Jupiter's polar ionospheric flows: Theoretical interpretation

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[1] Prompted by recent observations of ion flows from Doppler measurements of infrared auroras, we here discuss the nature of the plasma flow in Jupiter's high-latitude ionosphere. The physical picture is based on a combination of three elements, namely an inner Hill-type sub-corotating region containing outward-diffusing iogenic plasma, an outer sub-corotating region where iogenic plasma is lost down the tail, principally in the dusk and midnight sector via the reconnection-related Vasyliunas-cycle, and finally an outermost boundary region located principally in the dawn-side magnetosphere which is associated with solar wind interaction and the Dungey-cycle. The nature of the ionospheric flow and currents resulting from the combined action of these processes is outlined. In particular, we point out that the region of open field lines associated with the Dungey-cycle should be a region of near-stagnation in the ionosphere in the rest frame of the dipole, compared with surrounding regions of few-km s^{-1} sub-corotational flow. *INDEX TERMS:* 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2704 Auroral phenomena (2407); 2736 Magnetosphere/ionosphere interactions. **Citation:** Cowley, S. W. H., E. J. Bunce, T. S. Stallard, and S. Miller, Jupiter's polar ionospheric flows: Theoretical interpretation, *Geophys. Res. Lett.*, *30*(5), 1220, doi:10.1029/2002GL016030, 2003.

1. Introduction

[2] Recent observations have shown that Jupiter's polar regions possess a complex auroral morphology, observable over a wide range of wavelengths from infrared to X-ray, which is potentially revealing of the structure and dynamics of the large-scale jovian plasma environment [e.g., *Satoh et al.*, 1996; *Prangé et al.*, 1998; *Clarke et al.*, 1998; *Vasavada et al.*, 1999; *Grodent et al.*, 2002; *Gladstone et al.*, 2002]. With increasing latitude, these auroras comprise components associated with the footprints of the Galilean moons, a bright 'main oval' which encircles the magnetic poles in each hemisphere, and structured polar emissions lying within this oval, principally in the noon and dusk sectors, termed the 'bright polar region'. By comparison, the region within the main oval on the dawn side is dark in the UV, though not devoid of emission in the infra red, and is termed the 'dark polar region'. It has also recently been shown that spatially resolved Doppler shifts of spectral lines of the H_3^+ ion can be obtained from ground-based measurements in the infrared, thus opening up the possibility of remote sensing studies of jovian polar ionospheric flows. The first such observations, reported by *Rego et al.* [1999], revealed the presence of significant sub-corotation of the plasma flow in the main oval ionosphere. Most recently *Stallard et al.* [2001] have confirmed these results, and have also presented the first Doppler observations within both the bright and dark polar regions. They found that, relative to rigid corotation with the planet, the emission from the bright polar region in the dusk sector is weakly blue-shifted (i.e. is weakly sub-corotational), while that from the dark polar region in the dawn sector is strongly red-shifted (i.e. departs strongly in the sense of sub-corotation).

[3] These observations prompt consideration of the ionospheric flows expected on the basis of theory. The model we discuss is that outlined by *Cowley et al.* [1996] on the basis of theoretical considerations and spacecraft fly-by flow data, whose ionospheric ramifications have not previously been considered explicitly. Here we examine consequences for ionospheric flows and currents, and discuss relationships with auroral observations.

2. Equatorial Flow

[4] In the steady-state situation considered here, the jovian flow is taken to consist of three components. This is illustrated by the equatorial streamlines shown in Figure 1, where the direction towards the Sun is at the bottom of the figure, dawn is to the left, and dusk to the right. In the inner region the plasma streamlines are closed around the planet, though extending to greater distances on the night-side than on the dayside due to the asymmetry imposed by the confining effect of the solar wind [*Bunce and Cowley*, 2001a]. We have not shown explicitly the observed simultaneous shift of the streamlines towards dawn in this region, associated with a dawn-to-dusk electric field which may be produced by the day-night asymmetry [*Goertz and Ip*, 1984]. The physics of the region is dominated by the centrifugally-driven outflow of plasma from the Io torus, associated with small-scale 'diffusive' motions which are also not represented in the figure [e.g. *Siscoe and Summers*, 1981]. As the iogenic plasma diffuses outwards, its angular velocity falls from rigid corotation with the planet due to conservation of angular momentum, an effect which is offset by the frictional torque imposed by ion-neutral collisions in the Pedersen layer of the ionosphere. Steady-state angular velocity profiles were first calculated by *Hill* [1979] for the case of a dipole planetary field, and by *Pontius* [1997] for more realistic field geometries representative of the jovian middle magnetosphere. They found that significant departures from rigid corotation are expected at radial distances beyond a few tens of Jupiter radii (1 $R_J \approx 71{,}400$ km) for typical values of the ionospheric Pedersen conductivity (few $\times$ 0.1 mho) and iogenic plasma mass outflow rate ($\sim 10^3$ kg s^{-1}). The atmospheric torque is communicated to

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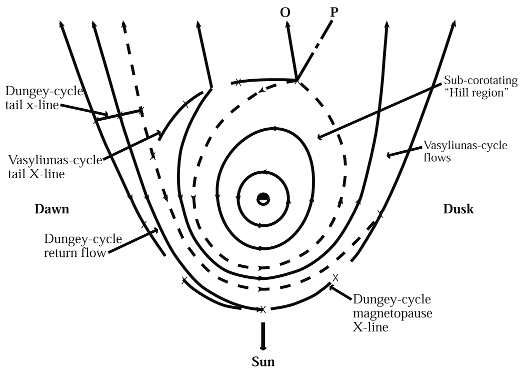

Figure 1. Sketch of the flows in the jovian equatorial plane.

the equatorial plasma by the magnetic field, which is bent out of magnetic meridians into a 'lagging' configuration. The associated current system involves equatorward Pedersen currents in the ionosphere in both hemispheres, and outward radial currents in the equatorial plane whose $\boldsymbol{j} \times \boldsymbol{B}$ force accelerates the plasma in the sense of planetary rotation. These field-perpendicular currents are then joined by field-aligned currents which flow outward from the ionosphere into the current sheet throughout this region, which have been suggested to be associated with the main oval auroras [*Bunce and Cowley*, 2001b; *Cowley and Bunce*, 2001; *Hill*, 2001; *Southwood and Kivelson*, 2001]. The related sub-corotational flow is that derived from ionospheric observations by *Rego et al.* [1999] and *Stallard et al.* [2001] as mentioned above, and also from magnetospheric particle data by e.g. *Sands and McNutt* [1988], *Kane et al.* [1995], and *Krupp et al.* [2001].

[5] This sub-corotating 'Hill region', as it is labelled in Figure 1, is taken to comprise the main part of the jovian middle magnetosphere, extending in the equatorial plane to distances of several tens of R_J, depending on the state of extension of the magnetosphere. It is then surrounded by a region, still driven by planetary rotation, in which current sheet dynamics and reconnection play an important role in the loss of cool iogenic plasma down-tail. As first discussed by *Vasyliunas* [1983], we envisage outer current sheet field lines that are confined by the solar wind on the dayside, stretching out down-tail as they rotate into the dusk sector, and then pinching off via reconnection and the formation of tailward-flowing plasmoids. In Figure 1 this is depicted as a steady-state process associated with a reconnection line marked by the dashes and X's, labelled 'Vasyliunas-cycle tail X-line'. Recent observations, however, indicate considerable time-dependency [*Woch et al.*, 2002]. In the figure the O-type line of the plasmoid, which is a plasma streamline, is marked by an 'O', while the outer edge of the plasmoid is shown by the dot-dashed line marked 'P', which eventually asymptotes to the dusk magnetopause. We thus anticipate on this basis that the inner 'Hill-region' will be surrounded by a layer of faster (but generally still sub-corotational) flow in the dawn sector as the mass-reduced flux tubes flow sunward downstream of the 'Vasyliunas' reconnection site. The coupling currents will thereby be reduced, associated with a 'return' field-aligned current flow from the current sheet to the ionosphere in this region, as inferred from spacecraft data in this sector by both *Bunce and Cowley* [2001b] and *Khurana* [2001]. This effect will be reduced by further mass-loading as the flux tubes subsequently rotate into the noon and dusk sector.

[6] The third region shown in Figure 1 contains the flow associated with the solar wind interaction and the Dungey-cycle [*Dungey*, 1961]. This process is initiated by magnetopause reconnection with the interplanetary magnetic field, which we suppose takes place over wide regions of the dayside boundary, as indicated by the dashed line and X's labelled 'Dungey-cycle magnetopause X-line'. The equatorial streamlines of this system end at this boundary as dayside reconnection takes place with northward-directed interplanetary field lines, such that the resulting 'open' field lines are carried over the poles of the planet and out of the plane of the diagram. Since the 'plasma sheet' in the center plane of the tail is occupied by outflowing iogenic plasma in the dusk and midnight sectors via the Vasyliunas-cycle, we propose that the reconnection site associated with the solar wind-driven process will be confined to the dawn sector, as indicated by the dashed line and X's labelled 'Dungey-cycle tail X-line'. The open lines will thus flow across the tail lobe predominantly from dusk to dawn. The flux tubes closed at the Dungey-cycle tail reconnection site will then flow back towards the dayside magnetopause to complete the cycle, forming a dayside boundary layer adjacent to the magnetopause that we identify with the 'outer magnetosphere' region observed in spacecraft data. The characteristic feature of such a layer will be the presence of low plasma densities compared with the interior region (the flux tubes having previously been 'open' in the tail lobe for significant intervals), in agreement with the observations e.g. of *Phillips et al.* [1993]. The flux tubes which are pinched off tailward of the tail reconnection site flow rapidly away from the planet, possibly related to the anti-sunward 'magnetospheric wind' observed adjacent to the dawn tail magnetopause by *Krimigis et al.* [1981] (to which the Vasyliunas-cycle may also contribute).

[7] With regard to the overall flux transport in these flow systems, *Cowley and Bunce* [2001] estimate a voltage of $\sim$50 MV across the middle magnetosphere plasma sheet from the inner edge of the Io torus at $\sim$5 R_J to an outer edge at $\sim$100 R_J, derived from observation-based empirical models of the equatorial field and flow. However, the voltage across the main region of outward field-aligned current mapping to the 'main oval', located in the equatorial plane between $\sim$25 and the outer edge at $\sim$100 R_J in their model, was found to be $\sim$2.5 MV. It seems likely that the flux transport in the Vasyliunas-cycle will be of a comparable order or smaller. By comparison, estimates of the flux transport in the Dungey-cycle are $\sim$0.5–1 MV [e.g. *Hill et al.*, 1983]. These values are obtained from estimating the voltage in the solar wind across a magnetospheric diameter, and then multiplying by an empirical Earth-based 'efficiency-factor' of 10–20% [e.g. *Reiff et al.*, 1981]. The voltage across the outer magnetosphere layer adjacent to the dayside magnetopause is also of this order, taking the layer to be 10–15 R_J wide, with a field strength of $B \approx 5$–10 nT, and flowing at a speed of 100–150 km s^{-1}. The above suggestion of a connection between the 'outer magnetosphere' and the dayside return flows of the Dungey-cycle is thus plausible in voltage terms.

3. Ionospheric Flow

[8] The ionospheric plasma flows and structures which correspond to the above equatorial discussion are sketched in Figure 2, where, as in Figure 1, the direction towards the Sun is at the bottom of the figure, dawn is to the left, and dusk to the right. We have also transformed to a frame where the planetary dipole axis is at rest, such that the flow pattern (to a first approximation) does not vary with time, assuming steady magnetospheric conditions. At the outer limit of the figure, corresponding to $\sim$20° co-latitude (and mapping to $\sim$10 R_J in the equatorial plane), the plasma approximately corotates with the planet. With decreasing co-latitude the plasma angular velocity then drops within the 'Hill-region', reaching perhaps half of rigid corotation at the poleward boundary of this region at $\sim$15° co-latitude [e.g. *Sands and McNutt*, 1988; *Kane et al.*, 1995; *Stallard et al.*, 2001], this corresponding to a flow speed in this frame of $\sim$1.6 km s^{-1}. In considering the electric currents which flow in the ionosphere, it must then be remembered that the neutral atmosphere is rotating about the magnetic pole in this frame at essentially the planetary angular velocity (unless significantly slowed by ion neutral frictional drag), and hence at a speed which is higher than the sub-corotating plasma flow. The Hall current is therefore directed anti-clockwise, in the same general direction of the plasma flow, carried by ions convected with the neutral gas, while the Pedersen current is directed equatorward, opposite to the direction of the electric field in this frame. Both currents increase as the plasma angular velocity falls. The equatorward-directed Pedersen current thus increases as the plasma angular velocity falls with decreasing co-latitude in the 'Hill region', thus requiring upward-directed field-aligned currents in this region as indicated above, and as depicted in Figure 2 by the circled dots. This is the current which is suggested to be directly related to the main oval auroras. Inside this region, the angular velocities may increase somewhat in the region occupied by the Vasyliunas-cycle flows, more particularly on the dawn side than on the dusk side, as mentioned above. The Pedersen current will then be reduced and the direction of the field-aligned current reversed to downwards, as indicated in Figure 2 by the circled crosses in the dawn sector. This pattern of current may then relate to the observed dawn-dusk asymmetry in the form of the main oval auroras, in which a relatively narrow arc is typical of the dawn sector, while broader more diffuse structures are typical of dusk.

[9] The final region is that occupied by Dungey-cycle flows, consisting of a region of open magnetic flux and anti-sunward flow, shown hatched, and a region of closed flux and return sunward flow. From the observed diameter and field strength of the lobes of the jovian tail [e.g. *Acuña et al.*, 1983], we estimate the open magnetic flux in each lobe to be $\sim 3.5 \times 10^{11}$ Wb, thus comprising a little less than half of the jovian polar magnetic flux which lies poleward of the boundary of the 'Hill region' at $\sim$15° co-latitude. This suggests that the magnetic flux mapping into the Vasyliunas-cycle in the polar region is of comparable order. If the region of open flux was circular and centered on the magnetic pole, it would then occupy a region down to $\sim$9° co-latitude. However, while the ionospheric image of the dayside reconnection line may lie roughly symmetrically with respect to noon, as shown in Figure 2, we suggest that

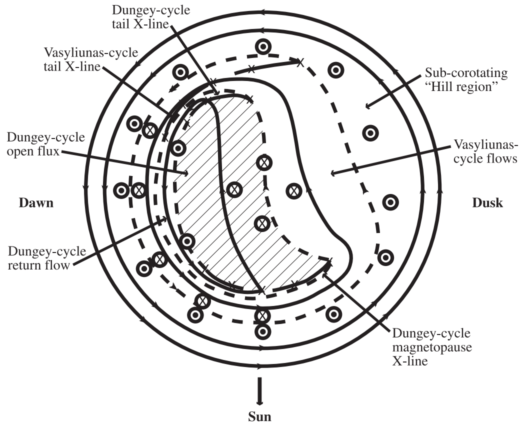

Figure 2. Sketch of the flows in the northern jovian ionosphere.

on the night side the open flux is displaced to the dawn side of the polar region by the magnetospheric asymmetry imposed by the Vasyliunas-cycle, specifically by the outflow of iogenic plasma down the dusk and midnight tail. The dusk sector of the polar region then corresponds to closed field lines which map to the tail duskward of the outer boundary of the plasmoid (marked 'P' in Figure 1). This asymmetric polar field structure was previously inferred by *Pallier and Prangé* [2001] from UV auroral images. An additional consequence of this asymmetry is that the return flows of the Dungey cycle take place only on the dawn side of the region of open flux, as shown in Figure 1, such that this cycle produces only a single flow cell at Jupiter rather than the two at Earth.

[10] The region of open flux may be expected to be aurorally 'dark', since it is magnetically connected to a tail lobe with very low plasma density and essentially no hot plasma [e.g. *Moses et al.*, 1987], having little flow dynamics, and with field-aligned currents which generally will be directed downwards in the central polar region. The dawn region of the Vasyliunas-cycle flows may also be dark, where the field-aligned currents have been suggested to be downward-directed, though these flux tubes will contain some hot accelerated plasma in the region downstream of the Vasyliunas-cycle tail reconnection line. However, the flows in these two potentially 'dark' regions will be very different, with the dawn Vasyliunas-cycle flux tubes flowing sunwards at speeds of $\sim$1–2 km s^{-1}, likewise probably the adjacent dawn 'return' flows of the Dungey-cycle, while the anti-sunward flow within the region of open flux will be very slow indeed, assuming insignificant twisting of the lobe field by the ionosphere. This is inferred from the estimated travel time of open field lines through the tail lobe. For example, if we take a Dungey-cycle transpolar voltage of $\sim$0.5–1 MV as indicated above, the travel time through a lobe of $\sim$2 nT field strength and $\sim$150 R_J radius is $\sim$5–10 days. This implies a jovian tail length of a few AU, with distended disconnected tail field structures stretching even further downstream from the planet. Such a travel time across the region of open flux in the ionosphere, however, implies anti-sunward flow speeds of only $\sim$50–100 m s^{-1}. The region of open flux will therefore be characteristically almost 'stagnant' compared with the regions of surrounding flow.

These auroral and flow properties suggest a connection to the central 'dark polar region' of *Stallard et al.* [2001], with its significant 'red-shift' compared with rigid corotation with the planet mentioned above. In fact, further investigation of these data in a companion paper [*Stallard et al.*, 2002], shows that this 'red shift' results typically in near-zero central 'dark polar region' plasma flows in the dipole rest frame (in the region they term 'f-DPR'), in agreement with this hypothesis. *Stallard et al.* [2002] also show that the central dark region is also surrounded by a region in the dawn and noon sectors which is also dark but has faster sub-corotating flows (termed 'r-DPR'). We here associate this latter region with the sunward-flowing layer of 'return' Dungey- and Vasyliunas-cycle flows in the dawn sector shown in Figure 2.

[11] A final point to be made concerns possible auroral and flow dynamics related to the reconnection sites associated with the Dungey- and Vasyliunas-cycles. Analogy with Earth leads one to expect transient phenomena akin to dayside 'flux transfer events' and nightside substorms. If so, we suggest that the transient phenomena observed near noon [e.g. *Pallier and Prangé*, 2001; *Gladstone et al.*, 2002] may relate to dayside magnetopause reconnection and cusp dynamics, while the 'dawn storms' and 'storm-like events' observed just poleward of the main oval in the dawn sector [e.g. *Gérard et al.*, 1994; *Clarke et al.*, 1998; *Grodent et al.*, 2002] may relate to activations at the Dungey- or Vasyliunas-cycle tail reconnection sites (or both). At the same time we recognise that if the Vasyliunas-cycle takes place through smaller-scale transient reconnection events in the outer region of the middle magnetosphere, as opposed to the large-scale steady-state flows discussed for simplicity here, this will lead to smaller-scale transient flows and auroras appearing in the region of Vasyliunas-cycle flow, which we may suppose will be located preferentially in the post-noon sector, that is, in the 'bright polar region'.

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