extent, with differences between the two planets coming from the relative strength of these interactions. The only remaining regions that continue to produce considerable debate are the polar regions of each planet, with both emission and ion flows leading the debate about what controls these regions.

Ion wind measurements have shown that Jupiter is significantly affected by the solar wind, despite past theories predicting this would not be possible; now the debate centers on whether this region is open to the solar wind, as on Earth, or is controlled through interactions with the solar wind along the flanks of the magnetosphere. At Saturn, corotating regions poleward of the open-closed field line boundary do not fit well into current models of the magnetosphere, suggesting the twisting of the polar magnetic field lines is confusing our understanding of this region.

Measurements of the ion winds could, theoretically, provide answers to this current debate, but, as we have seen, they are limited in spatial resolution by the turbulent effects of the Earth's atmosphere. However, in the near future, ground-based observations of the auroral region using adaptive optics could make spectral measurements of Jupiter auroral region, allowing us a detailed view of the velocities within the polar regions. Beyond such observations, the NASA Juno spacecraft will move into a polar orbit around Jupiter in 2016. This will allow detailed measurements of the aurora from above, observing the emission on the planet as the spacecraft passes through the very currents that form these aurorae, as they flow along the magnetic field lines into the planet. These observations should, at long last, properly explain the origin of Jupiter's polar aurora.

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