On the Dynamics of the Jovian Ionosphere and Thermosphere I: the Measurement of Ion Winds

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Abstract

We present profiles of the line-of-sight ionospheric wind velocities in the northern auroral/polar region of Jupiter. Our velocities are derived from the measurement of Doppler shifting of the H$_3^+$ v$_2$ Q(1,0') line at 3.953 microns. The data for this study were obtained using the facility high resolution spectrometer CSHELL on the NASA Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii, during the nights of September 7 to 11, 1998 (UT). A detailed analysis, allowing for several effects on the measured wavelength is presented. The velocity profiles finally derived are consistent with an H$_3^+$ electrojet of ~1.2kms$^{-1}$ to 1.5kms$^{-1}$ flowing clockwise (as viewed from above the north rotational pole) - i.e. counter to the rotation of the planet - around the main auroral oval, for the night of September 11, and with somewhat lower velocities for September 8 and 10. In addition, we note two main regions inside (poleward of) the main auroral oval, which we call the Dark Polar Region (DPR) and the Bright Polar Region (BPR). These features correspond to the yin-yang structure noted by Satoh and Connerney (1999). The DPR appears to be strongly redshifted, with poleward winds in the line of sight up to -2.5kms$^{-1}$. The BPR may have weakly blueshifted emission. The detection of the auroral electrojet continuously over our observing run confirms the initial electrojet detection of Rego et al. (1999a), as well the mechanism proposed by Hill (1979) to explain how Jupiter’s equatorial magnetospheric plasmasheet is kept in co-rotation with the planet. We discuss the results in the light of recent proposals and analyses of the jovian middle magnetosphere, and suggest that our DPR winds may be under solar wind control.
Introduction

The past few years have been of particular interest in developing our understanding of the upper atmosphere of Jupiter, the coupled ionosphere-thermosphere. High resolution images in the ultraviolet and infrared now give excellent views of the complex and dynamic auroral and polar regions of the planet (Ballester et al. 1996, Clarke et al. 1998, Prangé et al. 1998, Satoh and Connerney 1999), and spectroscopic studies have given new insights into the energy balance there (Lam et al. 1997, Miller et al. 1997, Rego et al. 2000). Results from the Galileo space probe (Kivelson et al. 1997), and the detection of an electrojet flowing along the main auroral oval (Rego et al. 1999a), has renewed interest in models proposed over 20 years ago to explain the coupling between the jovian atmosphere and the middle magnetosphere (Hill 1979, Hill and Dessler 1991). As a result there are a number of new studies investigating this connection (Achilleos et al. 2001, Cowley and Bunce 2001, Hill 2001, Khurana 2001, Southwood and Kivelson 2001).

The mechanism proposed by Hill in 1979 to explain how Jupiter accelerates ions and electrons from Io’s volcanoes, and maintains the resulting equatorial plasmasheet in co-rotation with the planet, involves a field-aligned current system which closes through the jovian ionosphere equatorwards.
across the main auroral oval (see Figure 1). The currents are initially generated by the slippage of the jovian magnetic field through the Io-generated plasma, through the dynamo effect. But the result of the passage of these currents is to produce forces that bring the plasma into co-rotation. As the plasma migrates outwards from Io’s orbit, at just under six jovian radii from the centre of the planet (5.9R_J: 1R_J = 71,373km), under centrifugal force, a “push-me-pull-you” effect is produced. In this, the plasma lags behind the jovian field, generates a current and is “instantaneously” brought back into co-rotation, thus switching the current off again. (In Fig. 1, we call this the “Inner Hill current system”, by analogy with that discussed by Hill, 1979.) Angular momentum is supplied from the planet’s upper atmosphere by the collision between the neutral thermosphere, in co-rotation with the planet, and the ionosphere, which tends to lag behind as the plasmasheet slows down the magnetic field lines to which they are both attached, before co-rotation is re-established. But, as explained by Hill (1979), this mechanism breaks down at radial distances around 20R_J, where the magnetic field strength is too low, and the required velocity too great, for full co-rotation to be maintained.

At this point, a continuous Birkeland field-aligned current flows upwards from Jupiter’s atmosphere, from the footprint of the 20R_J magnetic field line. The current continues radially outward through the plasmasheet until the point where co-rotation almost totally ceases, at around 50 to 60R_J; the current then flows downward along the magnetic field back into the ionosphere. The circuit is finally closed by a Pedersen current across the auroral ionosphere between the 20R_J and 50/60R_J footprints. We label this the “Outer Hill current system” in Fig. 1, although it was only this region that was actually discussed by Hill’s original paper. (N.B. these numbers are exemplary of those that have been suggested, rather than being exactly defined; there is likely to be considerable temporal variation in the exact values. In what follows we will use 20R_J to represent the inner edge of co-rotation breakdown and 60R_J the outer limit.)

Hill (2001) associates the bright region of the jovian auroral oval with field lines that cross the magnetic equator at ~30R_J, where the upward flowing Birkeland current corresponds to downward precipitation of ionising electrons. As Hill’s theory is developed by Cowley and Bunce (2001), the brightest section of auroral oval corresponds to the footprint of fieldlines crossing the jovian (magnetic) equatorial plane between ~40R_J. (N.B. these values are dependent on the radial profile of the lag to corotation used.) In the northern hemisphere, the interaction between the equatorward ionospheric electric field, E_oval, operative equatorward across the auroral oval between the 60R_J and
20R_j footprints, and the upward directed jovian magnetic field causes a Hall drift, \( \mathbf{v}_H \), \( = \mathbf{E}_{\text{oval}} \times \mathbf{B} / B^2 \), where \( B \) is the jovian surface field strength in the auroral zones, which drives both electrons and ions along the auroral oval in a clockwise direction as viewed from the North Pole. This direction is anti-co-rotational, and immediately brings the ionosphere into collision with the thermosphere. (In the southern hemisphere, the directions of both \( \mathbf{E}_{\text{oval}} \) and \( \mathbf{B} \) are reversed, so the direction of \( \mathbf{v}_H \) remains anti-corotational.)

The electrojet - in the true sense of the word - results from the fact that electrons are collisionally decelerated much less than the ions. Rego et al. (1999a), however, used the term “auroral electrojet” for the 2 to 3 km/s \(^{-1}\) clockwise flow of \( \text{H}_3^+ \) ions that they detected along the oval during a “auroral event” observed in 1997. Modelling using the Jovian Ionospheric Model (Achilleos et al., 1998; henceforth JIM) showed that collisions between \( \text{H}_3^+ \) ions and the thermosphere at the peak ionisation level - around 0.3\( \mu \)bar - accelerated the neutrals to some 40\% of the ion velocities for cross-auroral emfs of 2 MegaVolts (Miller et al. 2000, Achilleos et al. 2001). As these neutral winds interact with the bulk of the co-rotating thermosphere, approximately \( 10^{13} \) Watts is input into the upper atmosphere - an amount not dissimilar from that ascribed to particle precipitation (Achilleos et al. 1998).

The first direct detection by Rego and co-workers of the Hill mechanism at work has now opened up the possibility of using ground-based observations to study the interaction between the jovian ionosphere and the middle magnetosphere. But Rego et al. (1999a) had, by chance, observed during the period of an auroral event. The real challenge, therefore, remained the detection and characterisation of the auroral electrojet during “normal” times. Here we present the first detection of the electrojet continuously over a period of several jovian rotations. We also show that the whole auroral/polar region of Jupiter is extremely dynamic, with a complex - but apparently fairly stable - wind system.

**Observations**

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.
observations were made on the nights of September 7 to 11 (UT), 1998. For this study, the echelle was set up to measure the Q(1,0') line in the fundamental $v_2(v_2=1\rightarrow0)$ vibrational band of the H$_3^+$ molecular ion, which occurs at 3.9530\(\mu\)m (henceforth, the Q(1,0') line). This line has been used previously to measure both the energy inputs to and outputs from the ionosphere (Rego et al. 2000) and the jovian auroral electrojet (Rego et al. 1999a). It falls in the L' terrestrial infrared window and coincides with a region of Jupiter’s spectrum where the infrared continuum is minimised as a result of absorption by stratospheric methane. As a result, the contrast between the line and the continuum, for resolving powers of $\lambda/\Delta \lambda>10,000$ is good, even at the jovian equator, where the pathlength of absorbing methane is at a minimum. In the auroral/polar regions, where the absorption of the continuum by methane is very efficient and H$_3^+$ column densities exceed $10^{16}$m$^{-2}$, spectra with signal-to-noise (S/N) ratios between 20 and 100 may be obtained with exposure times of ~60s. The Q(1,0') line is therefore well suited to measuring the dynamic properties of the jovian upper atmosphere.

CSHELL may be used in both spectroscopic (SM) and direct imaging (DIM) modes. In SM, a filter is chosen to select the required wavelength range and the grating is set to the angle required to centre the line on the array - for the Q(1,0') line, this is 64.8°. DIM is effected by the use of a circular variable filter (CVF), which has a spectral resolving power of ~100. Used in DIM, the pixels on CSHELL subtend an area on the sky of 0.2” x 0.2”. In SM, CSHELL has a per pixel resolving power of ~100,000 at 3.953\(\mu\)m. The spectrometer operates with a variable slit-width; for this study, we used the narrowest available - 0.5” - giving a nominal resolving power of 40,000. We chose this set-up because, although one loses intensity by choosing a narrow slit, we wished to minimise apparent wavelength shifts caused by the uneven illumination across our slit, arising from the observation of an extended but non-uniformly emitting object: Jupiter’s surface brightness in the auroral/polar regions is known to vary on spatial scales of less than 0.5”. We will deal with the issue of spatial variations in Jupiter’s intensity in the next section. We also set the slit orientation so that it was parallel to the jovian equator. This set-up was designed to maximise our ability to detect upper atmosphere winds, in contrast to the set-up used by Rego et al. (1999a), who used a 1” slit aligned along the central meridian longitude (CML).
Prior to each evening’s observations, we measured a series of Krypton and Argon arc lines (see Figure 2). These lines were used to calibrate the wavelength of the array for each of 256 detector rows: both the exact position of a line and the wavelength dispersion across the array can vary as a function of detector row (denoted by the y-direction on the array). We return to these issues in the next section. We also measured flat and dark frames, to correct for variations in the array response to illumination. Interspersed with the observations we made of Jupiter during the nights of our observations, we also made regular observations of the standard star BS8647, an A0 star with an

Figure 2: The assemblage of Argon and Krypton arc lines used to calibrate the CSHELL array. The annotated wavelengths are the apparent wavelengths on the CSHELL detector array. They all show slightly curvature away from vertical on the array, which must be accounted for in determining wavelength dispersion across it. The Krypton 3 and Krypton 4 lines are closest to the H$_3^+$ Q(1,0) line.
apparent visual magnitude of 6.41. In DIM, this star was used to focus the telescope, and then to obtain the point spread function to estimate the seeing. During the course of our run, the seeing improved from ~1” to 0.5”, so we make greater use of the last night’s observations. We measured the star’s spectrum at two slit widths: at 4”, spectra were obtained to use for flux calibration purposes; at 0.5”, we used the stellar spectra to correct for the positional non-linearity of a continuum source, in the y-direction, as a function of wavelength (the x-direction). We refer to this, once more, in the following section, although for this particular study, y-direction non-linearity of a continuum source is a secondary issue.

Our observing strategy for Jupiter was to make a series of spectroscopic measurements moving the slit, in steps of 1”, from the polar limb of the planet equatorwards across the auroral/polar region, and then offsetting for a final spectrum along the jovian equator. In principle, one could always know where the slit was positioned on the planet by measuring the length of the chord subtended on the slit. Unfortunately, however, the CSHELL slit is only 30” long. At the time of our observations, Jupiter’s equatorial diameter subtended 49.6”; the planet is an oblate spheroid, so even at relatively high latitudes the slit was not able to encompass both limbs. Working out exact slit positioning on the planet therefore required the use of both images and spectra, the image of the planet on the array being positioned to coincide with the position of the slit.

The following images and spectra were obtained and saved to disk for analysis:

- A K-band image of Jupiter was obtained;
- An image with the CVF set at 3.953µm was obtained;
- The slit was then set to 0.5”, and a spectral image obtained at the polar limb;
- The slit was offset 2” off the planet and from this position a series of spectral images, stepping 1” equatorward each time, was obtained until the auroral/polar region had been covered;
- The slit was then offset to the equator, and a spectral image obtained;
- The slit was repositioned to the limb of the planet and images at 3.953µm and K were obtained.

From these measurements we were able to estimate the extent to which drifting and pointing errors had affected the notional positions on the planet that we had hoped to observe.
A typical sequence is shown in Figure 3. For the images, an exposure time of 0.08s was used, and 100 images were co-added. A sky image of the same duration was used to subtract the background intensity and produce the final image. Spectral images consisted of a single 50s exposure (plus sky subtraction). Although data were obtained from the northern and southern hemispheres, the sub-Earth latitude of Jupiter at the time of our observations was ~+3°. Thus the northern oval was far better displayed. In what follows, therefore, we discuss only observations made of this hemisphere.

**Data Reduction**

Images and spectral images were flat-fielded and calibrated in the normal fashion, using the flats, darks and stellar spectra obtained each night. Details of the data relevant to this study are given in Table I. Rego et al. (1999a) measured auroral electrojet velocities of ~2 to 3 km s⁻¹ in the line of sight in their 1997 spectral images. But we expected to find velocities less than this under “normal” jovian conditions.
conditions, and it was clear that even more care was required in deriving true wind speeds from the wavelength shifts we expected to measure. We therefore used a multi-step process to ensure that our velocities were as little affected by extraneous factors as possible. This process is outlined below. We leave the discussion of errors to the next section.

Figure 4: Line-of-sight corrected $Q(1,0')$ intensity profile for the 11N4 #166 spectral image, taken with a CML of $\lambda_{\text{m}}=159^\circ$ (bold line). East on the sky is on the left (rising planetary limb), West (setting planetary limb) on the right. Overplotted is the uncorrected intensity profile (light line). The regions discussed in this paper are marked: RAO – Rising Auroral Oval; DPR – Dark Polar Region; BPR – Bright Polar Region; SAO – Setting Auroral Oval. Also marked is the Body of Planet (BoP) emission which is also present in some of the measured profiles. Readers are referred to this figure to compare with following figures where inserting and/or labelling the intensity profile makes the plots overly complicated.
The $Q(1,0^-$) line profiles were first fitted by an IDL (data analysis software) gaussian fitting procedure which recorded peak intensities, line positions and line widths for each of the spectral rows across the planet: for the high S/N lines we were using, this program fitted the intensity to within $\pm 5\%$, and the line position and width to within 0.1 pixels ($\approx 300\text{ms}^{-1}$). Figure 4 shows the $Q(1,0^-$) East-West (on the sky) intensity profile across the planet for data taken at 08:34U.T. on the night of September 11, 1998, at a CML of 159° (System III Longitude) and N68° latitude. A line-of-sight (l.o.s.) correction has been applied, based on calculating the pathlength through a uniformly emitting shell, to produce the bold line in the figure; the light line is the uncorrected profile. The description of the data reduction given below will concentrated on this spectral image, chosen for two important reasons: there was, associated with it, a good quality CVF image taken at 3.953 $\mu$m, and; the slit at this particular position on the planet cut the main auroral oval more or less at the rising and setting ansas. Thus it was ideal for demonstrating our technique for removing the spatial effects from the velocity profile, whilst having the greatest possible line-of-sight velocity difference between the rising and setting auroral ansas.

The l.o.s. corrected profile shows a pronounced intensity peak, close to the rising (East on the sky) limb of the planet, which corresponds to the CSHELL slit cutting across the rising part of the main auroral oval (Rising Auroral Oval, RAO – pixels 110-125). The intensity then drops by about 40% as the slit encompasses part of the inner polar region, which is generally darker than the rest of the auroral/polar region. We call this the Dark Polar Region (DPR – pixels 125-143). Nonetheless, it should be noted that this is still an area of very considerable H$_3^+$ emission - a point that can be overlooked when considering infrared images. In the middle of the polar region the intensity increases once more to that of the RAO, and there are two clear peaks. (These may correspond to inner auroral ovals, such as those reported by Pallier and Prangé, 2001 - see Discussion.) We call this region the Bright Polar Region (BPR – pixels 125-143). Our DPR and BPR correspond to the yin-yang polar regions noted by Satoh and Connerney (1999). The intensity then increases to a final peak that is a further 40% brighter than the RAO, which corresponds to the slit cutting the main auroral

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oval once more, this time on the side of the planet which is closer to the setting limb. We call this the Setting Auroral Oval (SAO - pixels 160-182). Limbwards of the SAO there is an extended region of H$_3^+$ emission, which corresponds to the body of the planet. The intensity here falls off monotonically from about 20% of the RAO to zero at the planetary limb.

Figure 5 shows the measured wavelength of the Q(1,0) line, which corresponds to the data of Fig. 4, in terms of a velocity shift from an (at this stage) arbitrary zero, which we set approximately to the expected laboratory wavelength of the line. The velocity we measure as a function of y-position on the array, $v_m(y)$, may be considered to be made up of a number of components:

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

Figure 5: Q(1,0) measured velocity profile, $v_m(y)$, for the 11N4 #166 spectral image (light line) and the profile after correction for $\Delta v_r(y)$ (dark line). At this stage, the exact velocity zero is arbitrary. The straight dashed line represents the correction due to $\Delta v_r(y)$.
\( v_\alpha(y) \) is the actual velocity shift that should be produced by the wind system on Jupiter, i.e. the component we wish to determine. \( \Delta v_\alpha(y) \) arises because our slit is aligned perpendicular to the jovian axis of rotation. Thus the \( Q(1,0') \) is blue-shifted on the rising limb and red-shifted on the setting limb; the presence of \( \Delta v_\alpha(y) \) in our measured velocity profile explains the general downward slope going from left to right across the array. Correction for this is easily made in the case of a spherical planet with a sub-Earth latitude (S.E.L.) of 0\(^\circ\), since - in the line of sight - this produces an effect which varies linearly with \( y \), according to:

\[
\Delta v_r(y) = \frac{v_r y'}{R_p}
\]

where \( y' \) is the distance in pixels from the centre of the planet, \( R_p \) is the equatorial radius in pixels and \( v_r \) is the rotational velocity of the limb at the equator. Jupiter’s S.E.L. of 3\(^\circ\) and oblateness make a difference of -0.2\% to the radial velocity correction, even at the limb, where the velocity is 12.572kms\(^{-1}\). Thus we retained the linear approximation for \( \Delta v_r(y) \). With an equatorial diameter of 49.6\( '' \) at the time of our observations, and a pixel size of 0.2\( '' \), this gives a slope of 0.1013887kms\(^{-1}\)

**Figure 6:** \( Q(1,0') \) velocity profile for the 11N4 #166 spectral image, after correction for \( \Delta v_\alpha(y) \) (bold line). This profile now corresponds to \( v_p(y) \). Overplotted is the profile prior to the detector correction (light line).
The non-linearity of the wavelength registration on the detector array in the y-direction, $\Delta v_d(y)$, can be compensated for by using a geometric transformation. This straightens the arc lines on the array, which show some curvature (see Fig. 2). Figure 6 shows the effect on the velocity profile of correcting for $\Delta v_d(y)$, after removal of the rotational velocity.

These first two corrections were relatively straightforward, and we were able to carry them out for the data we obtained on all five nights of our observing run. The third correction, however, to allow for the spatial non-uniformity of jovian emission across our 0.5" slit, which gave rise to $\Delta v_s(y)$, required good quality images. These were only available for the night of September 11 and, to a lesser extent, for September 8 (see later). At this stage of our correction process, therefore, we defined a “pre-spatial” velocity profile, given by:

$$v_{ps}(y) = v_a(y) + \Delta v_s(y) + v_0$$

where this quantity still contains velocity shifts due to the uneven illumination across the slit and an arbitrary zero; thus Fig. 6 shows the profile of $v_{ps}(y)$. As we demonstrate in the next section, however, these “pre-spatial” profiles are useful for night-to-night comparisons to illustrate to what extent velocity features remain constant during the observing run, although this can only be done if the viewing geometry is similar.

The correction for spatial effects across the slit is not straightforward, and we made two simplifying assumptions before proceeding:

- The intensity varies linearly across the slit, so that we may approximate it by

$$\Delta I(x,y) = \frac{[I(x^-, y) - I(x^+, y)]}{[I(x^-, y) + I(x^+, y)]}$$

where $x$ refers to the pixel position at the centre of the slit and $x^-$ and $x^+$ to the pixels shifted one slit width on either side of it; and

- There is a linear relationship between $\Delta I(x,y)$ and $\Delta v_s(y)$, such that
\[ \Delta v_s(y) = b \Delta I(x,y), \text{ for all values of } y. \]

Using the linear approximation outlined above, the next task was to determine the value of \( \Delta I(x,y) \) for our velocity profiles. This may be approached theoretically: the effect of putting a delta-function intensity source in pixel \( x^+ \) and zero intensity elsewhere (giving \( \Delta I(x,y)=+1 \)) would be to produce a velocity shift \( \Delta v_s=-7 \text{ kms}^{-1} \), the theoretical velocity resolution of the 0.5" slit. Similarly, a delta-function intensity in pixel \( x^- \) (giving \( \Delta I(x,y)=-1 \)) gives \( \Delta v_s=+7 \text{ kms}^{-1} \). (N.B. increasing values of \( x \) correspond to higher wavelengths, which - in turn - correspond to red-shifted velocities.) This gives \( b=7 \text{ kms}^{-1} \).

![Figure 7: Plot of \( \Delta v_s(y):\Delta I(x,y) \) for the rising limb of 11N4 #166, where \( x \) represents the spatial position of slit north-south on the planet. Open triangles: measured datapoints; straight line: best fit line, with \( b=10 \).](image)

We also used a value of \( b \) determined empirically: between pixels 115 and 120 in Fig. 6, the measured profile shows a sharp increase in velocity. Comparison with Fig. 4 shows that this corresponds to the slit cutting the rising limb so that gradually more and more of the slit is illuminated by the planet until it is fully illuminated; the variation in velocity shift is due to this spatial
effect. To determine this effect we first matched the position of our slit to its position on the H$_3^+$ image measured a few minutes earlier, at the beginning of this observation sequence. This was effected by comparison of the chord-length subtended by the planet along the slit and checked by matching the intensity profiles along the slit of the spectral image and the H$_3^+$ image at the chosen position. Using the image, we could then simulate the illumination of the slit, and hence determine the value of $\Delta I(x,y)$. The values of $\Delta v_s$ were then plotted against $\Delta I(x,y)$. Figure 7 shows that these values fall on a straight line giving a value of $b\sim10\text{km}^{-1}$. This figure is about 50% higher than that determined from theoretical considerations. However, subsequent CSHELL observers reported that the 0.5” slit was actually producing a resolving power of $\sim10\text{km}^{-1}$, rather than the $7\text{km}^{-1}$ advertised (J. Rayner, private communication). This means that the two methods for determining $b$ were in close agreement.
Figure 8 shows the spatially corrected velocity profile for our sample data, along with the profile of \(v_{ps}(y)\). The new profile has also been adjusted so that the velocity of the \(H_3^+\) emission on the body of the planet, to the West (on the sky) of the SAO has been set to zero, effectively removing \(v_0\) and setting our velocities in the rest frame of Jupiter’s upper atmosphere. Thus Fig. 8 shows to the profile of \(v_a(y)\), our required velocity profile. It is interesting to compare \(v_{ps}(y)\) and \(v_a(y)\) and the intensity profile of the Q(1,0) line shown in Fig. 4. (N.B. for all discussions of the 11N4 #166 profiles, the pixel positions corresponding to our four regions are: RAO = 110 - 125; DPR = 125 - 143; BPR = 143 – 160; SAO = 160 – 182.)
• There is a clear difference of ~+2kms\(^{-1}\) in the line of sight velocity measured between the Q(1,0') intensity peaks representing the RAO and the SAO in both \(v_p(y)\) and \(v_d(y)\). With the removal of \(v_0\) in \(v_d(y)\), the RAO is redshifted by ~-1.0kms\(^{-1}\), and the SAO blueshifted by ~+1.1kms\(^{-1}\). Taking into account our line of sight along the auroral oval, this difference is indicative of an \(H_3^+\) wind clockwise (when viewed from above the northern rotational pole - i.e. counter-rotational) along the auroral oval of ~1.2kms\(^{-1}\) (assuming the angle of flow to be 30° to the line-of-sight) to 1.5kms\(^{-1}\) (45° to l.o.s.). This velocity is approximately half that found by Rego et al. (1999a), and may be more representative of “normal” conditions in the main auroral oval.

• The DPR velocities are ~-0.5 to -1.0kms\(^{-1}\) redshifted with respect to the RAO. After removal of \(\Delta v_s(y)\) there is more structure than prior to the spatial correction, which may reflect the difficulty in correctly ascertaining the spatial effect in this region of somewhat reduced intensity.

• The BPR velocity is ~-1kms\(^{-1}\) redshifted with respect to the SAO. In the final velocity profile, \(v_d(y)\), the BPR is uniformly blueshifted by ~+0.7kms\(^{-1}\). In \(v_p(y)\), the difference between the redshifted DPR and the BPR is ~+1.2kms\(^{-1}\); in \(v_d(y)\), the difference has grown to ~+2.2kms\(^{-1}\). But in both profiles, the DPR is redshifted with respect to the BPR.

The consistency of the general features between \(v_p(y)\) and \(v_d(y)\) is a good indication that our technique for removing the spatial effects from the velocity profiles is not introducing any spurious features. The exception to this might be in the DPR, where the redshifting is accentuated by the spatial correction, and some additional structure appears to be introduced. The gross features of the \(v_d(y)\) profile are relatively insensitive to the exact value chosen for \(b\) (see Figure 9); in changing from \(b=5\)kms\(^{-1}\) to \(b=15\)kms\(^{-1}\), for example, we find:

• The velocity difference between the RAO and SAO is +2.2kms\(^{-1}\) for \(b=5\)kms\(^{-1}\) and 0.8kms\(^{-1}\) for \(b=15\)kms\(^{-1}\).
The velocity shifts of between the BPR and SAO decrease from +0.8 km s\(^{-1}\) to ~0 km s\(^{-1}\) on going from \(b=5\) km s\(^{-1}\) to \(b=15\) km s\(^{-1}\). But, conversely, the magnitude of the RAO to DPR shift increases from ~−0.3 km s\(^{-1}\) to ~−0.8 km s\(^{-1}\).

Thus we feel that our technique for removing the various contributions to the measured velocity profile, \(v_m(y)\), produces a final profile, \(v_a(y)\), which is a good representation main features and general behaviour of the actual line-of-sight \(H_3^+\) velocities in the jovian ionosphere.

Errors
In the previous section, we deliberately left out the determination of probable errors associated with our final velocity profile, \( v_a(y) \). Each step in our process for deriving velocities has errors associated with it, and we now consider each of these in turn:

- **IDL peak fitting**: in the auroral/polar region the signal-to-noise ratio of the Q(1,0') is always in excess of 10, and often as high as 100 (peak signal/continuum noise). Thus the IDL gaussian fitting procedure that is part of the IDL package fits the peak well within 10% of a pixel, or 0.3\( \text{km/s} \). We checked this by generating a gaussian, with known peak position, adding noise typical of our data, and then fitting this with the IDL procedure.

- **\( \Delta v_d(y) \)**: the arc line wavelength variation across the array (in the y-direction) was fitted to a fourth order polynomial, which fitted the lines such that the parameters were determined with a 3\( \sigma \) error of +/-1%.

- **\( \Delta v_r(y) \)**: the rotational period of Jupiter is known to a very high degree of accuracy and this correction to our data is essentially errorless, except for a constant term due to the difficulty in ascertaining the exact centre of the planet on the array; we subsume this into \( v_0 \). Our velocities are thereby set with respect to the frame of reference co-rotating with the jovian equator.

- **\( v_0 \)**: this correction allows for a number of factors not taken individually into account - inaccuracy in determining the position of the centre of the planet in the y-direction, and hence the point at which to zero the rotational correction; the relative motion of the observer and the centre of rotation of Jupiter; any residual inaccuracies in determining the precise position of the Q(1,0') line on the array, due to uncertainties in the laboratory line frequency, etc. As in the case of Rego et al. (2000), \( v_0 \) is determined empirically in this study, by setting the velocity of the H\(_3^+\) line on the body of the planet to zero. Typically the error in doing this is +/-0.3\( \text{km/s} \). Note that this error affects the absolute value of the velocities we determine, but not their relative value.

- **\( \Delta v_s(y) \)**: this correction, as indicated above, is the most difficult to effect, and was not possible for most of our dataset. It is similarly difficult to estimate the errors associated with it. To do this to best effect, we have therefore taken the differences in \( \Delta v_s(y) \) for values of \( b=5 \) and \( b=15 \), i.e. +/-50% of our chosen value of \( b \), to represent typical errors. Fig. 9 shows the spatial correction curves for \( b=5 \), \( b=10 \) and \( b=15 \) for the data analysed in the previous section. This shows that the error for \( \Delta v_s(y)=0\text{km/s} \), typical of the RAO, is essentially 0, while it rises to +/-1.0\( \text{km/s} \) for
\[ \Delta v_s(y) = 1.5 \text{km/s}, \] a value typical of the DPR. We propose that this error be fitted quadratically by
\[ \varepsilon^2 = 0.44 \Delta v_s(y)^2, \] where the constant has been chosen to fit the figures above.

The main sources of error therefore come from the first and last of our data reduction procedures. We follow the usual statistical practice and assume that the overall error, \( \varepsilon \), from a set of independent errors adds quadratically - i.e. \( \varepsilon^2 = \Sigma \varepsilon_{\alpha}^2 \), where we sum over all the \( \alpha \) contributions. We find the per pixel error, \( \varepsilon(y) \), in the RAO and SAO is typically +/-0.45km/s (allowing for \( \varepsilon_s \) corresponding to a value of \( \Delta v_s = +/-0.5 \text{km/s} \)). In the same way, one gets \( \varepsilon(y) = +/-1.77 \text{km/s} \) for a typical DPR pixel; BPR errors are similar to those in the RAO and SAO. However, the profiles show trends in velocity across the individual regions. In the remainder of this article, we therefore deal with average regional velocities for our four regions.

**Results**

The data reduction procedure outlined above was in principle applicable to all our dataset. In practice, however, we were able to obtain good quality images only on the night of September 11: on September 7 and 9, the jovian northern aurora was orientated away from the Earth during the period of observations; on September 8, the seeing was only ~1” and this had the effect of smearing sub-
arcsecond spatial structure in the images; on September 10, the images were affected by a “declination bounce”, which had the effect of producing a double limb and oval. The exact cause of this bounce was never ascertained, but the most likely reason was flexure in the CSHELL DIM mechanism.

Later in this section, we will present night-by-night comparisons of profiles of \( v_p(y) \) to see to what extent features seen on one night reappear on others. But first we present the sequence of spectral images we have labelled 11N4, to signify the day, the hemisphere and the run number (where individual spectral image numbers indicate the saved data numbers in our observing log; see Table I).

In Figure 10, we show the H\( \text{\textsc{i}} \) CVF image taken at the start of 11N4, with the positioning of the slit marked for each of the spectral images obtained. The CMLs range from \( \lambda_{\text{III}} = 155^\circ \) to 162\(^\circ\), indicating that the elapse time for the sequence was \(~12\) minutes. The CVF image taken at the end of the run did not differ greatly from that taken at the start of 11N4, although it was less well positioned on the array. So the start image was used for the spatial correction throughout. 11N4 comprises six spectral images commencing at the northern limb of the planet and spanning the auroral/polar region, moving equatorward in steps of 1”, as well as two spectral images (#160 and #162) taken off the limb and one equatorward of the main oval (#174), and a further spectral image (#176) taken at the equator. There is no velocity structure discernible in these four, and they are not presented. Figure 11 shows the Q(1,0) intensity and \( v_a(y) \) profiles for #158 and #164 to #172. The following features may be observed:

- #158: The Q(1,0) intensity profile shows the slit cutting the polar limb of the planet, with the auroral oval on the limb. In this configuration the electrojet should be almost plane parallel to the observer’s line-of-sight (if it is flowing at a constant altitude). But the arc of the oval subtended on the slit means that at either end of the arc, the direction of the electrojet velocity makes an angle of \(~65^\circ\) to the line-of-sight. From the previous section, we deduced an electrojet velocity of \(~1.2\) km s\(^{-1}\) - \(1.5\) km s\(^{-1}\). Thus we would expect to observe a velocity difference of \(+1.0\) km s\(^{-1}\) - \(1.25\) km s\(^{-1}\) between the rising and setting extremities of the oval. The observed velocity difference, between pixels 150 and 175 is \(~+1.1\) km s\(^{-1}\), in good agreement with the predicted shift.
Figure 11: Velocity profiles, $v_a(y)$, for the 11N4 sequence of spectral images. Overplotted is the intensity profile for Q(1,0), uncorrected for line-of-sight. The profiles are presented going from polar limb towards the equator: top left - #158, polar limb; top right - #164; middle left - #166; middle right - #168; bottom left - #170; bottom right - #172.
• #164: With the slit ~1” equatorward from the limb, the intensity profile now shows all the features - the RAO, DPR, BPR and SAO - that we described in the previous section. At this position, the slit is south of the northern rotational pole, but still north of the magnetic pole, which is offset by ~10° equatorward along $\lambda_{III}=202^\circ$. The velocity profile shows that the DPR may be slightly redshifted (by ~-0.3km$s^{-1}$) with respect to the BPR, but a velocity shift of zero between these two regions would not be inconsistent with the data. There is a +0.6km$s^{-1}$ blueshift of the SAO and a -2km$s^{-1}$ redshift of the RAO, giving a difference of 2.6km$s^{-1}$ between the two. Given the viewing angle of the main auroral oval at this point, these observations are consistent with an electrojet H$_3^+$ velocity of ~1.5 km$s^{-1}$ - 1.7km$s^{-1}$ clockwise.

• #166 and #168: These two profiles are taken with the slit cutting the main auroral oval at, or close to, both ansas, with the slit position in #168 ~0.8” south of that in #166 (see Fig. 13). #166 has been described in some detail already. The intensities of the RAO and SAO are similar, at ~1.2Wm$^{-2}$µm$^{-1}$ for this spectral image. This is also the brightness for the RAO in #168, but the SAO has only ~65% of this value. Changes in the line-of-sight effect cannot account for this change, and we conclude we are observing real intensity structure along the main auroral oval. The electrojet velocity deduced from #168 is very similar to that deduced from #166, i.e. ~1.5km$s^{-1}$, if we include the RAO pixels with a large redshift in the average. This is also the situation for the redshifting of the DPR for #168, although its brightness is again ~65% of that of the #166 DPR. The good agreement in velocity structure for these two profiles, despite their rather different brightnesses for the DPR and SAO, indicates that our various corrections work consistently across the dataset.

• #170: This profile is taken with the slit cutting equatorward of the widest visible extent of the main auroral oval. The intensity profile shows that both the RAO and SAO had reduced intensities in the line-of-sight compared with #166. These can be more or less explained by line-of-sight effects. The electrojet velocity deduced from #170 is compatible with that of the previous two spectral images, although the reduced intensity makes fitting somewhat less reliable. The DPR redshift is only ~1km$s^{-1}$, although this reduction may be due to line-of-sight effects.

• #172: In this spectral image, the slit is close to the most equatorward extent of the main auroral oval. The intensity features noted for profiles #164 to #170 are still observable, but the RAO and DPR are only 50% of the intensity of #170, and are hard to distinguish. The velocity profile is
very noisy, but there may just be a vestige of redshift of the RAO compared with the SAO, similar to that observed in #158.

In order to test the persistence of the features noted above, we can compare data from other runs obtained on September 11. Figure 12 shows an assemblage of prespatial and spatially corrected velocity profiles, together with their Q(1,0') intensity profiles. The profiles have been selected so as to match the cut across the auroral/polar region of 11N4 #166 as closely as possible, to aid comparison. The top two panels show v_p(y) profiles for the 11N3 and 11N6 set of spectral images, obtained 38min. before and 2hrs. 4min. after the 11N4 dataset, respectively. The intensity profiles demonstrate the four regions we have already delineated, although in 11N6, the BPR is much less prominent. Unfortunately, the images associated with these two runs were not of sufficient quality to carry out spatial corrections. But the v_p(y) profiles show the same type of behaviour as that of 11N4 #166 (middle left panel). The difference in velocity between (the centres of) the RAO and SAO is \( \sim 1.5 \text{km/s} \) and \( \sim 1.0 \text{km/s} \) for 11N3 and 11N6, respectively, compared with 2.5km/s for 11N4. Assuming that 11N4 had the best line-of-sight viewing of the auroral electrojet, these results are compatible with the respective viewing geometries. The bottom two panels show profiles of v_p(y) and v_a(y) for the 11N5 dataset, taken 1hr 10min after 11N4. This translates into a CML of 202°, compared with 159° for the 11N4 profile. (The intensity profile shows even more structure in the DPR and BPR than in 11N4, at this viewing.) In 11N5, the v_p(y) difference between the RAO and SAO is again 1.5km/s, and the difference in v_a(y) is 1.3km/s, compared with 2.1km/s for 11N4. If we take the change in viewing geometry to be solely due to the 43° rotation of the planet between the two profiles, and we assume that the electrojet velocity remains constant in all other respects between the two runs, we would expect an RAO/SAO v_a(y) difference of 1.5km/s for the 11N5 profile, in good agreement with what is produced by our data analysis.
Figure 12: Velocity profiles, $v_p(y)$ and $v_a(y)$, for comparison with the 11N4 #166 profile. Overplotted is the intensity profile for Q(1,0), uncorrected for line-of-sight. The comparison profiles have been chosen as far as possible to display similar cuts through the auroral/polar regions: top left - $v_p(y)$ for 11N3 #132; top right - $v_p(y)$ for 11N6 #229; middle panels - $v_p(y)$ and $v_a(y)$ for 11N4 #166; bottom panels - $v_p(y)$ and $v_a(y)$ for 11N5 #198.
Having established the stability of the general features observed in our dataset, it is worthwhile looking at their variation over the period of observing run. Jupiter presented CMLs similar to those of the 11N4 run on September 8 and 10, the 8N5 and 10N6 datasets. Given the lack of good H$_3^+$ images for these nights, we make use of the profiles for $v_p(y)$; note that these profiles have not been corrected for the arbitrary velocity zero, $v_0$. Figure 13 shows the intensity and $v_p(y)$ profiles for #201 of run 8N5 and #332 of 10N6. These spectral images were obtained at latitudes similar to that of #166 of 11N4, and show many of the same intensity features. The main differences are that the DPR/BPR distinction is less pronounced for 10N6 #332 than in the other two profiles, and that in 8N5 #201 there is an additional small intensity peak around pixel 220: this may be the H$_3^+$ emission resulting from the magnetic footprint of Io (see Connerney et al. 1993 for a fuller explanation). The $v_p(y)$ profiles for all three nights are quite similar. The velocity shift between the RAO and SAO is clear; at $\sim$0.8kms$^{-1}$ on September 8 and $\sim$1.2kms$^{-1}$ on September 10, they are somewhat less than on September 11. This may be an indication that the electrojet velocity was increasing during the course of our observations, a conclusion that is borne out by the analysis of other sequences of spectral images taken during our observing run. Similarly the redshifting of the DPR with respect to the BPR is seen consistently in the three night’s data, showing differences of $\sim$1kms$^{-1}$.

If we make the assumption that the overall morphology of the auroral/polar region H$_3^+$ emission did not vary greatly over the period of our observations, we can expect that spatially corrected velocity...
 profiles would have remained fairly constant. There is support for this assumption in the images taken on September 8 and 10, shown in Figure 14. Allowing for the doubling effect on September 10, these images compare well with that taken on September 11 (Figures 3 and 10): indeed, simulating the “declination bounce” on the September 11 image produces an image barely distinguishable from the September 10 one. We therefore conclude that, for the period of our observations, the northern auroral/polar region wind dynamics can be divided into three main regions:

- The main auroral oval is dominated by the electrojet, flowing at between 0.5kms\(^{-1}\) (deduced from September 8 data, allowing for l.o.s. effects) and 1.5kms\(^{-1}\) (September 11). This flows in a clockwise direction, viewed from the northern rotational pole, i.e. in a counter-rotational sense, in agreement with Rego et al. (1999a) and in accordance with the prediction of the Hill (1979) model for enforcing plasmasheet co-rotation.

- The Dark Polar Region is dominated by a strong redshift, which may be produced by a poleward flowing wind. This wind appears to diminish past the magnetic pole.

- The Bright Polar Region appears to have only flaccid winds in the line-of-sight, possibly blueshifted.

**Discussion**

In recent months there has been a relative flurry of activity concerning the measurement and modelling of the auroral/polar regions of Jupiter’s upper atmosphere (Achilleos et al. 2001, Cowley and Bunce 2001, Hill 2001, Khurana 2001, Pallier and Prangé 2001, Southwood and Kivelson...
In order to fit well into the framework developed by these authors, for the purposes of this discussion we propose to deal with the main auroral oval separately from the rest of the auroral/polar region. Pallier and Prangé (2001), however, have demonstrated that polewards of the main auroral oval, sub-arcs/ovals may be observed, whose structure is similar to that of the main oval. We too have evidence for such structures in the BPR in the form of the additional peaks that our slit cut through on September 11, and - to a lesser extent - on September 8 and 10. We will return to this later.

Both Hill (2001) and Cowley and Bunce (2001) have reworked and developed the original Hill (1979) mechanism for maintaining the equatorial plasmasheet in co-rotation with the planet, and the consequences that arise as the ionospheric torque required to transfer the necessary angular momentum from Jupiter to the outward flowing plasma becomes too great to maintain full co-rotation. This study is clearly relevant to their efforts since the measurement of actual $v_{ion}$ values could be a vital input into an overall modelling effort to link the jovian equatorial plasmasheet to the coupled ionosphere/thermosphere in a way that is self-consistent, as the following considerations show.

In the Cowley and Bunce (2001) model - henceforth CB - the enforcement of plasmasheet co-rotation begins to break down at a radial distance (in the equatorial plane), $\rho_{eq}$, from the planet of \~20$R_J$; by \~60$R_J$ - depending on the exact parameterisation of the breakdown used - co-rotation has all but ceased. (The onset of breakdown at \~20$R_J$ seems to be well supported by Khurana, 2001’s, recent analysis of the plasmasheet radial currents measured by Galileo and other spacecraft.) In CB the bright main auroral oval emission results from the impact of high energy electrons that make up the field-aligned currents flowing in the circuit that arises from co-rotation breakdown (Fig. 1). This is upward from the planet at the footprints of the magnetic fieldlines that cut through the plasmasheet at $\rho_{eq}$\~20$R_J$\~40$R_J$, corresponding to a downward flow of electrons with energies of \~100keV. Thus the main auroral oval maps the point at which co-rotation is breaking down catastrophically. CB defines a useful operational parameter, $k$, given by:

$$(\Omega_J - \Omega_{T,n}) = k(\Omega_J - \omega_b)$$
where $\Omega_1 (= 1.76 \times 10^4 \text{rad/s})$ is the angular velocity of Jupiter and $\omega_n$ is the angular velocity of a plasmasheet shell at a given value of $\rho_{\text{Eq}} = nR_J$. $\Omega_{T,n}$ is the angular velocity of the neutral thermosphere in the Pedersen conducting layer in the main auroral oval, which is magnetically linked out to the plasmasheet at $\rho_{\text{Eq}} = nR_J$. At the point that co-rotation breaks down, this section of the neutral atmosphere is decelerated with respect to the rest of the thermosphere because of collisions with ions driven clockwise in the auroral electrojet, against the rotation of the planet. If one made the assumption that the ions were locked onto flux tubes that initially co-rotated rigidly with the plasmasheet, such that $\Omega_{I,n} = \omega_n$ (where $\Omega_{I,n}$ is the angular velocity of the relevant ionospheric region), we have:

$$k = \left( \frac{\Omega_1 - \Omega_{T,n}}{\Omega_1 - \Omega_{I,n}} \right)$$

This makes $k$ a measure of the collisional coupling between the electrojet ions and the thermospheric neutrals. Initial JIM modelling of the electrojet indicates that the neutrals can be accelerated to between 25% and 50% of the clockwise ion velocities along the auroral oval, for equatorward trans-oval fields, $E_{\text{oval}}$, of 1 to 2MV (Miller et al. 2000, Achilleos et al. 2001), resulting in $k = 0.25$ to 0.5. Knowing the ion velocity and the value of $k$ thus makes it possible to compute the energy transfer between Jupiter’s upper atmosphere and the plasmasheet resulting from the partial enforcement of corotation.

There is also a further component affecting the jovian middle magnetosphere, which has so far received rather scant observational attention - the influence of the solar wind. One infrared imaging study (Baron et al. 1996), carried out over the first four months of 1992, suggested that increasing solar wind ram pressure might result in increased overall auroral/polar brightness. But this suggestion has not been followed up since then. Southwood and Kivelson (2001) and Cowley and Bunce (2001) have recently advanced theoretical considerations that lead to the conclusion that decreasing solar wind pressure could lead to acceleration of the auroral electrojet and to enhanced auroral oval brightness. Their argument (drastically simplified) is that as the solar wind pressure eases off, jovian flux tubes expand radially outwards, and the increase in angular momentum required to keep them in co-rotation leads naturally to the intensification of the Hill current system - thus greater particle
precipitation and values of $E_{\text{oval}}$. Given the accuracy of our present dataset, the increase in average electrojet velocity noted in this study is far from conclusive, although we also observe an increase in auroral brightness – the subject of a further study (Stallard et al., 2001). But one can imagine, say, observing an increase in electrojet velocity during an observing run, and being able to link that to measurements of the changes in solar wind ram pressure.

The introduction of the possible effect of the solar wind into this discussion leads naturally on to an analysis of the wind structure observed poleward of the main auroral oval. In studies of the aurorae of Jupiter, it is natural to stress the extent to which the jovian magnetosphere is not simply the terrestrial one writ large: the middle magnetosphere of Jupiter is dominated by its internal plasma source - the volcanic activity of Io - not the solar wind. Yet, by analogy with the Earth, there should be a jovian polar cap, where field lines open to the solar wind, even if present magnetic field models (e.g. the VIP4 model of Connerney et al. 1998) cannot say for certain how that maps onto the planet itself. At present, JIM makes use of a two-cell Dungey (1961) convection system covering the whole of the polar region from the footprint of the 30R$_J$ field lines polewards. Thus it ascribes the whole of what we call here the polar region to the polar cap. The two cell convection system for the Earth is shown in Figure 15; it is driven by reconnection, with newly opened field lines moving poleward on the noonside, and return flows in the dawn and evening sectors. Were this actually the case for Jupiter, one might have expected to find a poleward ion wind centred between the RAO and SAO, with return flows alongside the main auroral electrojet. (Given the middle magnetosphere control of the jovian auroral, in contrast to the terrestrial situation, here we notionally confine “polar cap” flows to latitudes poleward of the oval.)
But - within the accuracy of our data - this is not what is observed. Instead, the polar region - as pointed out by Satoh and Connerney (1999) - has a yin-yang, or DPR/BPR, structure that has strong poleward winds in the DPR but little sign of a return flow. Not only that, but the BPR has definite intensity peaks and, therefore, structure that one might not associate with a simple two-cell polar cap. Pallier and Prangé (2001; henceforth PP) have ascribed inner (poleward of the main oval) arcs seen in their UV images to additional ovals. Their explanation for these features is that the breakdown of co-rotation is not a uniform phenomenon; rather it takes place in a series of “steps”, with the inner arcs corresponding to further Hill current systems generated by secondary co-rotation breakdown “catastrophes”, analogous to - if less drastic than - that responsible for the main auroral oval. Such a description clearly has a considerable portion of the polar region still under the control of field lines that are closed and connecting to the middle magnetosphere plasmasheet. If PP are right, just where these lines pass through the plasmasheet has to be the subject of further investigation and modelling. Whatever the outcome of this, their description confines the polar cap per se to a more restricted region than that currently modelled by JIM.

Figure 16: Proposed dayside jovian northern auroral/polar wind system. The electrojet flows continuously around the main auroral oval. In the DPR a strong poleward wind is observed when the main oval is well displayed on the dayside. There may be (as yet unobserved) return flows (dashed arrows). But the return flow may occur while the main oval is displayed on the nightside. In the BPR, there may be blueshifted winds due to (partial) inner auroral ovals, corresponding to a stepwise breakdown of plasmasheet co-rotation.
The observations reported here could be analysed in accordance with PP: the BPR could be the site of further auroral arcs, whose counterparts are either not present, or are subsumed in the main RAO; the possible existence of a small blueshift in the BPR region could be seen as evidence for this. That would leave the DPR as corresponding to the jovian polar cap, with its strong redshift representing the region of the ionosphere connecting to noonside field lines open to the solar wind. For this scenario, one would have to imagine that the analogue of the terrestrial two-cell structure had return winds that were too weak to be detected when the polar cap is on the dayside, or were too close to the RAO to be spatially resolved. Given the asymmetry of the jovian magnetic field, the offset of the magnetic pole from the rotational pole and the rapid rotation of the planet, one can also imagine a situation in which ion winds are driven poleward during the jovian day, leading to pressure build-ups which generate return flows through the polar cap at night. This overall auroral/polar wind system is represented schematically in Figure 16.

Khurana (2001), however, has highlighted another factor that may influence the dynamics of the high-latitude ionosphere, based on his analysis of Galileo data for the equatorial plane beyond \( \rho_{\text{Eq}} = 50 R_J \). He makes use of the relationship first derived by Vasyliunas (1983) in his treatment of the magneto-hydrodynamics relevant to Jupiter’s outward flowing plasma system. This relates the azimuthal magnetic field to the difference in rotational velocities of the magnetosphere and the ionosphere in what is called the “frozen-in field” approximation:

\[
\frac{\Delta B_\phi}{\rho_{\text{Eq}} B_\rho} = \frac{(\omega_\rho - \Omega_{I,n})}{v_\rho}
\]

where \( \Delta B_\phi \) is the differenced azimuthal magnetic field component, the measured component minus that due to the intrinsic, internally generated, planetary field; \( B_\rho \) is the radial component; and \( v_\rho \) is the radial outflow velocity of the plasma in the plasmasheet. Beyond \( \rho_{\text{Eq}} = 50 R_J \), the Galileo data give \( \Delta B_\phi/\rho B_\rho \sim 0 \), implying either that the plasmasheet has been brought back into co-rotation with the planet or that the angular velocity of the ionosphere is much less than co-rotational. So at least part of the line-of-sight poleward wind connected with the DPR might represent ionospheric lag with respect to the thermosphere.
Vasyliunas’ simplified relationship requires high ionospheric conductivities, such that the ionospheric field in the jovian co-rotating frame “vanishes”. JIM predicts $\Sigma_p \sim 0.1-1.0$ mho (height integrated) for the inputs currently under test (Millward and Miller, work in progress) for the main auroral oval, similar to those deduced by CB. While fairly large, these are not inordinately high, and the model makes use of megavolt potential differences across the auroral oval to produce ion flows of a few hundred ms$^{-1}$. The ionospheric conductivity poleward of the main oval has not yet been modelled in detail. But, judging by the Q(1,0') intensity profiles, H$_3^+$ densities, and hence those of electrons, are about 50% of those in the main oval. It is unlikely, therefore, that $\Sigma_p \gg 1$ mho. Whether this fact could account for the disappearance of $\Delta B/\rho B_\rho$ in the region beyond $\rho_{eq} = 50R_J$, reported by Khurana (2001), without invoking ionospheric lag is not yet clear.

**Conclusions**

The results presented here represent the first continuous observations of the jovian auroral electrojet over a period of several planetary rotations. As such they provide strong support for the Hill (1979) mechanism to explain the way in which Jupiter’s equatorial plasmasheet is maintained in co-rotation and the consequences of the breakdown of this mechanism. We have also detected additional wind features poleward of the main auroral oval, which may be linked to solar wind activity. The present time is clearly an exciting one for the development of our understanding of Jupiter and its magnetosphere. Theories that have been proposed some decades ago can now be tested against real-time satellite data, while ground-based and orbiting observatories have improved their instrument capabilities to give data showing unprecedented detail. The contributions on the interaction between the middle magnetosphere of Jupiter - between $\rho_{eq} \sim 6R_J$ out to around 50-60R$_J$, particularly that region from 20R$_J$ outward - and the planet’s upper atmosphere that we have discussed here, and others, herald a new era in understanding this crucial relationship dynamically. We hope this article makes a useful contribution to this discussion.
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