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Jupiter's polar ionospheric flows: Measured intensity and velocity variations poleward of the main auroral oval

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[1] Recent analysis of high-resolution spectra of Doppler-shifted H_3^+ emission from the auroral/polar regions of Jupiter revealed a complex wind system, with a persistent auroral electrojet and strong anti-sunward flows in a region of lesser intensity centred around the magnetic pole [*Stallard et al.*, 2001]. This region, which we have called the Dark Polar Region (DPR), is re-investigated, trans forming the observed line-of-sight velocities into a frame of reference fixed with respect to the magnetic pole. The DPR is shown to include a region essentially stagnant in this frame of reference (the f-DPR). We identify it as a region coupled to open magnetotail field lines. There is also a transition region in which the ion velocity returns to corotation (the r-DPR). *INDEX TERMS:* 5719 Planetology: Fluid Planets: Interactions with particles and fields; 5729 Planetology: Fluid Planets: Ionospheres (2459); 6220 Planetology: Solar System Objects: Jupiter; 2437 Ionosphere: Ionospheric dynamics; 2459 Ionosphere: Planetary ionospheres (5435, 5729, 6026, 6027, 6028). **Citation:** Stallard, T. S., S. Miller, S. W. H. Cowley, and E. J. Bunce, Jupiter's polar ionospheric flows: Measured intensity and velocity variations poleward of the main auroral oval, *Geophys. Res. Lett.*, *30*(5), 1221, doi:10.1029/2002GL016031, 2003.

1. Introduction

[2] Since the discovery of the overtone spectrum of H_3^+ in the auroral regions of Jupiter [*Drossart et al.*, 1989], infrared emission from this fundamental molecular ion has been used to probe the morphology and physical characteristics of the jovian auroral and polar regions of the ionosphere in great detail [e.g., *Connerney and Satoh*, 2000; *Miller et al.*, 2000]. Connerney and co-workers have used images of emission from the magnetic footprint of Io [*Connerney et al.*, 1993] to improve models of Jupiter's magnetic field [*Connerney et al.*, 1998]. *Satoh and Connerney* [1996] demonstrated, through inverse modelling of images, that the northern polar region - poleward of the main auroral oval - has a "yin-yang" structure, with a dark region in the local dawn to noon sector, and bright emission from noon to dusk. This picture correlates well with detailed ultraviolet images [e.g., *Clarke et al.*, 1998; *Prangé et al.*, 1998]; UV images have also shown that the bright polar emission region has considerable structure [*Pallier and Prangé*, 2001].

[3] More recently, *Rego et al.* [1999] discovered Doppler-shifted H_3^+ emission that could be ascribed to an electrojet flowing at ~3 kilometres per second around the auroral oval. This auroral electrojet was related to the lagging of the jovian equatorial plasma sheet behind corotation, a theory first put forward by *Hill* [1979]. Later work by *Hill* [2001] amplified this picture, and a more realistic model by *Cowley and Bunce* [2001] showed that plasma sheet lagging would generate voltages of ~2 MV across a narrow region of the auroral ionosphere, centred on a (magnetic) co-latitude corresponding to ~15°.

[4] Coincidentally with these theoretical developments, Stallard and co-workers investigated the auroral electrojet, using high-resolution ($\lambda/\Delta\lambda > 30{,}000$) spectroscopy. They found that there was an electrojet continuously present, with velocities ranging from a few hundred metres per second to over 1 km s^{-1} in the planet's rest frame [*Stallard et al.*, 2001; henceforth Paper 1]. This fitted well with theoretical predictions of ionospheric potentials [*Hill*, 2001; *Cowley and Bunce*, 2001]. In addition, Paper 1 revealed details of the structure in the auroral/polar region. With their spectrometer slit set west-east across the planet (from local dawn to dusk), Stallard and co-workers identified a Rising and Setting Auroral Oval, (RAO and SAO), showing up as high peaks in their intensity profiles. Poleward of this, they identified Dark and Bright Polar Regions (DPR and BPR), corresponding to *Satoh and Connerney*'s [1996] yin-yang structure. Paper 1 noted two unexpected features of the DPR:

- In contrast to the very weak emission seen in UV images, the DPR intensity is typically 30–40% of that of the auroral oval;
- The DPR velocity profiles are strongly (>2 km/s) red-shifted relative to the planet.

[5] Velocities (in the line-of-sight, l.o.s.) in Paper 1 were all presented in the frame of reference corotating with the planet (henceforth the planetary reference frame, PRF). By analogy with the Earth's *Dungey* [1961] cycle, the authors of Paper 1 suggested the DPR corresponded to a jovian polar cap in which field lines are open to the solar wind. Thus the ions within this region would be connected to field lines that are being swept back across the top of the planet. However, the extent of the jovian magnetosphere is such that the timescale of the solar wind passage down towards the tail is very long when compared with the length of the jovian day, unlike the situation on Earth. Thus, the open field lines connecting to Jupiter within this region would be held in place against the atmosphere corotating in the PRF. Were Jupiter's magnetic poles coincident with the rotational axis, one might then expect the DPR to be a region in which winds were stagnant in the frame of reference fixed with

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respect to the Sun-Jupiter axis [*Cowley et al.*, companion paper]. To a first approximation, given the relative periods of a jovian day and a jovian year, we can refer to this as the inertial reference frame (IRF). However, Jupiter's dipole is considerably offset from the rotational axis, and this paper re-presents the data from Paper 1 in the frame of reference fixed to the magnetic poles as they rotate around with the planet, to reveal the pattern of flow in the frame that, to a first approximation, is fixed relative to a local-time/magnetic-pole-centred, auroral structure. We call this the magnetic-pole reference frame (MPRF).

2. Observations

[6] All the observations reported here were carried out using the CSHELL facility infrared echelle spectrometer on the NASA Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii, during the nights of September 7 to 11 (UT), 1998. At that time, the apparent equatorial diameter of Jupiter was 49.6″ and the sub-Earth latitude (SEL) was ~+3°. Because of this positive SEL, only the northern auroral/polar region was well displayed and - as in Paper 1 - this paper deals exclusively with this hemisphere. The position of the peak intensity of the $Q(1,0^-)$ line in the fundamental $\nu_2(v_2 = 1 \rightarrow 0)$ vibrational band of the H_3^+ molecular ion (at 3.9530 μm) was analysed for Doppler shifting. A full explanation of both the data collection and subsequent analysis is given in Paper 1. For clarity, we now provide a synopsis of the processes used there, but refer the reader to Paper 1, if they require further clarification.

[7] The dataset consists of a series of spectroscopic measurements taken with the 30″ × 0.5″ slit aligned perpendicular to the rotational axis. The slit was moved in 1″ steps from the polar limb of the planet equatorwards across the auroral/polar region. The sequence of observations combined images and spectra and was devised specifically to allow us to remove the apparent wavelength shifts caused by the uneven illumination across our slit, arising from the observation of an extended but non-uniformly emitting object, the largest cause of imprecision within our measurements. Each spectral image was analysed by fitting the individual spatial rows of the $Q(1,0^-)$ line with a Gaussian, providing values for intensity and relative peak position for each point across the observed planetary chord. By using the narrowest available slit – 0.5″ - a nominal resolving power of 40,000 was obtained, which not only allowed a high wavelength resolution in the line (translating to an accuracy of $\sim \pm 300 \mathrm{ms}^{-1}$ after Gaussian fitting), but also minimised the apparent wavelength shifts due to uneven illumination across the slit.

[8] The Doppler-shifted l.o.s. velocity, measured as a function of y-position on the array (equivalent to variation in longitude at almost constant latitude), $v_m(y)$, was considered to be made up of a number of l.o.s. components:

$$v_m(y) = v_a(y) + \Delta v_r(y) + \Delta v_d(y) + \Delta v_s(y) + v_0 \qquad (1)$$

where $v_a(y)$ is the actual velocity shift which should be produced by the wind system on Jupiter in the PRF; $\Delta v_r(y)$ accounts for the rotation of the planet; $\Delta v_d(y)$ represents the non-linearity of the wavelength position across the detector array in the y-direction, corrected for through arc lamp calibration; $\Delta v_s(y)$ is the correction for the asymmetric illumination across the slit, which is briefly discussed below; and v_0 is the absolute zero velocity position in the planetary frame of reference, assumed to be the velocity on the body of the planet.

[9] The spatial correction $\Delta v_s(y)$ is not straightforward, and is detailed fully in Paper 1. The calibration used to correct for the effect of asymmetric illumination across the slit involves measuring the variation in intensity across the slit width position on H_3^+ images taken at 3.953 μm. High quality images were only available for the night of September 8 and 11, so values for $v_a(y)$ were only produced for these nights. Overall, Paper 1 estimated the individual pixel errors in $v_a(y)$ in the DPR to be 1.77 km/s, including systematic errors - due to the exact determination of the planetary centre on the slit and the velocity zero - that are constant across the slit for any particular spectral image. Averaged, the DPR error is between 0.5 km/s and 0.6 km/s.

3. Transformation to the Magnetic-Pole Reference Frame (MPRF)

[10] By plotting values for $v_a(y)$ in the PRF, Paper 1 made the electrojet associated with the auroral oval, which flows against the rotation of the planet (i.e. clockwise when viewed from above the north pole), easy to see. Paper 1 showed that the DPR has strong red-shifting in the PRF. To interpret this region in the Magnetic Pole Reference Frame (MPRF), the l.o.s. velocity measurements given in Paper 1 have to be transformed first to the IRF to give $V_{IRF}(y)$, by re-adding the planetary rotation back into the velocity profile:

$$V_{IRF}(y) = v_a(y) + \Delta v_r(y) \qquad (2)$$

Then a second transformation to the MPRF is required, allowing for the pole's velocity in the line of sight, Δv_{mp}, in order to obtain velocities relative to a fixed local-time, circum-magnetic-pole auroral pattern (as seen on Earth). This gives the MPRF l.o.s. velocity, $V_{MPRF}(y)$ via:

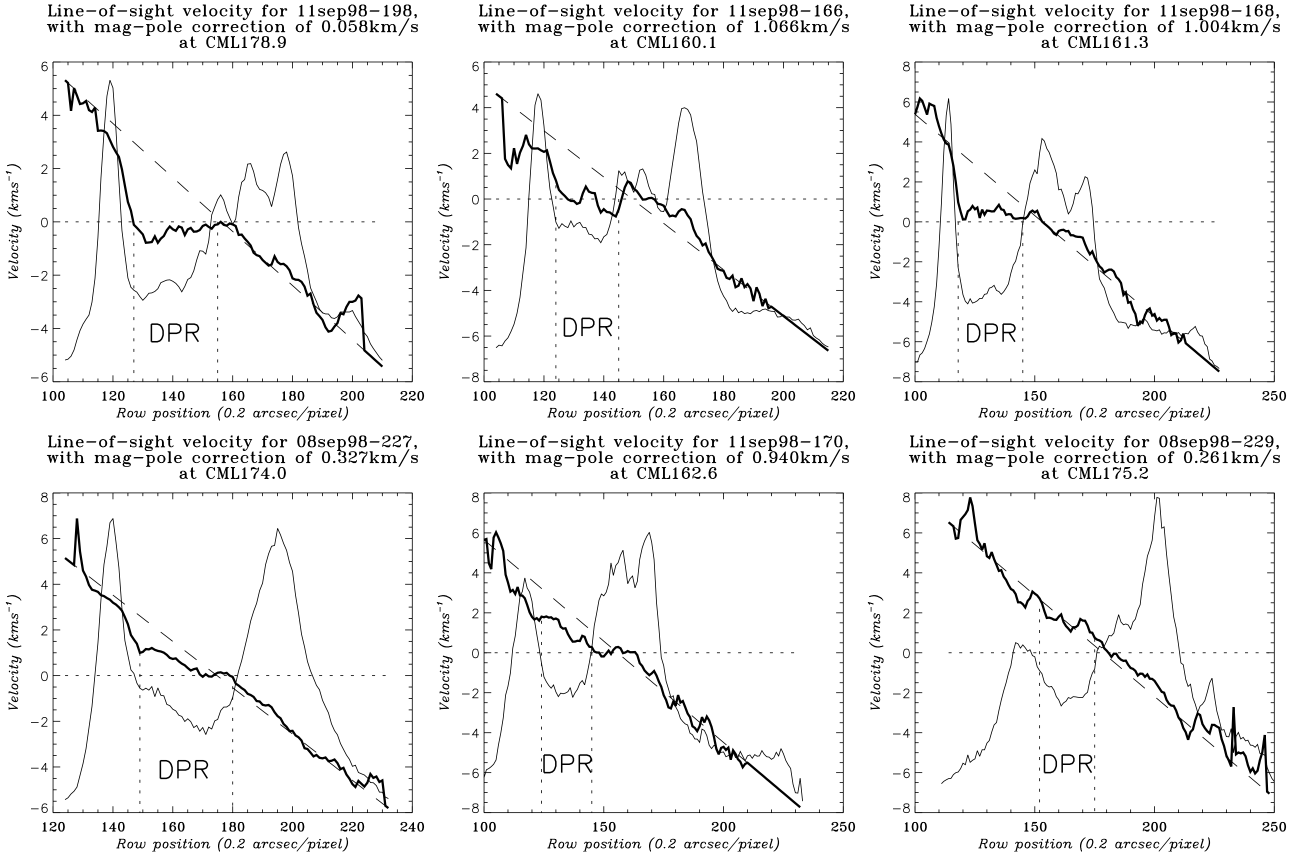
$$V_{MPRF}(y) = V_{IRF}(y) - v_{mp} \qquad (3)$$

In order to calculate Δv_{mp} we have approximated the position of the pole from the Offset Tilted Dipole model, using the values given by *Connerney* [1993]. This places the northern magnetic pole at ~15° co-latitude along the 180° line of longitude (System III). Its velocity about the rotational pole, measured in the IRF, is $3.15 \mathrm{km\ s}^{-1}$. Thus, for a measurement taken at any particular central meridian longitude (CML):

$$\Delta v_{mp} = 3.15 \times \sin(180 - \mathrm{CML}) \times \cos(\mathrm{SEL}) \qquad (4)$$

4. Analysis

[11] L.o.s. velocity profiles (bold line) in the MPRF are shown in Figure 1a. We show the intensity along the slit as a fine line to aid visualisation. To assist visualisation further, a dashed line shows the l.o.s. velocity of corotation with the planet after subtracting Δv_{mp}. This dashed line corresponds


Line-of-sight velocity for 11sep98-198, with mag-pole correction of 0.058km/s at CML178.9

Line-of-sight velocity for 11sep98-166, with mag-pole correction of 1.066km/s at CML160.1

Line-of-sight velocity for 11sep98-168, with mag-pole correction of 1.004km/s at CML161.3

Line-of-sight velocity for 08sep98-227, with mag-pole correction of 0.327km/s at CML174.0

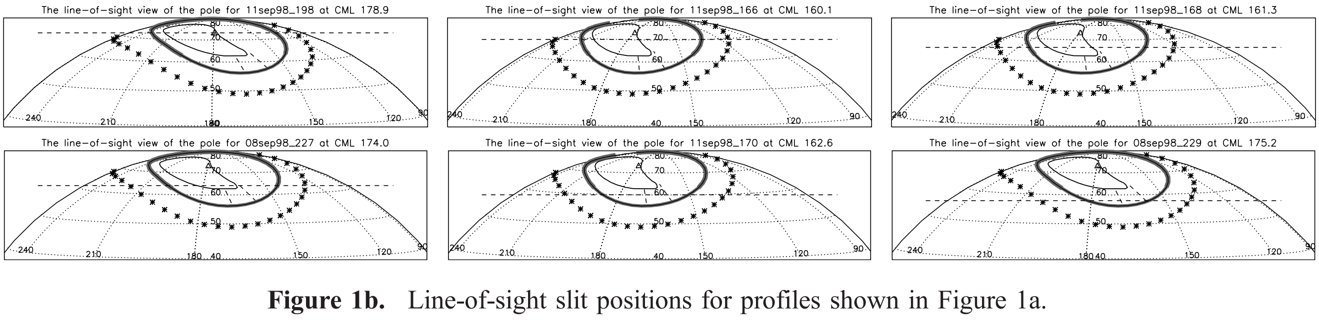
Line-of-sight velocity for 11sep98-170, with mag-pole correction of 0.940km/s at CML162.6

Line-of-sight velocity for 08sep98-229, with mag-pole correction of 0.261km/s at CML175.2

Figure 1a. Plots of the magnetic pole reference frame (MPRF) velocity, in the line of sight (l.o.s.), in descending latitudinal order. The bold line shows the derived l.o.s. velocity profile in the MPRF. The dashed line indicates expected magnetic-pole corotational velocity (l.o.s.), as a function of pixel position, where we have subtracted the l.o.s. velocity of the magnetic pole from the l.o.s. corotational velocity in the inertial reference frame. The normalised intensity (dot-dashed line) is shown for ease of visualisation. The DPR is indicated as the region between the two vertical dotted lines.

to what would be obtained as the l.o.s. corotational velocity if the rotational and magnetic poles coincided, as assumed in the models of *Hill* [1979, 2001] and *Cowley and Bunce* [2001]. For simplicity, we call this the "MPRF corotation velocity". The DPR is also indicated. The plots are displayed with decreasing latitude, cutting equatorward down through the polar region in roughly 4° steps. The position of the slit on the planet is shown in Figure 1b. The MPRF l.o.s. velocities indicate that the regions identified in Paper 1 show varying departure from MPRF corotation. The first three plots in Figure 1a show the MPRF l.o.s. velocity in the DPR to be nearly zero. In contrast, the velocity within the BPR (adjacent to, and to the right of, the DPR in our plots) is close to MPRF corotation. The fourth and fifth plots in Figure 1a represent cuts through the polar region towards the lower latitude (higher co-latitude) edge of the DPR. These show the DPR as sub-MPRF corotating, but not enough to be stationary relative to the magnetic pole. The degree of MPRF corotation increases with co-latitude, and returns to full MPRF corotation in the final plot of Figure 1a.

[12] These results lead to the identification of two separate regions within the DPR, distinguished by the extent to which they are at rest in the MPRF. Figure 2 shows an overview of the form the auroral polar region (as seen in infrared emission) now takes, being split into three separate regions inside the main oval. These regions consist of the BPR of Paper 1 and the newly distinguished fixed- and rotating-Dark Polar Regions (f-DPR and r-DPR). These new


The line-of-sight view of the pole for 11sep98_198 at CML 178.9

The line-of-sight view of the pole for 11sep98_166 at CML 160.1

The line-of-sight view of the pole for 11sep98_168 at CML 161.3

The line-of-sight view of the pole for 08sep98_227 at CML 174.0

The line-of-sight view of the pole for 11sep98_170 at CML 162.6

The line-of-sight view of the pole for 08sep98_229 at CML 175.2

Figure 1b. Line-of-sight slit positions for profiles shown in Figure 1a.

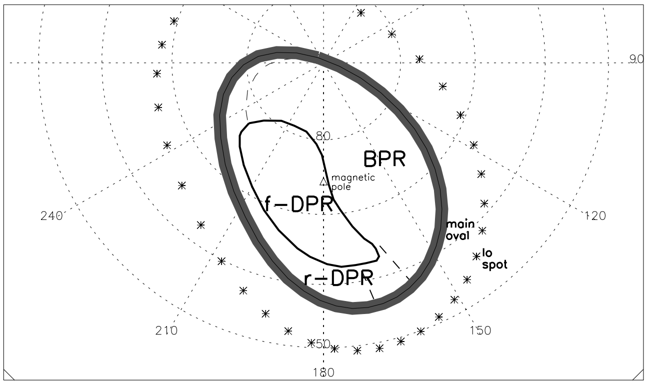


Figure 2. Polar projection of the jovian northern auroral region, showing the polar regions mapped out in this paper: the Fixed Dark Polar Region (f-DPR), Rotating Dark Polar Region (r-DPR), and the Bright Polar Region (BPR). The $30R_J$ oval is marked by a thick grey line, and the $6R_J$ line by stars.

regions are delineated by the variations in intensity and velocity on each profile, assuming the peak intensity associated with the auroral oval maps to the $30R_J$ oval from the VIP4 model [*Connerney et al.*, 1998]. The main - kidney bean-shaped - region, the f-DPR, is a region of zero l.o.s. velocity in the MPRF, stagnant with respect to the north magnetic pole. It is defined on the dawn side by the point at which the MPRF l.o.s. velocity begins to return to the velocity of the RAO, and on the noon side through a combination of return towards MPRF corotation and increase in intensity. The dashed lines at the base of the polar region show the regional transition between bright and dark intensities.

5. Conclusions

[13] The polar region within Jupiter's main auroral oval (as seen in infrared emission) appears to consist of three regions, rather than the two previously discussed Bright and Dark Polar Regions. This is due to a notable variation in the velocity structure within the Dark Polar Region, dependent upon position. Higher latitude velocity profiles show the DPR is stationary in the MPRF. Lower latitude DPR velocity profiles show an increasing deviation from a zero velocity with increasing co-latitude. The drift from zero velocity at the edges of the DPR shows that the field lines associated with these sections are starting to rotate with velocities similar to those associated with the auroral oval. Although a detailed comparison with UV studies is outside the scope of this paper, the location of the polar cusp identified by *Pallier and Prangé* [2001] is reasonably consistent with our f-DPR.

[14] Although, taken together with the companion paper [*Cowley et al.*, this issue], this paper marks progress in our understanding of the jovian polar regions and their connections to the magnetosphere, there remain unresolved issues. The DPR shows much higher levels of H_3^+ emission than can be produced by solar EUV ionisation. That suggests either that particle precipitation is occurring or that H_3^+ is being transported from the auroral oval itself. The latter suggestion is unlikely: *Rego et al.* [2000] ruled this out as an explanation for the (much lower) intensity mid-to-low latitude emission, on the grounds that the high dissociative recombination rate would not allow H_3^+ lifetimes long enough for appreciable transport. So, if our picture of the DPR being the region coupled to open magnetotail field lines is correct, an issue for further investigation must be how relatively high levels of ionisation can be produced in an ionospheric region coupled to essentially "empty" flux tubes.

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