Relating Jupiter's Auroral Features to Magnetospheric Sources

Marissa F. Vogt[1]

Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California, USA
Department of Earth and Space Sciences, University of California, Los Angeles, California, USA

Margaret G. Kivelson

Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California, USA
Department of Earth and Space Sciences, University of California, Los Angeles, California, USA
Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor, Michigan, USA

The magnetospheric processes responsible for Jupiter's auroral emissions differ from those that drive the Earth's aurora. For example, Jupiter's main auroral emissions are associated with the breakdown of plasma corotation in the middle magnetosphere and not, as at the Earth, with the boundary between open and closed magnetic flux. In this chapter, we review some of the main features of Jupiter's auroral emissions and describe how they map to magnetospheric source regions or dynamic processes. Identifying the source of Jupiter's polar auroral features has been difficult because global field models are inaccurate beyond the inner magnetosphere (<30 R_J). However, a recently developed model that relates measured magnetic flux at different radial and local time locations in the magnetosphere to equivalent magnetic flux in the ionosphere (rather than tracing field lines from a global field model) provides a more accurate way to relate the polar auroral regions to magnetospheric sources and, particularly, to identify and constrain the size and location of Jupiter's polar cap. The results give insight into global dynamics and the open or closed nature of the Jovian magnetosphere.

1. INTRODUCTION

For more than a decade, ground and space-based telescope observations have produced dazzling images of Jupiter's auroral emissions in UV, IR, and visible wavelengths. These images have shown that Jupiter's aurora displays some unique features, such as satellite footprints, which are not present in the Earth's aurora. Additionally, there are some features, such as Jupiter's main oval, that may seem similar to their terrestrial counterparts, but are linked to different magnetospheric processes, than those that drive the Earth's aurora.

The purpose of this chapter is to discuss the magnetic links between Jupiter's auroral features and magnetospheric source regions. In particular, we focus on the available global field models and discuss why they are insufficient to reliably map between the ionosphere and the middle to outer magnetosphere, then we review recent work that uses flux equivalence to determine the mapping. This approach provides a more accurate way to relate the polar auroral regions to sources in the outer magnetosphere and provides insight into the sources of auroral activity.

[1]Now at Department of Physics and Astronomy, University of Leicester, Leicester, UK.

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2. OVERVIEW OF AURORAL FEATURES

Jupiter's auroral emissions can be classified into three main types: the satellite footprints, the main oval (main emissions), and the polar emissions [*Clarke et al.*, 1998]. All three components can be seen in Figure 1, which shows a polar projection of the UV auroral emissions in the northern hemisphere, and a comparison between the auroral observations and the

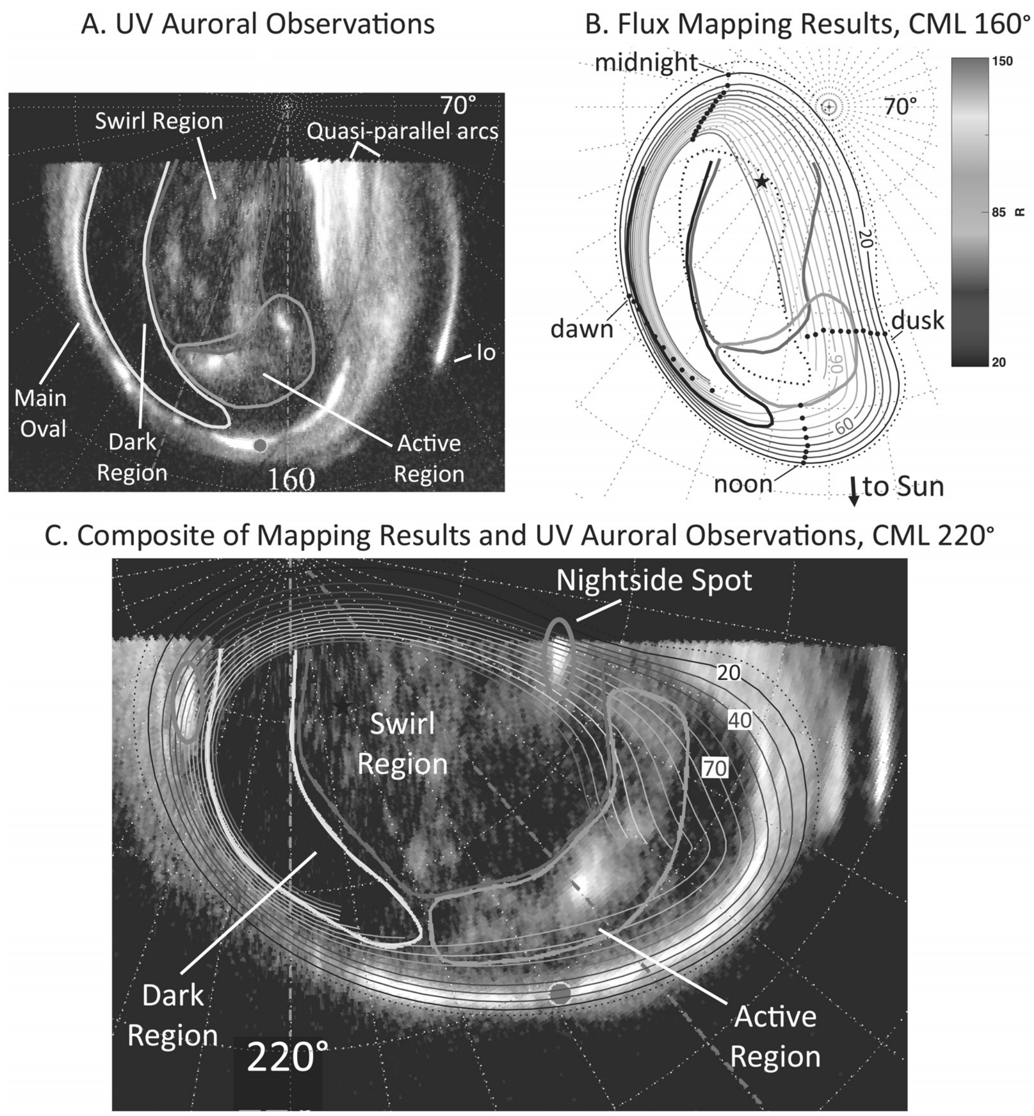

Figure 1. (a) UV observations of Jupiter's northern aurora as imaged by the Hubble Space Telescope (HST) on 16 December 2000. The three polar auroral regions, main oval, and Io footprint are labeled. From *Vogt et al.* [2011, Figure 1]. Modified from *Grodent et al.* [2003b, Figure 5]. (b) Mapping results for central meridian longitude (CML) 160° for the same viewing geometry as in Figure 1a. Contours are drawn every 10 R_J at the equator from 20 to 150 R_J and are not drawn for distances beyond the expanded magnetopause [*Joy et al.*, 2002]. The star symbol indicates the location of the magnetic pole at 9.6° colatitude and 212° SIII longitude, and black dots indicate the approximate mapping of four local times (midnight, dawn, noon, dusk). The outer black dashed line indicates the 15 R_J starting reference contour. The inner black dashed line shows the location of the fixed Dark Polar region [*Stallard et al.*, 2003]. From *Vogt et al.* [2011, Figure 14]. (c) Composite of auroral observations for CML 220° and mapping results, showing that the active region maps to just beyond the dayside magnetopause, the swirl region maps to open field lines on the nightside, and the dark region maps to open field lines near dawn. Also shown in the gray circles are a polar dawn spot and a nightside spot, which both map inside of the statistical X line, consistent with their association with inward flow from tail reconnection. From *Vogt et al.* [2011, Figure 15]. Modified from *Grodent et al.* [2003b, Figure 5].

mapping results of *Vogt et al.* [2011] (see section 5). Some of the auroral features, like the satellite footprints, have a clear and relatively well-understood link to magnetospheric source regions. Others, like the puzzling polar emissions, are more complicated and cannot be mapped reliably.

In this section, we review briefly the primary features of Jupiter's auroral emissions, focusing on the current understanding of how these features relate to magnetospheric processes. An extended discussion is given by *Clarke* [this volume].

2.1. Satellite Footprints

The most equatorward components of the Jovian auroral emissions are the satellite footprints, which, despite displacements arising from azimuthally extended interaction regions, are the features that can be most reliably linked to their magnetospheric source regions. Emissions have been observed at the ionospheric footprints of Io (5.9 R_J), Europa (9.4 R_J), and Ganymede (15 R_J) [*Connerney et al.*, 1993; *Clarke et al.*, 2002]. More details about the satellite footprints are given by *Bonfond* [this volume].

The footprints are key to our ability to map between the ionosphere and the magnetosphere because the satellites' orbital locations are known, and a footprint's ionospheric location can, therefore, be linked reliably to a source at a known radial distance in the equatorial magnetosphere. The longitudinal position can also be inferred with some small uncertainty (~1–2 h LT) as a consequence of the signal propagation time between the satellite and the Jupiter's ionosphere. Thus, satellite footprints substantially constrain global field models.

2.2. Main Oval Emissions

Poleward of the satellite footprints are the main auroral emissions. It has long been argued that the Jovian main auroral emissions do not map to the open/closed field line boundary as they do on the Earth. Instead, they are thought to be associated with the region where plasma corotation breaks down in the middle magnetosphere [e.g., *Kennel and Coroniti*, 1975; *Hill*, 1979, 2001; *Cowley and Bunce*, 2001]. In particular, the main emissions are thought to be produced in the region near and beyond ~20 R_J where corotation enforcement currents flow upward from the ionospheres, carried by downward moving accelerated electrons. Further details on the origin of the main emissions are given by *Clarke* [this volume].

2.3. Polar Aurora

At higher latitudes, the magnetospheric sources of emissions are less well established. *Grodent et al.* [2003b] have identified a number of systematic aspects of the high-latitude emissions, which they have categorized into three regions, the active, dark, and swirl regions, based on average brightness and dynamic behavior. The mapping of the polar emissions to the equator is exceptionally uncertain, partly because field models become increasingly undependable for high-latitude field lines and partly because the shapes and locations of the three regions vary with the rotation phase of Jupiter (see *Grodent et al.* [2003b], Figure 5).

The active region is very dynamic and is characterized by the presence of flares, bright spots, and arc-like features. It maps roughly to the noon LT sector and is located just poleward of the main oval. The active region flares have a brightness of a few hundred kR (by comparison, the main oval brightness is typically 50–500 kR) [*Grodent et al.*, 2003a] and a characteristic time scale of approximately minutes. Because of their location near noon LT, the spots, arcs, and flares in the active region are thought to be signatures of interaction with the solar wind or the polar cusp region [e.g., *Pallier and Prangé*, 2001; *Waite et al.*, 2001; *Grodent et al.*, 2003b].

As its name suggests, the dark region appears dim in UV images, emitting only weakly (0–10 kR) above the background level. The dark region occupies a crescent shape located just poleward of the main oval. It is fixed in LT in the dawn to prenoon local time sector, although its size contracts and expands as Jupiter rotates. This region roughly matches the area where *Pallier and Prangé* [2001] observed faint inner ovals, or arcs, which they suggested map to closed field lines in the outer magnetosphere (out to ~70 R_J).

At the center of the polar auroral emissions is the swirl region, an area of patchy, ephemeral emissions that exhibit disordered, swirling motions. Recent observations have shown the presence of "polar auroral filaments," (PAFs) thin (less than 1° width) structures, which extend in the antisunward direction from the active region through the swirl region [*Nichols et al.*, 2009]. The PAFs were observed in fewer than 10% of the observation intervals during 2007 and do not appear to occur preferentially for particular solar wind conditions, so their origin is quite puzzling, though *Nichols et al.* [2009] suggested that the PAFs could be the signature of plasmoids moving slowly down the magnetotail. *Grodent et al.* [2003b] found that the UV swirl region is nearly colocated with a feature seen in the IR emission called the fixed Dark Polar region (f-DPR), wherein ionospheric flows are nearly stagnant in a reference frame fixed to the magnetic poles as they rotate with the planet [*Stallard et al.*, 2003]. Near stagnation of flow would be expected in the region threaded by open flux tubes in an extremely extended magnetosphere, although it remains unclear what processes produce auroral emissions on open field lines.

3. JOVIAN MAGNETOSPHERIC DYNAMICS

Dynamics in the Jovian magnetosphere are predominantly rotationally driven rather than solar wind–driven as they are on the Earth. Jupiter's short rotation period (~10 h) and the vast size of the Jovian magnetosphere both contribute to the dynamical importance of rotational stresses. In this section, we briefly review the prevailing views of Jovian magnetospheric dynamics and then discuss what the aurora can teach us about global dynamics.

3.1. Dynamics in a Rotationally Driven Magnetosphere

The model of rotationally driven dynamics was first described by *Vasyliūnas* [1983]. In his model, mass-loaded flux tubes dragged from Jupiter's dayside are stretched due to centrifugal acceleration of rotating particles. The stretched flux tubes eventually pinch off, releasing mass and energy in the form of plasmoids that can escape down the tail. Observations from the energetic particle detector and the magnetometer on board Galileo have shown evidence for this internally driven mass loading and release process, referred to as the Vasyliūnas cycle [*Cowley et al.*, 2003], and have identified the location of a statistical X line separating inward and outward flow [*Woch et al.*, 2002; *Vogt et al.*, 2010]. The so-called particle "reconfiguration events" display a ~2–3 day periodicity thought to be related to the time scale of the internally driven mass loading and release process at Jupiter [*Kronberg et al.*, 2007]; the 2–3 day periodicity also appears intermittently in the magnetometer data but is not statistically significant [*Vogt et al.*, 2010]. The absence of a statistically significant internal driving period could mean that reconnection is partly influenced by external factors like the solar wind.

It is widely agreed that although the solar wind dynamic pressure controls the size and shape of the magnetosphere [*Joy et al.*, 2002] and may influence the system through viscous processes at the boundary [*Delamere and Bagenal*, 2010], the interplanetary magnetic field plays a minor role in driving dynamics at Jupiter. However, there is considerable disagreement [e.g., *Cowley et al.*, 2003; *McComas and Bagenal*, 2007; *Cowley et al.*, 2008] on just what that role may be and, in particular, the extent to which Jupiter's magnetosphere is open. However, if present, the Dungey cycle X line at Jupiter would likely be restricted to the dawnside because of the effects of corotational flow that opposes sunward flow in the dusk sectors [*Cowley et al.*, 2003; *Khurana et al.*, 2004]. However, the Vasyliūnas cycle is expected to form an X line across much of the nightside. Therefore, if signatures of in situ or auroral reconnection are observed premidnight, they are most probably internally driven. Ambiguity remains regarding reconnection signatures observed postmidnight.

3.2. How Big, and Where, Is Jupiter's Polar Cap?

A major hindrance to understanding the role of the solar wind in dynamics at Jupiter is the fact that the polar aurora does not display clear evidence of a persistent polar cap bounding the region of open flux tubes, although *Pallier and Prangé* [2001] have identified a possible auroral signature of the open-closed field line boundary. This ambiguity has led to considerable disagreement regarding the amount of open flux in Jupiter's magnetosphere.

The UV polar swirl region and the IR f-DPR are frequently interpreted as manifestations of open field lines that lie within the polar cap [*Grodent et al.*, 2003b; *Stallard et al.*, 2003]. It has been suggested that the effectively stagnant ionospheric flows of the f-DPR are associated with Dungey cycle return flows [*Cowley et al.*, 2003] whose flow speed across the ionosphere would be very slow (~km s^{-1}) because their equatorial elements in the Jovian magnetotail would require many hours or even days to convect antisunward over distances of approximately many hundreds or thousands of R_J from the nose of the magnetosphere to the distant X line.

A number of questions arise from this interpretation. For example, if the swirl region is indeed associated with open field lines, what is the mechanism that produces the UV emissions? Why is the feature identified as the boundary of the polar cap by *Pallier and Prangé* [2001] not more persistent? Are *Delamere and Bagenal* [2010] correct in their suggestion that the high variability in the size, shape, and brightness of the swirl region indicates that it is not on open field lines and that there is little steady open flux? What processes produce the *Nichols et al.* [2009] PAFs? Some of these questions become particularly significant when examined in relation to the boundaries identified by magnetic mapping and discussed in section 6.

3.3. Auroral Signatures of Jovian Tail Reconnection

Transient spots appear in auroral images in both the UV and the IR; they are thought to be associated with inward moving magnetospheric flow initiated during reconnection [*Grodent et al.*, 2004; *Radioti et al.*, 2008]. Most of these spots, referred to as polar dawn spots, are located at the equatorward edge of the dark region, near the dawn LT sector, but nightside spots, mapping roughly to the premidnight local time sector, have also been observed [*Grodent et al.*, 2004; *Radioti et al.*, 2011].

The polar dawn spots have been associated with the internally driven reconnection process because of their location, emitted power, and periodic recurrence [*Radioti et al.*, 2008, 2010]. The polar dawn spots sometimes occur with a 2–3 day periodicity similar to the reported recurrence interval of reconfiguration events seen in the particle data [*Kronberg et al.*, 2007] and persist on time scales similar to the duration of the reconnection events observed in the magnetometer data [*Vogt et al.*, 2010]. The apparent link between the magnetospheric events and the localized auroral emissions requires magnetic connectivity. Although magnetic mapping is uncertain, the magnetic model discussed in section 6 can be used to demonstrate that the proposed linkage is plausible.

4. CURRENT MAGNETIC FIELD MODELS AND THEIR LIMITATIONS

Three widely used Jovian internal magnetic field models have employed the auroral footprints of one or more Galilean moons as constraints on the properties of the field at relatively low latitudes. The VIP4 field model [*Connerney et al.*, 1998] made use of Voyager 1 and Pioneer 11 magnetic field observations and required that the model field lines traced from 5.9 R_J matched the Io footprint in the ionosphere. The VIP4 model generally does a good job of fitting the Io footprint, although in the northern hemisphere, the model deviates from the observations in the “kink” sector that gives the Io footprint its characteristic kidney bean shape.

The Grodent anomaly model (GAM) [*Grodent et al.*, 2008b] improved the agreement between the model and footprint observations in the northern hemisphere by adding a magnetic anomaly in the northern hemisphere. Inclusion of the magnetic anomaly improved the match to the Io footprint, especially in the “kink” sector, and the match to the Europa and Ganymede footprints, which shifted by approximately several degrees in the northern hemisphere, as seen in Figure 2. For all models, the inaccuracy is mostly in the direction along the curve rather than across the curve and is likely due to inaccuracies in the field models and not to the propagation time delay of the Alfvén waves [*Bonfond et al.*, 2009].

Most recently, the VIPAL internal field model [*Hess et al.*, 2011] updated the VIP4 model by placing longitudinal constraints on the mapping of the Io footprint. As a result, the VIPAL model fits the observed Io, Europa, and Ganymede footprints better than does VIP4. VIPAL does not match the satellite footprint locations as well as does the GAM in the northern hemisphere (see Figure 2), but it does predict a surface magnetic field strength that agrees better with the values deduced from observed radio emissions.

Even with recent improvements such as the inclusion of a magnetic anomaly, beyond 15 R_J where there are no satellite

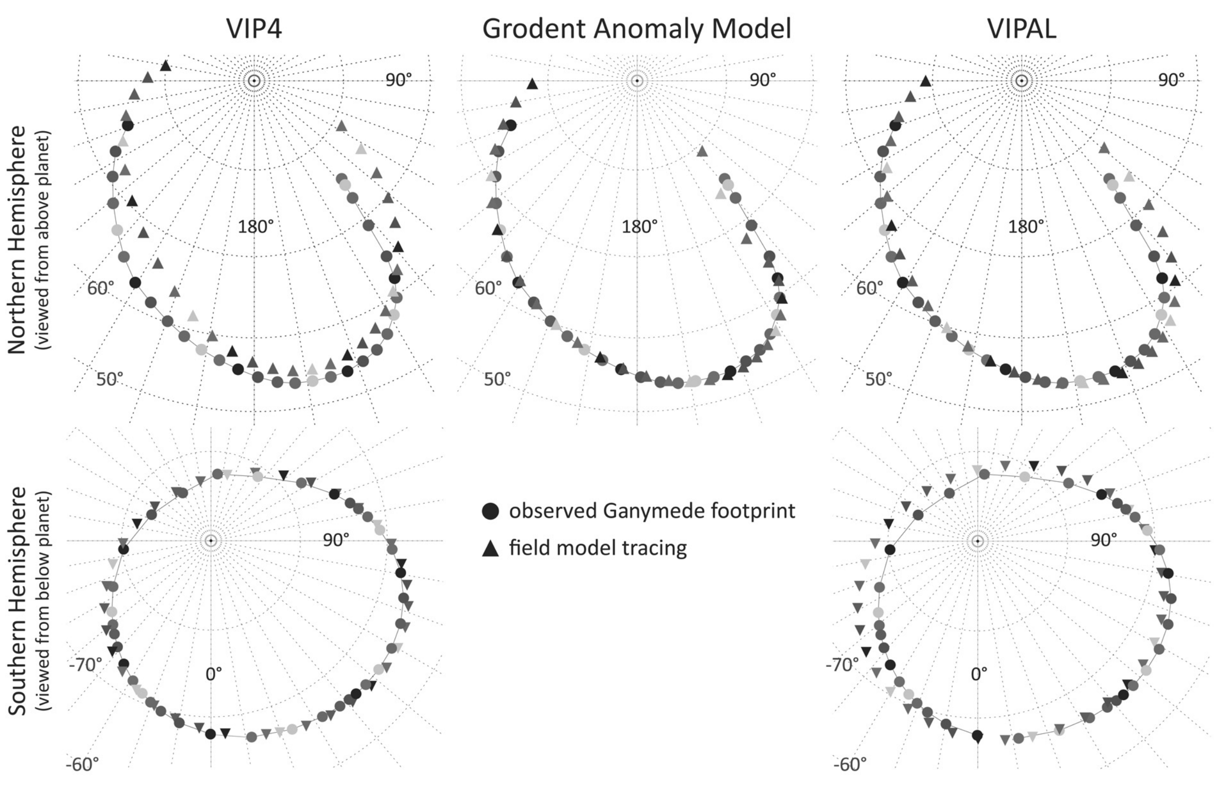

Figure 2. The locations of the observed Ganymede footprint (circles) and the ionospheric footprint of model field lines traced from 15 R_J at the equator (triangles) for three different models of Jupiter's magnetic field.

footprints to constrain the models, azimuthal currents flowing in the magnetosphere stretch field lines and compromise the mapping. Currents flowing near the magnetic equator have been incorporated into some global field models, although those models have limitations such as neglecting the effects of magnetopause currents [*Khurana*, 1997] or ignoring the 10° dipole tilt and dawn-dusk asymmetry of the equatorial magnetic field [*Alexeev and Belenkaya*, 2005]. Clearly, another approach is needed to obtain an improved field mapping in the middle and outer magnetosphere.

5. NEW MAPPING MODEL USING FLUX EQUIVALENCE

A new approach to the problem of linking polar auroral features to the equatorial magnetosphere was adopted by *Vogt et al.* [2011]. Rather than tracing equatorial magnetic field lines from the magnetosphere to the ionosphere, they quantified the distribution of magnetic flux across the nightside magnetosphere as a function of local time and radial distance in the equator from spacecraft observations and mapped the field from equator to ionosphere by means of a flux equivalence calculation. In this section, we review briefly the methods and results of the flux equivalence mapping (details are given by *Vogt et al.* [2011]).

5.1. Mapping by Flux Equivalence: Methods and Limitations

The flux equivalence calculation is based on the requirement that the magnetic flux threading a specified region at the equator must equal the magnetic flux in the area to which it maps in the ionosphere. The approach requires a reasonably accurate model for both the radial magnetic field strength in the ionosphere and the north-south component of the magnetic field at the equator.

A flux equivalence analysis had been used previously to estimate currents, flows, and magnetic mapping of Jupiter's ionosphere [*Cowley and Bunce*, 2001] making use of a simplified axisymmetric magnetic field model to estimate the magnetic flux in both the ionosphere and the magnetosphere. A key contribution of the *Vogt et al.* [2011] work is that, instead of using a model field, they fit the average observed field measurements in the equatorial plane as a function of radial distance and LT. They found that LT variations in $B_{N,\mathrm{equator}}$, the normal component of the magnetic field across the magnetotail at the equator can be as large as a factor of ~5, so including the observed dawn-dusk asymmetries in the equatorial magnetic field is crucial for a meaningful mapping of dawn-dusk asymmetries in the auroral emissions.

The advantage of the flux equivalence calculation over using the available field models is that it allows for a more reliable mapping beyond 30 R_J into the middle and outer magnetosphere. However, this approach has limitations and is subject to inaccuracies. One source of potential inaccuracy is the internal field model used in both determining the 15 R_J reference contour at the footprint of Ganymede and in determining the magnetic field values used to calculate the flux at the ionosphere. For example, points obtained by tracing the GAM from 15 R_J fall close to the observed Ganymede footprint (see Figure 2) in latitude but have an estimated average local time inaccuracy of ~0.7 h. The GAM overestimates B_R compared to the VIPAL model, which predicts a surface magnetic field strength that better agrees with the observed radio emissions, though VIPAL does not match the Ganymede footprint as well, and such inaccuracies affect the flux mapping. Clearly, each internal field model has its relative strengths and weaknesses that affect the flux equivalence calculation, but the differences of flux mapping based on the three different field models (VIP4, GAM, VIPAL) has not yet been established.

Additional uncertainty of flux mapping arises from the data-based model B_N used to calculate the flux through the equatorial magnetosphere. That model is based on measurements acquired in differing magnetospheric states (compressed and expanded) and solar wind conditions. The assumption that B_N in the equatorial plane is unaffected, for example, by the changing size of the magnetosphere is undoubtedly an oversimplification. Consequently, one must not expect the model to apply precisely to the polar auroral observations taken at a specific moment in time, under a specific set of solar wind conditions.

5.2. Results and Comparison to Auroral Observations

The ionospheric maps obtained by the flux equivalence calculation can be compared to auroral observations [*Grodent et al.*, 2003b] to identify the magnetospheric sources of different auroral regions and features. Such a comparison is shown in Figure 1, which shows UV auroral observations for two central meridian longitudes (CMLs), i.e., the Jovian longitude facing the direction of the Earth). Figures 1b and 1c show contours corresponding to constant radial distances in the magnetosphere, every 10 R_J from 20 to 150 R_J. The white or empty area interior to the colored contours maps beyond 150 R_J on the nightside and beyond the expanded magnetopause on the dayside leading to the suggestion that it is threaded predominantly by open flux tubes.

In Figure 1, contours outlining the locations of the three polar auroral regions, following *Grodent et al.* [2003b], have been superimposed on the mapped magnetic contours. The shapes, sizes, and locations of the three polar regions change as the planet rotates or with varying solar wind conditions as is evident from a comparison of the regions of polar emissions in Figures 1a and 1c. However, although the jovigraphic location of these auroral features and their shapes change with CML, each of the three polar auroral regions maps predominantly to the same magnetospheric region(s) for the two cases.

A comparison of the mapping results with auroral observations shows that the main oval maps to different radial distances at different local times. Near dawn, the main oval maps relatively close to the planet, ~15–30 R_J; the mapped radial location then increases with increasing LT, from ~30–50 R_J at noon to ~50–60 R_J at ~15:00 LT. These results suggest that either the radial location of the corotation enforcement currents varies with local time or the outward plasma flux differs among local time sectors, or both. In studying 9 years of Hubble Space Telescope (HST) data, *Grodent et al.* [2008a] found that the main oval location observed at different times can shift by as much as 3° in latitude. They proposed that the latitudinal shift could be explained by variations in the current sheet density or thickness [e.g., *Kivelson and Southwood*, 2005] and not just by a response to changing solar wind conditions.

From the comparison between the flux equivalence mapping results and the auroral observations, *Vogt et al.* [2011] concluded that the polar auroral active region maps to Jupiter's polar cusp. Interpretations of the other mappings, still somewhat speculative, are presented in the next section.

6. APPLICATIONS OF THE FLUX EQUIVALENCE MAPPING MODEL

The flux equivalence model has many potential applications to understanding aspects of the ionospheric manifestations of the structure and dynamics of Jupiter's magnetosphere. In this section, we review briefly three of those applications.

6.1. Identifying the Size and Location of the Polar Cap

It is of interest to identify the area of the high-latitude auroral zone that maps to open field lines. Vogt et al. interpret the regions poleward of the mapped field lines from 150 R_J as only a bit larger than Jupiter's polar cap, whose locus has not yet been unambiguously identified. This leads them to propose that the swirl region links to the magnetotail, i.e., it is principally threaded with open field lines. The fixed f-DPR identified in IR measurements by *Stallard et al.* [2003] and shown as a black contour in Figure 1b also maps predominantly to the distant magnetotail, plausibly to open field lines, so it is possible that it, too, is part of the polar cap. As discussed in section 3.2, the flow is virtually stagnant in this region, a feature taken to support the interpretation. Thus, if the magnetic mapping is accepted, both the swirl region and the f-DPR (which largely overlaps the UV dark region) map predominantly to open tail field lines on the nightside. Although these conclusions agree with the interpretations made in several previous studies [e.g., *Cowley et al.*, 2003; *Stallard et al.*, 2003; *Grodent et al.*, 2003b], they raise an unanswered question regarding how emissions are generated on open field lines.

One way of estimating the size of the polar cap is to consider the total flux in the lobes of the magnetotail, based on the argument that their very low plasma density ($<10^{-5}$ cm^{-3}) [*Gurnett et al.*, 1980] implies that they contain open field lines. Assuming that the polar areas mapping beyond the magnetopause or beyond 150 R_J on the nightside are predominantly on open field lines, *Vogt et al.* [2011] calculated the amount of open flux through that region. They found that the flux through the region identified as the northern hemisphere polar cap is less than ~760 GWb. If the polar cap has been accurately identified, the polar cap flux should be comparable to the tail lobe flux, which they estimate as ~740 GWb. However, accounting for the uncertainty of the flux mapping procedure, the variability associated with changing solar wind conditions, and the fact that some magnetotail flux closes beyond 150 R_J downtail, we expect that the amount of open flux is likely closer to ~600 GWb. These estimates of the open flux are somewhat larger than the upper limit values used by *Nichols et al.* [2006], who found an average 500 GWb of open flux in the tail lobes but also noted that the amount of open flux varied through the solar cycle with higher mean values near solar maximum.

Finally, Vogt et al. determined that the area of what they identified as the northern polar cap is equivalent to that of a circle around the pole with a half width of ~11°, only slightly smaller than the ~15° latitudinal half width of the polar cap on the Earth. If 20% of the flux beyond 150 R_J closes further downtail, the polar cap half width would decrease to 9.8°. By comparison, the polar cap identified by *Pallier and Prangé* [2001] in auroral images was only ~5° half width or about ~20% of the area of the polar cap identified by *Vogt et al.* [2011]. Similarly, *McComas and Bagenal* [2007], who argue that Jupiter's magnetosphere is nearly closed, proposed that the latitudinal half width of the polar cap is only ~5°. Such small areas are inconsistent with the flux mapping of *Vogt et al.* [2011]. It should be clear from the above discussion that there remains considerable uncertainty regarding the extent of the polar region that maps to open field lines.

6.2. Improved Understanding of Magnetotail Dynamics

Observations of the aurora provide an excellent tool for studying magnetospheric dynamics on a global scale because the aurora responds to activity occurring simultaneously across a large range of radial distances and local times. By comparison, spacecraft measurements provide information about only one location at an instance in time, so it is difficult to distinguish between temporally and spatially varying features. One potential use for the flux equivalence model presented here is to identify the magnetospheric activity that drives the observed polar dawn spots, introduced in section 3.3.

The auroral observations shown in Figure 1c include two spots, one in the dawn sector and one on the nightside. Both spots appear to map to equatorial regions well inside of the statistical X line [*Woch et al.*, 2002; *Vogt et al.*, 2010], consistent with their association with inward moving flow released during tail reconnection [*Radioti et al.*, 2010]. Similarly, in a recent study, *Radioti et al.* [2011] used the flux equivalence mapping model to map UV and IR auroral spots to distances inside of the statistical X line. The UV nightside spot mapped close to the position of the Galileo spacecraft, which recorded a reconnection signature in the magnetometer data at nearly the same time [*Vogt et al.*, 2010]. Additionally, the emitted power derived from the flow bubble in the magnetic field measurements closely matches the emitted power of the nightside spot seen with HST.

It is interesting to note that in both Figure 1c and the Radioti et al. study, the nightside reconnection spots were accompanied by polar dawn spots. Could this mean that reconnection at Jupiter typically occurs simultaneously at multiple points across the tail or is the field bent back so strongly that the feet of nightside field lines are displaced in LT far more than proposed by field models? Without multipoint spacecraft measurements, and with only small statistics from which to draw inferences from the auroral data (spots at any local time appear infrequently in the auroral images), it is impossible to say. Further observations of these auroral features are needed to help answer this question and provide further insight into Jupiter's global magnetospheric dynamics.

6.3. Source Regions of Polar Flares

Quasiperiodic polar flares have recently been observed inside the main oval [*Bonfond et al.*, 2011] but have not yet

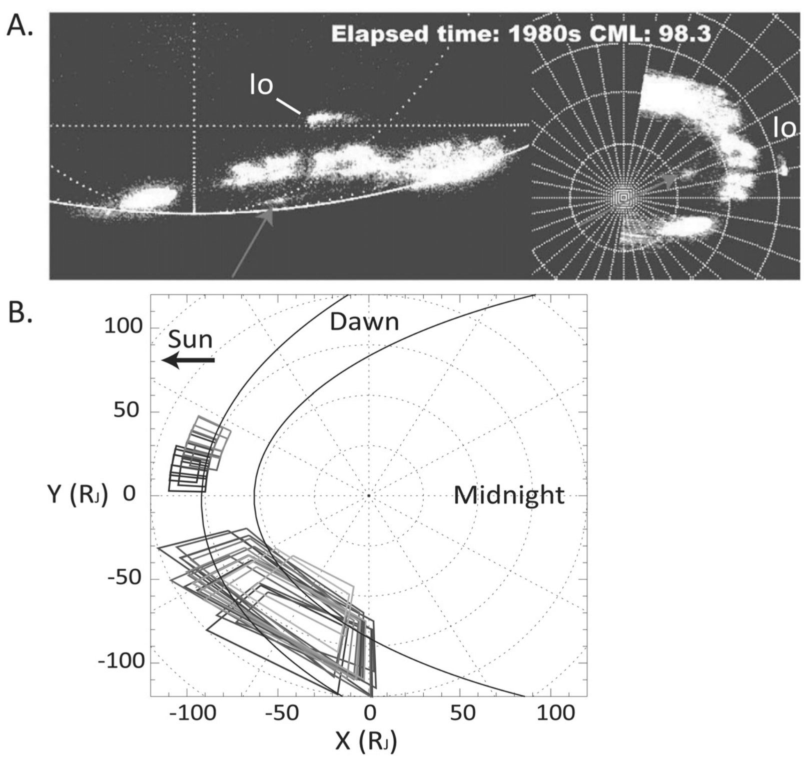

Figure 3. (a) HST observations of a flare in Jupiter's southern UV aurora. The left-hand side shows the aurora as observed from HST, with the flare identified by an arrow. The right-hand side of the image is a polar projection, and again, an arrow identifies the flare. (b) The mapped location of the flares in the equatorial plane. The thick black lines show the two preferred locations of Jupiter's magnetosphere [*Joy et al.*, 2002], and the two sets of boxes represent two different dates of observations. The size of the boxes reflects the position uncertainty of the flares because they are located close to the limb. From *Bonfond et al.* [2011].

been fully explained. These pulsating emissions were observed in the southern hemisphere during two HST observation orbits and display a typical 2–3 min recurrence period. *Bonfond et al.* [2011] used the flux equivalence mapping model to map the polar location of the flares to the dayside magnetopause, in one case near 11:00 LT and in the other case near ~16:00 LT. Figure 3 shows an example of the flares and their mapped location in the equatorial plane.

Based on the mapped location near the dayside magnetopause and the 2–3 min recurrence period, *Bonfond et al.* [2011] suggested that the periodic flares could be the signature of flux transfer events due to pulsed reconnection with the solar wind. Flux transfer events at Jupiter have been observed to have a ~1–4 min recurrence time [*Walker and Russell*, 1985], similar to the periodicity of the auroral flares. Further work on this interesting phenomenon is called for.

7. SUMMARY

This chapter has focused on the link between magnetospheric source regions and features of auroral emissions, seeking to understand the sources of the different types of emissions observed in Jupiter's aurora. We have described the links inferred from a flux equivalence model in which equatorial magnetic flux, evaluated from spacecraft measurements, is related to the equivalent magnetic flux in the ionosphere. This approach suggests, in particular, that the active region, poleward of the main oval and centered on the dayside, maps to regions that could plausibly be the dayside polar cusp and that the nearby swirl region is also on open field lines. The analysis associates the different auroral structures with sources in the middle and outer magnetospheres. Both dawn and nightside spots and quasiperiodic dayside flares have been shown to map to regions in which reconnection-associated phenomena provide plausible triggers for the emissions.

The models we have described are generic. Solar wind conditions are not known for most Jupiter observations, so the model fails to account for the roles of solar wind dynamic pressure and for possible dependence on the orientation of the interplanetary magnetic field. Despite these limitations, the methods described in this chapter have begun to elucidate the links between the magnetosphere and the ionosphere. Continued observations and new spacecraft data from JUNO are needed to provide further tests of the links proposed in these studies and to identify more unambiguously the drivers of auroral activity.

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M. G. Kivelson, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095, USA.

M. F. Vogt, Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK. (mv106@le.ac.uk)