Jupiter’s polar ionospheric flows: High resolution mapping of spectral intensity and line-of-sight velocity of H$_3^+$ ions

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Abstract We present a detailed study of the H$_3^+$ auroral emission at Jupiter, which uses data taken on 31 December 2012 with the long-slit echelle spectrometer Cryogenic Infrared Echelle Spectrograph (European Southern Observatory’s Very Large Telescope). The entire northern auroral region was observed using significantly more slit positions than previous studies, providing a highly detailed view of ionospheric flows, which were mapped onto polar projections. Previous observations of ionospheric flows in Jupiter’s northern auroral ionosphere, using the long-slit echelle spectrometer CSHELL (NASA Infrared Telescope Facility) to measure the Doppler-shifted H$_3^+$ $V_2$ Q(1,0) line at 3.953 μm, showed a strongly subrotating region that was nearly stationary in the inertial magnetic frame of reference, suggesting an interaction with the solar wind. In this work, we observe this stationary region coincident with a polar region with very weak infrared emission, typically described as the dark region in UV observations. Although our observations cannot determine the exact mechanisms of this coupling, the coincidence between solar wind controlled ionospheric flows and a region with very low auroral brightness may provide new insights into the nature of the solar wind coupling. We also detected a superrotating ionospheric flow measured both at and equatorward of the narrow bright portion of the main auroral emission. The origin of this flow remains uncertain. Additionally, we detect a strong velocity shear poleward of the peak in brightness of the main auroral emission. This is in agreement with past models which predict that conductivity, as well as velocity shear, plays an important role in generating the main auroral emission.

Plain Language Summary This study is about Jupiter’s northern lights and the molecules which create it that exist in Jupiter’s upper atmosphere. We study Jupiter in the infrared using the Very Large Telescope, located in Chile. This telescope has an instrument which is able to split up the light and allow us to observe the infrared spectra of Jupiter’s northern lights. From the infrared spectra, we can work out the brightness and velocity of an individual molecule, known as H$_3^+$, which creates the majority of the infrared northern lights. By using the instrument to scan Jupiter, we can make a map of the flows of the H$_3^+$ molecule. Through studying these flows, we further understand the interplay between the upper atmosphere and magnetic field. This work is important as it shows that part of the upper atmosphere is connected to the solar wind, which is a stream of particles continuously flowing out from the Sun and dragging the Sun’s magnetic field with it. Exactly how part of the upper atmosphere of Jupiter is connected to the solar wind is highly debated and remains uncertain. This study is work toward understanding the complex mechanisms which govern Jupiter’s northern lights.

1. Introduction

Jupiter’s aurora is the most powerful aurora in the solar system and has been studied extensively using both Earth-based and space-based observations. It is known to consist of at least three distinct regions of emission [Delamere et al., 2015, and references therein].

1. The main auroral emission which forms an irregular oval surrounding the magnetic pole.
2. The auroral signatures of the Galilean moons, equatorward of the main auroral emission, which create spots and trailing arcs about the magnetic footprints of the moons.
3. The polar aurora which is all aurora poleward of the main auroral emission and is highly variable and dynamic over short time scales.

Similarly to this paper, many studies focus on the northern aurora due to the observing geometry of Jupiter from the Earth. The bulk of the morphology of the main auroral emission is fixed in System III longitude.
The origin of the main emission has been linked to the magnetosphere-ionosphere coupling by a number of studies [Cowley and Bunce, 2001; Hill, 2001; Southwood and Kivelson, 2001; Nichols and Cowley, 2003]. As iogenic plasma diffuses radially outward from the planet, its angular velocity falls below that of the planet if angular moment is conserved. The subcorotation then sets up a large-scale meridional current system which accelerates this plasma back towards corotation through the $\vec{J} \times \vec{B}$ force. These radially outward directed currents are sufficient to maintain near-rigid corotation to equatorial radial distances of about ~20 $R_J$ where corotation breakdown occurs, such that beyond this distance the plasma increasingly and significantly lags behind corotation. The meridional currents connect to Jupiter via field-aligned currents, directed upward from the planet in the inner part of the system and downward at large distances, and the circuit is closed in the ionosphere via equatorward directed Pedersen currents. However, there is a limit to the upward current density which can be carried by unaccelerated precipitating hot magnetospheric electrons, beyond which downward acceleration by upward directed field-aligned electric fields is required, as described by the kinetic theory of Knight [1973]. Estimates for Jupiter’s corotation enforcement currents suggest current densities peaking at values more than an order of magnitude larger than the limiting value, such that the magnetospheric electrons must be accelerated downward to energies of ~100 keV, thereby producing the bright emissions of the main auroral oval [e.g., Cowley et al., 2008b].

The generation of the main auroral emission has been extensively studied; however, the origin of Jupiter’s polar aurora is less clear. Gustin et al. [2004] showed that there is usually a correlation between the energy flux and the energy of the precipitating electrons in the main auroral emission, determining that the acceleration of the electrons is caused by field-aligned voltages. However, no clear correlation was found in the polar aurora, suggesting that the mechanisms here involve different processes to those which generate the main auroral emission. It is thought that this region maps to the outer magnetosphere, and both open and close magnetospheric models have been theorized to understand this emission.

The polar aurora is highly variable and dynamic when observed at ultraviolet wavelengths (UV) over short time scales [see Grodent, 2015, and references therein]. The UV emission is caused by inelastic collision between atomic or molecular hydrogen and energetic electrons which precipitate down the magnetic field lines into the auroral regions and excite the atomic or molecular hydrogen. When the atomic or molecular hydrogen de-excite to their ground state, UV photons are emitted forming H Lyman $\alpha$ and H$_2$ Lyman and Werner bands. The polar emission is usually grouped into three regions, the swirl, active, and dark regions; however, when observed over short time scales, the morphology observed is usually more complex than three simple and distinct regions. Over moderate time scales, Stallard et al. [2016] showed that the morphology of the UV aurora was similar to the infrared (IR) aurora. Jupiter’s near-IR aurora is mainly due to the thermal emission from H$_3^+$, which is generated by a chain reaction which begins with ionization of H$_2$ by energetic magnetospheric electrons. Satoh and Connerney [1999] simplified the H$_3^+$ emission on the polar aurora into a simplistic “yin and yang” arrangement of a dark polar region and a bright polar region. However, Stallard et al. [2016] found further regions that were repeatedly identifiable in the IR polar aurora and these are displayed in Figure 1.

Figure 1 is a polar map of Jupiter’s H$_3^+$ aurora showing data taken with the Cryogenic Infrared Echelle Spectrograph (CRIRES) [Kaufl et al., 2004], an instrument previously available at the European Southern Observatory (ESO)’s Very Large Telescope (VLT) at the Paranal Observatory, Chile, and is currently undergoing an upgrade. The spectra shown in Figure 1 were obtained on the 31 December 2012. The scan took ~20 min to complete and is composed of 35 spectral images, beginning at 02:35 UT. Therefore, the scan covers a central meridian longitude (CML) range of 181°–193°. This polar map was produced using techniques described later in the paper. A gamma correction of 0.2 was applied to the polar map, which lowers the contrast allowing different features in Jupiter’s aurora to be easily identified. The gamma correction ($\gamma$) is applied to the spectral intensity using the following equation:

$$I_{\text{out}} = I^\gamma$$  \hspace{1cm} (1)$$

where $I$ is the linearly scaled spectral intensity and $I_{\text{out}}$ is the nonlinear-corrected spectral intensity. There are some saturated values on the dawn limb where the H$_3^+$ signal is weak.
The main auroral emission \((M_1, M_2)\) is labeled in Figure 1. Although faint, the Io’s auroral emission is also labeled and lies close to 180° longitude (System III). The polar aurora has been separated into different morphological regions according to spectral intensity. The bright polar region in the IR corresponds to the active region in the UV (A). The IR dark polar region has been split up further into a crescent-shaped dark region confined to the dawn which corresponds to the UV dark region (D), a brighter region which corresponds to the UV swirl region (S), and a second dark region located near to the magnetic pole (P). Determining the mechanisms that drive such a complex morphology is a difficult task, and the origin of the polar aurora is yet to be fully understood.

The endeavor to understand the mechanisms involved in generating Jupiter’s polar aurora requires measurements of the dynamics in Jupiter’s ionosphere and magnetosphere. To investigate the flows of ions in the upper atmosphere, and hence infer the motions of the coupled magnetic field lines, ionospheric flows are derived from observations of the Doppler-shifted \(H_3^+\) emission lines. Energetic electrons precipitating down the magnetic field lines ionize the \(H_2\) in the auroral regions as shown in equation (2). Following this ionization, the \(H_2^+\) rapidly reacts with more \(H_2\) to produce \(H_3^+\), as shown in equation (4) \([\text{Miller et al.}, 2000]\).

Lower concentrations of \(H_3^+\) make up the disk population in Jupiter’s ionosphere. This population is generated from the fast chain reaction beginning with ionization by solar EUV \([\text{Lam et al.}, 1997; \text{Miller et al.}, 1997]\), as shown in equation (3), and does not exist in the nightside ionosphere of Jupiter \([\text{Stallard et al.}, 2015]\).

The \(H_3^+\) spectra are highly dependent on temperature, and therefore, in addition to ionospheric flows, the temperature of Jupiter’s ionosphere can be derived from the spectra. Hence, \(H_3^+\) ions can be used to probe the physical properties and bulk motions of the upper atmosphere and ionosphere. Using observations of \(H_3^+\), previous studies have identified ionospheric flows in Jupiter’s auroral regions. \(\text{Rego et al.} [1999]\) measured significant flows in the northern auroral regions using the long-slit Echelle Spectrometer CSHELL \([\text{Greene et al., 1993}]\) previously available at the NASA Infrared Telescope Facility (IRTF) at the Mauna Kea Observatories, Hawaii. They measured a maximum line-of-sight (LOS) velocity of \(3.3 \pm 0.4 \text{ km s}^{-1}\) for the bright part of the main auroral emission at \(\sim 264^\circ\) and an average LOS velocity of \(2.7 \pm 0.3 \text{ km s}^{-1}\), relative to the rotation of the planet. Further measurements using IRTF-CSHELL by \(\text{Stallard et al.} [2001]\) measured LOS velocities of \(1.5 \text{ km s}^{-1}\) in the region of the main auroral emission and stronger flows of \(-3 \text{ km s}^{-1}\) in a dark region of Jupiter’s polar aurora, taken from discrete slit positions in the CML range \(132^\circ–229^\circ\), at
a variety of auroral latitudes. Using the Fourier transform spectrometer (FTS/BEAR) instrument available at the Canada-France Hawaii Telescope (CFHT) at the Mauna Kea Observatories, Hawaii, Chaufray et al. [2011] measured an average LOS velocity of $3.1 \pm 0.4 \text{ km s}^{-1}$ in the northern auroral region for CML $\approx 179^\circ$.

Rego et al. [1999], Stallard et al. [2001] and Chaufray et al. [2011] analyzed the LOS velocity of the H$_3^+$ ions in a reference frame which is fixed in System III and thus rotates with the planet. Stallard et al. [2003] transformed the velocities derived by Stallard et al. [2001] into the magnetic pole reference frame, where the LOS component of the velocity of the magnetic pole is set to zero. They discovered that part of the IR dark polar region was stationary in this inertial frame, which they defined as the fixed dark polar region (f-DPR). The f-DPR was approximately coincident with the UV swirl region. The remainder of the dark polar region was found to be corotational and was defined as the rotating dark polar region (r-DPR) as this region rotated with the planet. Stallard et al. [2003] postulated that the stationary f-DPR was coupled to the solar wind.

Cowley et al. [2003] suggested that part of Jupiter’s polar aurora is coupled to a Dungey cycle process, confined to the dawn region of the polar aura by the Vasyliunas cycle [Vasyliunas, 1983], as shown in Figure 2a. Magnetic flux is opened on the dayside through reconnection with the interplanetary magnetic field (IMF), transported across the pole to close in the magnetotail, and finally, returned in the restricted dawn region. Due to the asymmetry imposed by the Vasyliunas cycle, the Dungey cycle at Jupiter would be confined to a single-cell ionospheric pattern in the dawn region, as shown in Figure 2b where the open flux is shown as the hatched region. Cowley et al. [2003] described how this coupling is governed by Dungey cycle flows [Dungey, 1961] in Jupiter’s magnetosphere.

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McComas and Bagenal [2007], however, suggested that due to the vast scale of the Jovian magnetosphere the time scales involved in a Dungey-style global cycle of reconnection are improbable. Instead, they proposed that flux is opened on the dayside and then closed through double lobe reconnection, which leaves Jupiter’s magnetosphere mainly closed. However, Cowley et al. [2008a] refuted this, as they argued that unless the reconnection rate in both lobes was equal, the mechanisms put forward by McComas and Bagenal [2007] would not hold true, and the magnetosphere would not stay mainly closed. The debate continued, with McComas and Bagenal [2008] stating that their new concept is consistent with observations by New Horizons [McComas et al., 2007] which implied that the magnetotail is largely filled with detached blobs of ionogenic plasma. Ultimately, McComas and Bagenal [2008] called for more measurements of Jupiter’s ionosphere and magnetosphere to further investigate these issues.

Figure 2. Sketches of the flows in (a) the Jovian equatorial plane and (b) the northern Jovian ionosphere, reproduced from Cowley et al. [2003]. The Sun is toward the bottom of the figure, with dawn to the left and dusk to the right. The solid lines shows closed plasma streamlines. The dashed lines with crosses represent the Dungey cycle and Vasyliunas cycle talk X lines. In Figure 2a the label O denotes the O-type plasmoids and the label P and dash-dotted line shows the outer edge of the plasmoid. The sketch in Figure 2b is in a reference frame where the planetary dipole is at rest and the outer limit of the figure is at $\approx 20^\circ$ colatitude. In Figure 2b circles with a dot at the center denote upward field-aligned currents and circles with crosses in the middle denote downward field-aligned currents. The hatched region in Figure 2b represents the open region, which is based on results from Stallard et al. [2003].
Delamere and Bagenal [2010] proposed that Jupiter’s polar aurora was connected intermittently to the IMF through viscous interaction along the dawn flank of the magnetopause. They based their model on Axford and Hines [1961], and described how Kelvin-Helmholtz instabilities moderate the viscous interaction of the magnetopause and IMF. They postulated that the ionospheric wind measurements of Stallard et al. [2001, 2003] are explainable in a regime of a closed magnetosphere, where the stationary velocities of the $H_3^+$ ions could be associated with the solar wind driven viscous drag.

One drawback of the ionospheric flow study carried out by Stallard et al. [2003] was the limited data set. Here we present a new analysis of Jupiter’s ionospheric flows using higher spatial and spectral resolution data taken with VLT-CRIRES. Polar projections of the spectral intensity (such as Figure 1) and LOS velocities of the $H_3^+$ ions were created. Several regions of significant flows were identified in Jupiter’s ionosphere and related to different regions of auroral morphology. These flows not only help us understand the motions of the ionosphere but give us information about the dynamics of Jupiter magnetosphere due to the coupling of the ionosphere and magnetosphere.

2. Observations

The previous work by Stallard et al. [2003] was derived from measurements taken with IRTF-CSHELL, which is no longer available at IRTF due to the instrument being replaced by iSHELL in October 2016. The slit width used at CSHELL was 0.5″ which is the smallest available and achieves a resolving power of ~38,000. In the present study measurements were taken with VLT-CRIRES with a slit width of 0.2″, which gives a resolving power of ~100,000, significantly higher than the resolving power of CSHELL. In addition to having a higher spectral resolution, CRIRES recorded the spectral data on four Aladdin spectral detector arrays which had a total of 4096 spectral pixels by 512 spatial pixels and a pixel plate scale of 0.089″ per pixel. CSHELL only had one detector array which is 256 spectral pixels by 256 spatial pixels and a pixel plate scale of 0.2″ per pixel. The CRIRES instrument could gather more spatial information because the slit length was 40″, whereas the CSHELL slit length was 30″.

To collect the data used in this study, the auroral region was repeatedly scanned with the slit aligned west-east on Jupiter, perpendicular to the rotational axis. A scan involves positioning the slit on the polar limb with the center of the 40″ slit of CRIRES aligned on the center of the planet and then incrementally adjusting the telescope so that the slit is stepped equatorward through the auroral region, with step sizes equivalent to the slit width of 0.2″. The scans cover a region from the polar limb of the planet through to ~45° latitude which takes 35 steps. The exposure time for each spectrum was 25 s. By using this rigorous observing sequence, significantly more spatial information was collected with CRIRES than in the data reported in Stallard et al. [2003]. The observer sublatitude of Jupiter was +3.35°; therefore, the northern aurora was favorably displayed. For this investigation six scans taken from 02:13 to 04:15 UT on 31 December 2012 are used as these provide the most complete view of Jupiter’s northern $H_3^+$ aura.

CRIRES allowed the simultaneous measurement of a number of $H_3^+$ emission lines from the Q branch as shown in Figure 3, where the x axis represents spatial pixels and the y axis represents spectral pixels over the four detector arrays. This figure shows the spectra after all the corrections involved in the data reduction process had been performed, which are discussed in detail in section 3. Order 14 was chosen to observe the $H_3^+$ emission lines, and therefore, the four detectors covered a wavelength range of 3.884–3.986 μm, with a gap of 0.006 μm between each detector array. This wavelength range falls within the L’ window in the Earth’s atmosphere, allowing the $H_3^+$ emission from Jupiter to be easily observed by ground-based observations. An average was taken of the emission lines bound by the white dashed lines to create an average spectral line, which is shown next to the color bar and is discussed in section 3.

Six spectra were taken with the slit of CRIRES in a north-south orientation with the slit aligned along the CML. As Jupiter’s equatorial diameter subtended 46.92° on the sky on 31 December 2012, the 40° slit of CRIRES encompassed the northern aurora and the mid-to-low latitude region of Jupiter’s ionosphere. These spectra are used in the process of deriving the LOS velocity of the $H_3^+$ ions and will be discussed in section 4.3. In addition to measuring spectra from Jupiter, other measurements were required for the data reduction process. At the beginning and end of the scan the position of the telescope was adjusted so the slit of CRIRES was 30° north of the planet and spectra of the telluric emission were measured. After the scans of Jupiter’s
aurora were completed, spectra were taken of a standard A0 star (HR1578), which was used in the flux calibration procedure. Finally, dark and flat frames were measured, which were used to remove instrumental effects from the spectra. During the observations Jupiter was setting, causing the air mass to increase from 1.4 to 1.6 atmospheres, which increased the signal-to-noise ratio. The weather was clear and stable, with the seeing at ~0.5″, causing minimal smearing of the spectra.

3. Data Reduction

The usual method of flat fielding, subtracting dark frames and using the stellar spectra to calibrate the flux, was applied to the raw spectra, in keeping with previous methods described in greater detail by Stallard et al. [2001]. Then telluric spectra were subtracted from the spectra to create spectra solely consisting of Jovian emission lines. Previously, Stallard et al. [2001] have used emission lines measured from arc lamps to correct the spectral dispersion across the array. However, this was not possible with CRIRES since appropriate emission lines from the available arc lamps did not fall in the required wavelength range. Therefore, the telluric emission lines were used to correct the spectral dispersion across the array. This is an appropriate substitution due to the high spectral resolution of CRIRES making it possible to find the spectral dispersion close to the position of the H3⁺ emission lines because of the large number of well-characterized telluric emission lines. By fitting a surface to the telluric emission lines across each array, the spectral dispersion across each array, in both x and y, was determined.

In the auroral regions, methane absorption in Jupiter’s lower atmosphere efficiently removes reflected sunlight from the spectra; however, as the slit is stepped equatorward a larger amount of reflected sunlight is measured. Figure 3b shows a greater amount of reflected sunlight than Figure 3a, as the slit position in Figure 3b is more equatorial. It can also be noted that there are several more emission lines observed at auroral slit positions, and these emission lines are stronger than the corresponding emission lines at subauroral latitudes. As the H3⁺ emission is thermal emission, different rovibrational transitions are achieved at different temperatures. Therefore, different ratios of emission lines are observed in auroral and nonauroral regions due to changes in temperature of the ionosphere.

A wavelength calibration of the four detector arrays was performed by fitting the telluric emission lines with an infrared spectrum of the atmospheric transmission generated using the ATRAN modeling software [Lord, 1992], accessed via the Gemini Observatory (http://www.gemini.edu/sciops/telescopes-and-sites/observing-condition-constraints/ir-transmission-spectra). Once calibrated, the wavelength resolution for each detector array was calculated. Using an average of six spectra taken when the slit of CRIRES was aligned along the CML in a north-south orientation, the most prominent H3⁺ emission lines were identified in each array, and the observed wavelengths of these H3⁺ emission lines are shown in Table 1. It is possible to calculate the stationary wavelength of these emission lines using the average of the emission lines taken in the equatorial region.
due to two assumptions. The first assumption is there will be a minimal LOS component measured in this location as the slit is aligned at the center of the planet, to an accuracy of ~±1° in the longitudinal direction. The second assumption is that there was no Doppler shifts present in spectra measured in the equatorial region due to ionospheric flows. Johnson et al. [2016] showed that in Jupiter’s mid-to-low latitude region the LOS velocity of the $\text{H}_3^+$ ions in the PRF was 0.091 ± 0.25 km s$^{-1}$, 0.0082 ± 0.30 km s$^{-1}$, and 0.31 ± 0.51 km s$^{-1}$ in 1998, 2007, and 2013, respectively, which means the ions were corotating. The only Doppler shift measured in the wavelength of these emission lines will be due to the relative motion of Jupiter and the observer, a value for which is obtained from HORIZONS Web-Interface (http://ssd.jpl.nasa.gov/horizons.cgi).

The sum of each prominent emission line was taken in the spatial direction (y direction in Figure 3) to enhance the signal to noise. Then the Doppler-shifted wavelength was determined by fitting a Gaussian to the sum of each prominent emission line, and this wavelength is shown in Table 1. Once the relative motion between Jupiter and the observer was removed, the measured rest wavelengths of the prominent $\text{H}_3^+$ lines was found to be $Q(3,3^+)$ at 3.90397 μm in detector array 1; $Q(2,2^+)$ at 3.91443 μm in detector array 2; $Q(1,0^+)$ at 3.95295 μm in detector array 3; and $Q(2,1^+)$ at 3.97103 μm in detector array 4, as shown in Table 1. The numbers in the brackets, such as $Q(1,0^+)$, correspond to $Q(J, K)$, where $J$ is the rotational angular momentum, $K$ is the rotational angular momentum along the spin axis, and $Q$ denotes the emission line is from the Q branch of emission lines. Table 1 also shows the ab initio values of the wavelength of these emission lines, taken from Neale et al. [1996]. The calculated stationary wavelength matches well with the Neale et al. [1996] ab initio values, within the given errors as shown in Table 1.

Now that the exact wavelength of these prominent $\text{H}_3^+$ line has been determined, the average of these lines (bound by the white dashed line in Figure 3) was taken, which maximized the signal at all slit positions across the auroral regions. Finally, the average emission line was smoothed using a box car average with a width of five pixels. After data reduction, the brightest portion of the main auroral emission had a maximum signal-to-noise of ~38, whereas in the nonauroral regions the maximum signal-to-noise ratio was less than ~10.

### 4. Data Analysis

**4.1. Deriving the Spectral Intensity**

A Gaussian profile superposed on a slowly varying quadratic background was fitted to every spatial position along the average $\text{H}_3^+$ emission line using the following equation:

$$f(x) = A_0e^{-z^2/2} + A_3 + A_4x + A_5x^2$$

where

$$z = \frac{x - A_1}{A_2},$$

$A_0$ is the height of the Gaussian, $A_1$ is the pixel position of the peak of the Gaussian, and $A_2$ is the width of the Gaussian. The additional terms $A_3$, $A_4$, and $A_5$ are included to acquire a suitable fit to the background, where $A_3$ is the constant term, $A_4$ is the linear term, and $A_5$ is the quadratic term. The variable $x$ is the row position in
Using the height of the Gaussian profile ($A_0 (W \text{ m}^{-2} \text{ sr}^{-1} \mu m^{-1})$) and the full width at half maximum (FWHM ($\mu m$)), the spectral intensity ($I (W \text{ m}^{-2} \text{ sr}^{-1})$) can be derived as follows:

$$I = A_0 \times \text{FWHM}$$


4.2. Polar Projections

In order to create polar projections of the $\text{H}_3^+$ spectral intensity, the limbs of the planet in the spectral intensity map must first be identified. By using a calculated planetary limb and fitting it to the fully illuminated dusk limb, the latitude and longitude can be assigned to the corner of each pixel in the spectral intensity map. The latitude and longitude information is used to map the values, in an array 360° longitude (System III) and 180° latitude, onto a polar projection with 0.1° bins. Figure 4 shows six polar projections of the spectral intensity created from the scans of Jupiter’s northern auroral region. The white diamond marks the position of an auroral center defined by Grodent et al. [2003] at 185° longitude (System III) and 74° latitude. The white dashed line is the magnetic footprint of Io according to the Grodent et al. [2008] model.
To confirm that the longitudes and latitudes had been correctly assigned to the appropriate pixels the UV statistical oval taken from Nichols et al. [2009] was overlaid on the polar projections, as shown in Figure 4 by the blue line. Studies such as Clarke et al. [2004] and Radioti et al. [2013] have shown that the UV main auroral emission can be used as a proxy for the position of the IR main auroral emission. It can be seen in Figure 4 that the UV statistical oval fits reasonably well with the IR main auroral emission; hence, the assignment of longitudes and latitudes in the projections appear to be correct.

Due to the observer’s line-of-sight intercepting more H$_3^+$ emission toward the limb of Jupiter, a limb brightening effect is observed in the uncorrected polar projections. Figure 4 shows the corrected polar projections. The full description of the LOS intensity correction and how it was applied to the data is presented in supporting information S3.

### 4.3. Deriving the Line-of-Sight Velocity

The LOS velocity of the H$_3^+$ ions can be derived from the Doppler shift of the average H$_3^+$ emission line. By relating the spectral resolution ($R = \lambda / \Delta \lambda$) to the Doppler shift of the H$_3^+$ emission line, which is taken as the position of the peak of the Gaussian ($A_1$), the measured LOS velocity ($v_m$) can be derived using the following equation:

$$v_m(y) = A_1(y) \times \frac{1}{R} \times c$$  \hspace{1cm} (8)

where $c$ is the speed of light and $y$ is the spatial position along the average H$_3^+$ emission line. In this study we have chosen to take an average of the H$_3^+$ lines listed in Table 1 to enhance the signal. The average wavelength ($\lambda \sim 3.94559 \mu$m) and average change in wavelength per pixel ($\Delta \lambda = 2.06447 \times 10^{-5} \mu$m per pixel) were used in equation (8). A positive $v_m$ implies the H$_3^+$ ions are moving toward the observer (blue-shifted) and a negative $v_m$ implies moving away (red shifted).

The measured LOS velocity ($v_m$) includes the relative velocity of the observer and Jupiter hence a zero-point velocity ($v_0$) must be subtracted from $v_m$. The average was taken of the six spectra with a north-south orientation and the value $v_0$ was determined using LOS velocity derived in the equatorial region. It is possible to use this LOS velocity as $v_0$ because Johnson et al. [2016] showed that the H$_3^+$ ions were corotating here and since we are deriving at LOS velocity at the CML, there will be no component of the planets rotation. It is assumed that meridional ionospheric flows are negligible as no significant flows were identified in Johnson et al. [2016]. To transform into the observers reference frame (ORF), $v_0$ is subtracted from $v_m$ to derive LOS velocities in the ORF, $v_{\text{ORF}}$.

$$v_{\text{ORF}}(y) = v_m(y) - v_0$$  \hspace{1cm} (9)

Through interpretation of the LOS velocity of the H$_3^+$ ions in different reference frames and observing the aurora as it rotates through different CMLs, a near-complete picture of the flows in Jupiter’s ionosphere can be attained. Figure 5b shows a summary of the results shown in the different reference frames used to interpret the LOS velocities, which are derived from the average H$_3^+$ emission line shown in Figure 5a. The large scatter of values of LOS velocity at distances beyond $-0.2 \, D_J$ (where the radius of the disk $D_J$ is equal to the 1 bar equatorial radius of Jupiter, $\sim 71492$ km, plus the peak emission height of H$_3^+$ of 550 km above the 1 bar level as discussed by Melin et al. [2005]) are generated by noise measured in the dawn sector of Jupiter’s ionosphere. The H$_3^+$ emission in this subauroral dawn region is weak due to low production rates. Stallard et al. [2015] showed an absence in H$_3^+$ disk emission on the nightside, but once the nightside ionosphere rotates through dawn, the H$_3^+$ production can begin, which starts with ionization of H$_2$ by EUV. This generation of H$_3^+$ is not instantaneous, at the equator Melin and Stallard [2016] determined a H$_3^+$ lifetime of $1.6 \pm 0.4$ h. Similar lifetimes are assumed to be present in this subauroral dawn region. Additionally, the dawn limb is not fully illuminated, and therefore the production rates of H$_3^+$ are lower at dawn ($\sim < -0.2 \, D_J$) than dusk ($\sim > +0.2 \, D_J$).

Figure 5b shows the LOS velocities in the ORF as a red line, with the line of corotation indicated by the red dashed line. Since the slit of CRIRES was centered on the planet’s rotation axis, in this reference frame the center of the planet is set to zero velocity relative to the observer. At $-0.2 \, D_J$ the prenoon sector of Jupiter’s ionosphere is rotating toward the observer; hence, positive values of LOS velocity are derived.
from the blue-shifted portion of the average H$_3^+$ emission line. The opposite occurs at +0.2 $D_J$ where the post-noon sector of Jupiter’s ionosphere is rotating away from the observer, causing negative values of LOS velocity to be derived from the red-shifted portion of the average H$_3^+$ emission line.

The thermosphere is strongly coupled to the ionosphere at Jupiter [e.g., Smith and Aylward, 2009; Achilleos et al., 1998], and so it is useful to derive a reference frame in which flows are relative to the planet. As in Stallard et al. [2001], the LOS velocities are transformed into the planetary reference frame (PRF), which rotates with System III.

The LOS component of Jupiter’s rotation varies linearly across the disk of the planet, as described by Stallard et al. [2001],

$$v_r(y) = \frac{v_{0,y}}{R_{\text{pixels}}}$$

where $v_{0,y}$ is the LOS velocity at the equatorial limb, $y$ is the distance in pixels from the center of the planet, and $R_{\text{pixels}}$ is the equatorial radius in pixels.

In Figure 5b, $v_r(y)$ is represented as the red dashed line, which is the corotational velocity in the ORF. The transformation is completed by removing the LOS component of the planet’s rotation, $v_r(y)$,

$$v_{\text{PRF}}(y) = v_{\text{ORF}}(y) - v_r(y)$$

The LOS velocities in the MPRF are shown in Figure 5b as the blue line, and the corotation in this reference frame is shown as the blue dashed line.

The ionosphere is also strongly coupled to the magnetosphere [Smith and Aylward, 2009]; hence, it is useful to derive a reference frame in which the LOS component of the angular velocity of the magnetic pole is set to zero. In this study we are using the auroral center defined by Grodent et al. [2003] as a proxy for the northern magnetic pole as the dipole location was not suitable for this study. This reference frame is known as the magnetic pole reference frame (MPRF) and was defined in Stallard et al. [2003]. The magnetic pole correction velocity for each slit position ($v_{\text{MP}}$) is determined by considering the observing geometry (sub-Earth latitude of the telescope, SEL), the longitudinal position of the auroral center (185°) relative to the central meridian line (CML), and the calculated velocity of the magnetic pole (~3.41 km s$^{-1}$),

$$v_{\text{MP}} = 3.41 \times \sin(185 - \text{CML}) \times \cos(\text{SEL})$$

Once calculated, the magnetic pole correction velocity can be subtracted from the velocities in the ORF,

$$v_{\text{MPRF}}(y) = v_{\text{ORF}}(y) - v_{\text{MP}}$$

The LOS velocities in the MPRF are shown in Figure 5b as the blue line, and the corotation in this reference frame is shown as the blue dashed line.
A final correction is applied to the LOS velocities in all reference frames to remove implied wavelength variations caused by the uneven illumination across the slit width. These variations are seen on extended sources, such as Jupiter. The slit width of 0.2″ represents ~610 km of the disk of Jupiter at the equator, a distance over which the aurora is known to vary and create intensity anisotropy across the slit \cite{Stallard et al., 2001}. The spatial anisotropies across the slit can cause additional shifts in the apparent line position on top of those generated by the motion of the H$_3^+$ ions. A full description of how the spatial velocities were removed from the LOS velocities is presented in supporting information S4.

Polar projections of LOS velocities in the PRF and MPRF were created using the method outlined in section 4.2. Exactly how the LOS velocities are interpreted and the limitations of each reference frame will be discussed in sections 5 and 6.

4.4. Errors

Figure 6 shows the uncertainty in LOS velocity which is applicable to the derived LOS velocities in all reference frames. This error consists of uncertainties due to correcting the spectral dispersion across the detector array, fitting a Gaussian to the H$_3^+$ emission spectra, determining $v_0$, and correcting the spatial effect and is discussed further in supporting information S5.

Outside the auroral regions, where the H$_3^+$ signal is weaker, it can be seen in Figure 6 that the error increases. In this investigation we focus on morphological features and H$_3^+$ flows which are poleward of the Io magnetic footprint, which is a region of relatively low uncertainties (typically $\pm 0.3$ km s$^{-1}$). The uncertainty in the nonauroral regions at lower latitudes can be seen to vary in a pattern which approximates curved stripes across the polar projection. We believe this effect is caused by the flat-fielding process of the data reduction being partly erroneous. This error is thought to be instrumental, potentially caused by temperature changes inside the instrument due to the flat frames being taken at a separate time prior to the observations. It appears that this effect is prominent in
regions of poor signal-to-noise ratio, while inside the auroral regions the effect seems limited. Figure 6 shows a general increase in the magnitude of the error as CML increases across the whole of the polar projection. This could be due to the air mass increasing from 1.4 to 1.6 atmospheres during the observations, which increases the signal-to-noise ratio. This may also be due to changing weather conditions over the observations.

5. Key Results

5.1. Spectral Intensity

The spectral intensities for the six scans of Jupiter’s northern aurora are shown in Figure 4. The average of these scans is shown in Figure 7. In addition to the UV statistical oval [Nichols et al., 2009] is a white line which represents the most intense part of the IR main auroral emission and was identified manually from the peak brightness of the average spectral intensity. The location of this overlay is roughly coincident with the 4° region which Nichols et al. [2009] uses to define the main auroral emission. In Figure 7 there is some noise, in particular on the dawn limb where the H₃⁺ emission is weak, and hence, some values outside of the auroral regions are considered to be unreliable.

The main auroral emission in the dawn sector (M₁) is narrow and bright. The spectral intensity varies from ~1.2 × 10⁻⁴ W m⁻² sr⁻¹ at ~250° longitude to ~0.3 × 10⁻⁴ W m⁻² sr⁻¹ at ~180° longitude. At ~180° longitude the spectral intensity of the main auroral emission is at its lowest magnitude, which is a region of low spectral intensity also seen in the UV [Grodent, 2015].

The dusk sector of the main auroral emission (M₂) is more diffuse than emission in the M₁ region. The spectral intensity of the M₂ region is ~0.3–0.9 × 10⁻⁴ W m⁻² sr⁻¹, coming to a maximum near to the location of the kink in the shape of the main auroral emission, in the approximate location of the magnetic anomaly [Grodent et al., 2008]. The dusk limb is brighter than the rest of the subauroral disk emission, with a spectral intensity of ~ < 0.15 × 10⁻⁴ W m⁻² sr⁻¹, whereas the disk emission of H₃⁺ is usually has a spectral intensity of ~ < 0.1 × 10⁻⁴ W m⁻² sr⁻¹.

The two dark regions, D and P have spectral intensities of ~0.2–0.3 × 10⁻⁴ W m⁻² sr⁻¹. Region D is approximately coincident with the UV dark region. The dark region P is not so readily observed in the UV as this region is between the UV swirl and active regions. The morphology of emission in the swirl and active regions can be dynamic, variable, and bright in the UV. However, in the IR Stallard et al. [2016] observed that the polar regions appeared to remain consistently absent of variability. The polar region S has a spectral intensity of ~0.25–0.35 × 10⁻⁴ W m⁻² sr⁻¹ and is coincident with the UV swirl region. Polar region A has a spectral intensity ~0.3–0.6 × 10⁻⁴ W m⁻² sr⁻¹ and is coincident with the UV active region. There is an arc of H₃⁺ emission which extends from the A region, below the P region, along the boundary between the D and S regions.

5.2. LOS Velocity

At Earth, the ionosphere is very strongly coupled to the magnetosphere and therefore geomagnetic coordinates are usually used to present terrestrial ionospheric flows [Rishbeth, 1988]. However, at Jupiter, there is complex thermosphere-ionosphere-magnetosphere coupling, such that no single reference frame can used in isolation to study the H₃⁺ flows in Jupiter’s ionosphere. The degree to which the ionosphere is coupled to the magnetosphere and the thermosphere changes depending on the location in the ionosphere. Away from the aurora, in the mid-to-low latitude regions, it is possible to work in the PRF as Johnson et al. [2016] showed that the ionosphere rotated with System III. It is not possible to solely work in the PRF in the auroral regions due to currents induced by the strong coupling to the middle magnetosphere [e.g., Cowley and Bunce, 2001]; therefore, the MPRF must also be considered. The neutral atmosphere remains partially coupled to the
ionosphere in the auroral regions and cannot be disregarded in favor of a purely magnetic reference frame. It is important to consider both reference frames when studying the dynamics of Jupiter’s ionosphere, in particular, when studying the polar aurora as the origin of this aurora is not very well understood. Through identification of different regions of morphology, the spectral intensity can be associated with the flows measured in Jupiter’s ionosphere. Hence, the notation established in Figure 1 will be used to describe the regions of different ionospheric $\text{H}_3^+$ flows.

When dealing with LOS velocity measurements, it is important to consider the effect of the viewing geometry of the observer on the velocities. As certain ionospheric flows become increasingly perpendicular to the line-of-sight of the observer, and hence parallel to the slit, the LOS component of the velocity of the $\text{H}_3^+$ is greatly reduced. Therefore, it is important to observe the aurora as it rotates across the dayside of the planet.

5.2.1. LOS Velocities in the Planetary Reference Frame

Using the method described in section 4.2, polar projections of the LOS velocities in the PRF were created. Six LOS velocity projections in the PRF are shown in Figure 8 corresponding to the six scans. In the PRF the LOS component of the planet’s rotation has been removed, so that a LOS velocity of zero is interpreted as the ions moving with rigid corotation. As discussed in section 4.4, instrumental artifacts cause variations in signal-to-noise ratio in the subauroral region, where the patterns in Figure 8 are associated with the errors shown in Figure 6. The large variation and saturated LOS velocities measured on the dawn limb are unreliable and due to the poor signal-to-noise ratio in this region and are reflected in the large uncertainties in this region in Figure 6.

It was expected that the subauroral region would corotate due to a lack of auroral currents in those regions, and the majority of the subauroral region has been found to corotate within the bounds of experimental error. However, it can be seen from Figure 7 that this is not the case for the dusk limb of Jupiter where the $\text{H}_3^+$ flows on the dusk limb are moving away from the observer and exceed planetary rotation for reasons...
which are not clear. In this paper we will focus on auroral ionospheric flows, leaving the study of subauroral ionospheric flows to future studies.

In the auroral regions several regimes of strong ionospheric flows can be observed. An ionospheric flow with a LOS velocity toward the observer, relative to the planet, is observed between 190° and 270° longitude (System III) and is interpreted as a superrotational flow. This superrotation is mainly located in the M1 region. Rego et al. [1999] measured superrotational flow of $\sim 1$ km s$^{-1}$ at a CML of 270° (System III), and this study measures a flow of $\sim 0.7$ km s$^{-1}$ at the same longitude as shown in Figures 8e and 8f. However, the superrotational flow measured by Rego et al. [1999] was equatorward of those measured in this study, lying closer to the Io magnetic footprint than the main auroral emission. Stallard et al. [2001] measured a superrotational flow in some of the slit positions they investigated at a similar position to this study. For example, when the east-west orientated slit was aligned on a CML of 155°, Stallard et al. [2001] measured a superrotational flow of $\sim 0.5$ km s$^{-1}$.

A strong velocity shear is observed between 190° and 270° longitude (System III), located near to M1 region. The peak of the velocity shear is located just poleward of the peak in the average spectral intensity of the H$_3^+$ emission, as shown by the solid black line in Figure 8.

In the region coincident with the UV dark region (D) strong ionospheric flows with a LOS velocity away from the observer relative to the planet are observed between 180° and 225° longitude (System III), with a maximum derived LOS velocity of $\sim 2.2$ km s$^{-1}$, which implies a significant subrotation. In the region A, coincident with the UV active region, flows toward the observer relative to the planet are measured, implying subrotation. The subrotation in the region A extends through region M$_2$, with a maximum derived LOS velocity of $\sim 1.5$ km s$^{-1}$. Weaker flows are derived in the S and P regions with LOS velocities lying approximately within the range $-0.5 < v_{\text{LOS}} < 0.5$ km s$^{-1}$. These results differ somewhat from those of Stallard et al. [2001]. We now measure strong subrotation in are the region D and weaker flows are measured mainly in the S and P regions, whereas Stallard et al. [2001] identified strong red shifts in the region bounded by the black dash-dotted line in Figure 8, which overlaps parts of the S and P regions and measured weaker flows in the region D.

Figure 9. (a–f) Six LOS velocity polar projections in the magnetic pole reference frame (MPRF). Similar format to Figure 8.
6. Discussion

Several distinct regions of H$_3^+$ ionospheric flows have been identified in Jupiter’s auroral region. Through comparison of the PRF and MPRF, and with the aid of the average spectral intensity polar projection, these ionospheric flows have been associated with the different morphological regions. The black arrows in Figure 10 approximate the ionospheric flow direction which we infer. The three main flows are illustrated in the schematic in Figure 10.

1. In the PRF and MPRF, the H$_3^+$ ions observed in the main auroral emission in the M$_1$ region (~180°–270° System III longitude) have a LOS velocity which surpasses the rate of planetary rotation, which means they are superrotating (green shaded region in Figure 10).

2. In the PRF, the H$_3^+$ ions observed in the UV dark region (D) have a LOS velocity which is lagging behind the rate of planetary rotation, which means that they are subrotational. In the MPRF, near-zero values are observed in this region, which implies this region is stationary relative to the magnetic pole (dark blue shaded region in Figure 10).

3. In the PRF and MPRF, the H$_3^+$ ions observed in the main auroral emission in the M$_2$ and A regions have a LOS velocity which is lagging behind the rate of planetary rotation, which means they are subrotating (light blue shaded region in Figure 10).

The superrotational flows measured by Rego et al. [1999] in the PRF were observed slightly equatorward to the superrotational flows measured in this study and were attributed to coupling with radial currents in Jupiter’s magnetosphere ~0.2 R$_J$ inside Io’s orbit, which also caused auroral hiss measured by Voyager and discussed by Morgan et al. [1994]. From Figure 8, it can be seen that the superrotational flows measured in this study never fully extend to the Io magnetic footprint and therefore cannot be attributed to the same source region in the magnetosphere. The differences in the location of the superrotational flows between this study and the study by Rego et al. [1999] could be due to the spatial detail of the Rego et al. [1999] study. The slit of CSHELL was aligned along the CML in a north-south orientation in the study by Rego et al. [1999], which limited their ability to map the flows of H$_3^+$ ions. In this study numerous west-east slit positions are used to obtain greater spatial detail, providing a more accurate position of the superrotational flows in Jupiter ionosphere.

Figure 13 in Stallard et al. [2001] shows superrotational flows in a similar location to this study, in the region M$_2$; however, this flow is not discussed in the paper. The orientation of the CSHELL slit was east-west in the Stallard et al. [2001] study; however, the orientation of the CRIRES slit was west-east in this study. With...
differnt slit orientations the spatial velocities will change along with the spatial anisotropies across the slit. However, physical flows will remain the same regardless of slit orientation, although the magnitude will alter depending on the viewing geometry of the observer and the accuracy of the measurements will depend on the slit width and the spectral resolution of the instrument. Therefore, by observing the same flows with three different slit orientations (north-south in Rego et al. [1999], east-west in Stallard et al. [2001], and west-east in the present study) and two different instruments (CSHELL in Rego et al. [1999] and Stallard et al. [2001] and CRRES in this study), this shows that the blue shift measured in this region is a real flow and not a spatial effect error. This also implies that all other flows observed in Rego et al. [1999], Stallard et al. [2001], and this study are physical.

Perhaps the origin of the superrotating ionospheric flows in the M1 region is a superrotating flow in the thermosphere, generating ion drag and causing the H$_3^+$ ions to rotate faster than corotation. Models of Jupiter’s ionosphere-thermosphere are typically simplified; for example, the JIM model [Achilleos et al., 1998] uses a circular auroral oval and simplistic Dungey cycle midnight flow. This model shows regions of superrotation equatorward of the main oval, which are very small (tens of m s$^{-1}$). However, all H$_3^+$ wind speeds predicted by this paper are lower than those measured by Stallard et al. [2001] and in this present study; hence, the calculated superrotational flows may fall short of actual measured values. Majeed et al. [2016] showed that neutral flows are easily produced by ionospheric flows, but they provide no longitudinal variability to compare with this paper. At Earth, more detailed three-dimensional models of ion drag during periods of high geomagnetic activity show that the neutrals can move to form vortices in the thermosphere, resulting in regions of superrotation, notability in the dawn subauroral region [Walterscheid and Crowley, 2009]. The only measurements of thermospheric winds at Jupiter were made by Chaufray et al. [2011]. They showed that, typically, neutral H$_2$ winds were much weaker than their H$_3^+$ counterparts, although in some locations the neutrals did appear to lead the ions. Although Chaufray et al. [2011] did not identify any superrotations, their data set was limited and hence such a flow in the prenoon ionosphere cannot be ruled out.

A more likely explanation for the superrotational flows in the M1 region involves a region of the magnetosphere, but at larger distances of $R_J$ than discussed by Rego et al. [1999]. Since the superrotation appears to be confined to the prenoon sector, it is possible that the origin of this flow is linked to flux tubes rotating through the dawn sector of the dayside magnetosphere. Figure 2a shows the extended flux tubes full of ionomic plasma pinch off on the nightside of Jupiter in the region of the Vasyliunas cycle tail X line and rotate round into the dawn sector of the dayside magnetosphere. As the field lines rotate through the dawn sector, they move radially inward so that the angular velocity of the plasma increases to conserve angular momentum. Field lines which map further out in the magnetosphere, closer to the magnetopause, and have footprints more poleward in the ionosphere will have the greatest fractional change in radial distance and hence the greatest fractional increase in angular velocity. However, the actual angular velocity will also depend on the initial angular velocity of the field line before it is compressed. If the field line is severely lagging behind corotation, then the compression of the field line may not be sufficient to increase the angular velocity to superrotation. It could be the case that a field line is near corotating such that a small change in the radial distance could increase the angular velocity to a point where the field line is superrotating as observed in Figures 8 and 9.

Although we would expect this superrotation to increase in magnitude toward the pole, the above discussion based on conservation of angular momentum does not apply to the region D as separate processes appear to be driving different ionospheric flows there, and these processes will be discussed later in this section. Additionally, we do not know the location to which region M1 maps in the magnetosphere, and very small areas of Jupiter’s ionosphere can map to a wide range of distances in the outer magnetosphere, which we cannot resolve with the spatial resolution of CRRES. Hence, it is possible that the M1 superrotating region actually maps further out than expected, mapping to regions which are significantly affected by the compression due to the shape of the magnetopause. It cannot be said for certain that this superrotational flow is confined to the prenoon sector of the ionosphere as our measurements are subject to observational bias. From Earth we can only observe the dayside ionosphere, and currently there have not been any measurements of the LOS velocity of H$_3^+$ ions in the nightside ionosphere.

We do not know the initial distribution of angular velocity of the field lines mapping to region M1 as the region rotates through the nightside into the dawn sector, so it is difficult to be definitive about the details...
of the resulting angular velocity distribution, other than that the compression will cause an overall increase as discussed above. Presently, there is no evidence of the dawn sector of the dayside magnetosphere superrotating. Prenoon Voyager 1 and 2 and Ulysses inbound passes have shown the plasma to be corotational at 10–20 R_J. [Belcher, 1983; Sands and McEwen, 1983; Kane et al., 1995]. Plasma flows derived through forward modeling from Galileo data by Bagenal et al. [2016] has shown that within 5–20 R_J the flow is dominated by azimuthal flow which is between 80 and 100% of corotation. Beyond distances of 20 R_J the flow is expected to fall below corotation and one would expect the region M_1 to map to regions of the magnetosphere which are beginning to lag behind corotation rather than exceed corotation. However, these observations are based on limited data of a very small sample size and it may be the case that the magnetosphere does superrotate in certain regions. The more extensive data set of Juno may provide the plasma flow speeds in Jupiter’s magnetosphere and potentially determine whether the superrotational flows in the ionosphere have a magnetospheric origin.

Superrotational flows in the region M_1 were not expected by models such as Cowley and Bunce [2001]. However, Nichols and Cowley [2003] predicted that the peak intensity of the main auroral emission will coincide with the peak in velocity shear assuming a constant conductivity in the ionosphere. This is because a gradient in the velocity in the meridional direction causes gradient in the electric field, as the ions and neutrals are moving at different speeds relative to each other, which sets up a Pedersen current. The model assumes an axisymmetric system; therefore, any divergence of this Pedersen current leads to upward field-aligned currents which generate the main auroral emission at Jupiter. The orientation of the shear that this study observed between the M_1 and D regions implies an upward field-aligned current as shown in Figure 2b.

A further model by Nichols and Cowley [2004] includes Pedersen conductance modulated self-consistently by auroral precipitation. This model predicted a local maximum in the angular velocity moving poleward from high-latitude subauroral regions into toward the main auroral emission. We observe this increase in angular velocity in Figure 8, measured as an increase in LOS velocities between the Io magnetic footprint and the M_1 region.

Furthermore, the model by Nichols and Cowley [2004] showed that, by taking variable conductivity into account, the peak in velocity shear will lie poleward of the peak in the Pedersen current. Figures 8 and 9 show that the peak in the velocity shear is poleward of the peak in average H_3^+ spectral intensity, as predicted by Nichols and Cowley [2004]. Since the velocity shear is poleward of the peak in average spectral intensity, this implies that the conductivity is affected by the field-aligned currents themselves. This result is not as clear in the M_2 region where the aurora is more diffuse. There are several steps interrupting the shear in the LOS velocities which coincide with several arcs of diffuse emission, implying more complex processes are present than the signal shear in the M_1 region.

In the UV dark region (D), this study identifies strong flows of up to ~ -2.2 km s\(^{-1}\) in the PRF, which imply subrotation relative to the rotation of the planet. The same region is being held stationary in the MPRF. Figure 9 shows that the region D is always held stationary no matter what the viewing geometry is, and therefore, this region is stationary relative to Jupiter’s fast rotation. Stallard et al. [2003] defined a region of the DPR, which was largely coincident with the UV swirl region (S), as the f-DPR since the ions here were being held stationary relative to the magnetic pole. The past observations do not match with those present in this study, which identifies the stationary region in the UV dark region (D) of Jupiter’s ionosphere and not coincident with the f-DPR as shown by Figure 10. The change in position of the stationary region in Jupiter’s ionosphere between the Stallard et al. [2003] study and the present study is likely to be due to the higher spatial resolution of CRIRES and the larger number of slit positions used to scan the aurora. However, since we are comparing two case studies, without any information on the solar wind or the internal conditions of Jupiter’s magnetosphere, it could be the case that conditions have changed since the study conducted by Stallard et al. [2001] and this present study causing the stationary region to be observed in a different location.

Stallard et al. [2003] and Cowley et al. [2003] discuss how the f-DPR is coupled to the solar wind through a single cell convection cell as part of a restricted Dungey cycle. They propose that the ions in this region are coupled to open magnetic field lines which are convecting so slowly across the polar aurora that they are stationary relative to the corotational and subrotational closed magnetic field lines. However, Delamere and Bagenal [2010] discuss how the results from Stallard et al. [2003] could also be explained by solar
wind viscous drag. The magnetic field lines would be stationary as they are intermittently opened and closed along the dawn flank of the magnetopause. Delamere and Bagenal (2010) suggested that the f-DPR could not be open as it was approximately coincident with the UV swirl region which experiences aurora both in the UV and IR. The Kelvin-Helmholtz interaction would be indicative of a boundary layer populated by near-magnetosheath densities of cool plasma, with relatively low-energy flux of the sheath plasma [Cowley et al., 2008b], which would create weak aurora. Small-scale reconnection may occur due to twisting of field lines in the Kelvin-Helmholtz boundary layer, which could heat the plasma leading to a brighter emission at the footprint. In this this study we have shown that the stationary region is lacking in IR emission and coincident with the UV dark region (D), which is suggestive of open field lines. However, it should be noted that while the lack emission in the stationary region supports the arguments put forward by Cowley et al. [2003], this data set alone cannot confirm that the field lines here are coupled to the solar wind through a Dungey cycle like process.

This paper has presented a case study of one night of observations. Future studies which utilize more extensive data sets may be able to determine whether the superrotational flow in the M₁ region of the main auroral emission is a permanent ionospheric flow in Jupiter’s ionosphere or a transient flow. Additionally, further studies with larger data sets will also confirm the position of the stationary region. Future simultaneous measurements of ionospheric flows determined from H³⁺ emissions with the Juno in situ data will help determine the characteristics of the magnetic field lines which the ionospheric flows map to. The Juno data may determine whether the source of the superrotational flow in the M₁ region is driven by the magnetosphere the mechanisms by sampling the flux tubes in situ. Using simultaneous measurements with ground-based observations and measurements taken by Juno, it may be possible to determine whether the stationary D region is coupled to the solar wind through a Dungey cycle like process or through viscous interaction moderated by Kelvin-Helmholtz instabilities.

7. Conclusions

We have presented a highly detailed case study of Jupiter’s auroral H³⁺ ionosphere using projections of the spectral intensity and ionospheric flows in several reference frames. In the PRF and MPRF a superrotational flow is observed in the M₁ region. This flow could be generated by neutral winds yet to be understood; however, it is more likely to be caused by the magnetosphere. The superrotational flow could be generated by the flux tubes, which are rotating through the dawn sector of the dayside magnetosphere, being compressed and speeding up. However, current measurements of plasma flow in the dawn sector of the magnetosphere have not revealed any superrotation; therefore, the exact mechanisms causing the superrotational flow remains unknown.

Two of the ionospheric flows reported upon in this study confirm predictions by Nichols and Cowley [2004]. An increase in angular velocity was expected by Nichols and Cowley [2004] in the region between the Io magnetic footprint and the M₁ region. We observe an increase in the LOS velocity in this region and believe it is related to an increase in conductivity as described by Nichols and Cowley [2004]. A strong velocity shear has been observed poleward of the peak in average H³⁺ spectral intensity, implying a major gradient in plasma angular velocity, as predicted by the model of Nichols and Cowley [2004]. The poleward position of the velocity shear relative to the peak in spectral intensity means that conductivity in the ionosphere is being affected by the field-aligned current itself. Velocity shears are observed in the M₂ region; however, the relation between the peak in the shear, the conductivity, and the peak in H³⁺ spectral intensity is clearly more complex in this region of the main auroral emission. Overall, it seems clear that conductivity, as well as changes in angular momentum, has a major role in the generation of Jupiter’s aurora.

In the PRF, subrotational flows are observed in the D region, these flows are near stationary in the MPRF. The location of this flow has changed since it was first identified by Stallard et al. [2001], and perhaps this study reveals a more accurate location of the flow due to the larger amount of spatial information. However, the location of this flow may have changed due to environmental changes in Jupiter’s magnetosphere, the solar wind or a combination of the two. The H³⁺ ions in this region are stationary when transformed, into the MPRF, which suggests an interaction with the solar wind. This study cannot determine the exact mechanisms through which this region of Jupiter’s ionosphere is coupled to the solar wind. Future work, including simultaneous measurements of Jupiter’s H³⁺ aurora with Juno, will be able to help determine how the ionosphere coupled to the solar wind.
References


