

Measurements of the rotation rate of the jovian mid-to-low latitude ionosphere



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ABSTRACT

Previous studies of Jupiter's upper atmosphere often assume that the mid-to-low latitude ionosphere is corotating, but a model describing an observed asymmetry in hydrogen Lyman- α emission (~ 1000 km above the 1 bar level) disagrees with this assumption. From measurements of the Doppler shifted $H_3^+ \nu_2 Q(1, 0^-)$ line at $3.953 \mu\text{m}$ using the IRTF, the line-of-sight velocities of the H_3^+ ions were derived in the planetary reference frame and found to be $0.091 \pm 0.25 \text{ km s}^{-1}$, $0.0082 \pm 0.30 \text{ km s}^{-1}$ and $0.31 \pm 0.51 \text{ km s}^{-1}$ in 1998, 2007 and 2013 respectively. These zero velocities represent corotation at the mid-to-low latitude region of Jupiter's ionosphere. There is no evidence of flows associated with the hydrogen Lyman- α emission asymmetries detected in the peak H_3^+ emission layer (~ 550 km above the 1 bar level), and we assert that the H_3^+ ions in Jupiter's mid-to-low latitude are rigidly corotating.

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1. Introduction

Our current understanding of Jupiter's main auroral emission comes from models which couple the main auroral emission to corotation breakdown in the middle magnetosphere (e.g. Hill, 2001; Cowley and Bunce, 2001). These models include the specific assumption that the non-auroral thermosphere is corotating. A model by Smith and Aylwood (2009) suggests that the equatorial region of Jupiter's thermosphere is corotating, and the model describes how angular momentum from this region is transferred to the polar region through meridional advection. They imply that the rotation of the magnetosphere inward of $\sim 30 R_J$ is very sensitive to the thermospheric velocities.

In the auroral regions, the H_3^+ ions deviate from corotation, driven by strong auroral currents, as predicted by Cowley and Bunce (2001). Stallard et al. (2001) measured velocities in the auroral regions of $\sim 1\text{--}3 \text{ km s}^{-1}$ from IRTF-CSHELL observations and Chaufray et al. (2011) measured velocities of up to $3.1 \pm 0.4 \text{ km s}^{-1}$ from CFHT-FTS/BEAR observations. These velocities are measured in the planetary reference frame, a reference frame which rotates with the planet at its rotation rate. A corotational velocity in this reference frame is 0 km s^{-1} , and ions moving at this velocity appear stationary to an observer situated on the planet.

Since the mid-to-low latitude ionosphere maps to Jupiter's inner magnetosphere, which near rigidly corotates, it is assumed that there are no auroral currents present at these latitudes and therefore electron excited H and H_2 emissions are expected to be limited in this region.

Sounding rocket measurements in 1978 by Clarke et al. (1980) and Voyager 1 and 2 observations in 1979 by Sandel and Broadfoot (1980) have shown a longitudinal asymmetry in the equatorial H Ly- α emission, referred to as the H Ly- α 'bulge'. The position of the bulge is fixed in magnetic System III longitude, peaking at about 100° (Dessler et al., 1981; Skinner et al., 1988). The bulge was observed on the night side from Voyager 2 UVS observations (McConnell et al., 1980). Clarke et al. (1991) observed evidence of broadening of the H Ly- α line profile for measurements taken at the location of the bulge. This may suggest that the bulge is produced by a broadening of the H Ly- α line profile rather than an increased H density. It has been shown by Emerich et al. (1996) that the broadening may be due to turbulent flows. However McGrath et al. (1990) found no corresponding asymmetry in the integrated H_2 Lyman and Werner band emission; hence the bulge is not a result of precipitation and therefore not an auroral process. A slight decrease in H_3^+ emission has been observed by Lam et al. (1997) at the position of the bulge. However, this increase is only $2.3 \mu\text{Wm}^{-2}\text{sr}^{-1}$ and its relationship with the H Ly- α bulge remains unclear.

A model was developed by Sommeria et al. (1995) to investigate the flows required to produce the observed broadening of

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the H Ly- α line profile at the position of the bulge. The circulatory pattern suggested by Sommeria et al. (1995) describes two jets, initiated in the polar regions at 20 km s^{-1} at $\sim 1000 \text{ km}$ above the 1 bar level. This velocity is significantly larger than observations in the auroral regions of $\sim 4\text{--}8 \text{ km s}^{-1}$ at $\sim 1500 \text{ km}$ above the 1 bar level by Chaufray et al. (2010) from HST-STIS observations of H Ly- α emission. These two jets travel equatorward from the auroral regions and collide in the equatorial region at the location of the bulge. After the jets collide, the calculations of Sommeria et al. (1995) produce an Eastward jet with initial velocity of 9.3 km s^{-1} and a Westward jet with initial velocity of 7.9 km s^{-1} . The prediction of strong Eastward and Westward jets in the upper atmosphere, opposes the assumption that Jupiter's mid-to-low ionosphere is corotating.

H Ly- α emission occurs over a wide range of altitudes, from approximately 200 km to 2200 km above the 1 bar level (Chaufray et al., 2010). The H_3^+ emission occurs over a more limited range, with the peak auroral emission at $\sim 550 \text{ km}$ above the 1 bar level (Melin et al., 2005). The wings of the H Ly- α emission spectra are produced deeper in the atmosphere (Jaffel et al., 2007); therefore the emission from the broadened component of H and H_3^+ could be produced at similar altitudes. However the differences in velocity between H and H_3^+ measured by Chaufray et al. (2010) and Stallard et al. (2001) could arise due to a difference in emission altitude. If a similar coupling of velocities and altitudes of H and H_3^+ in the auroral region exists in the equatorial region, and if the flow proposed by Sommeria et al. (1995) also exists, then one would expect to observe strong H_3^+ flows of several km s^{-1} at the mid-to-low latitude region of Jupiter's ionosphere. No studies to date have measured the velocity of the H_3^+ ions at mid-to-low latitudes. In this study we address these contradicting ideas and investigate whether the H_3^+ ions in Jupiter's mid-to-low latitude ionosphere are corotating.

2. Observations and data analysis

In this paper ionospheric flows in the mid-to-low latitude region were investigated by measurements of the Doppler shifted $\text{H}_3^+ \nu_2 \text{ Q}(0, 1^-)$ emission line at $3.953 \mu\text{m}$. Data were taken with the long-slit echelle spectrometer CSHELL (Greene et al., 1993), at the NASA Infrared Telescope Facility (IRTF) in Hawaii, which has a resolving power of 40,000 for a slit width of $0.5''$. H_3^+ ions can be observed across the whole disk of Jupiter, generated through a fast chain reaction that begins with the ionisation of H_2 by solar EUV, producing H_2^+ , which rapidly reacts with H_2 to produce H_3^+ (Lam et al., 1997; Miller et al., 1997). Greater concentrations of H_3^+ ions are created in the auroral regions due to energetic particles precipitating down the magnetic field lines that ionise the H_2 (Miller et al., 2000). The data were taken from several nights of observations: 5 nights in 1998, 6 nights in 2007 and 3 nights in 2013. In 1998, scans of the Northern and Southern auroral regions were carried out using an observing methodology described in detail by Stallard et al. (2001). The observations in 2007 were made in a similar way. During a scan the telescope is positioned so that the slit of CSHELL is at the Northern or Southern polar limb of Jupiter and then the telescope is moved equatorward in steps with size equivalent to the slit width. In addition to the auroral scan, the 1998 and 2007 observing procedure includes a jump to the equatorial regions and it is these measurements that are reported upon in this study. No auroral data was taken in 2013 and the telescope was at a fixed position, with the slit of CSHELL approximately at Jupiter's equator, hence all the measurements taken in this year were used in this investigation.

At high latitudes, where the limbs of the planet are visible inside the slit, it is possible to determine the latitude of the slit using the length of the chord of emission. However, it is difficult

to identify the exact latitude position of the low latitude observations, as the body of the planet entirely fills the slit. The latitude ranges of the data have been approximated and are shown by the shaded regions in Fig. 1a. The maximum range of latitudes of the mid-to-low latitude data was calculated by relating Jupiter's apparent equatorial diameter to CSHELL's slit length of $30''$. As Jupiter and the Earth are moving relative to each other, Jupiter's apparent equatorial diameter changes over the years observed: over the three separate observations it was $\sim 49.65''$, $45.75''$ and $34.19''$. As the apparent diameter decreases, the maximum latitude range also decreases, which can be seen in Fig. 1a. The light grey region in Fig. 1a represents the maximum range of latitude which includes data equatorward of $\sim 48.3^\circ$, $\sim 43.3^\circ$ and $\sim 15.0^\circ$ latitude in both hemispheres over the three separate observations. The maximum range is a broad range which accounts for drift of the telescope, which can occur, for example, if the guide star is lost due to bad weather, and it also accounts for human error in correcting for this drift. This range was refined by using the change in declination caused by the telescope moving from the equatorial measurement back to the polar limb, effectively providing the expected latitude range given perfect observing conditions. This reduced the latitude range in 1998 and 2007 to $\sim 25.8^\circ$ and $\sim 27.1^\circ$ colatitude and is represented by the dark grey region in Fig. 1a. The latitude range could not be refined in this way for 2013 as the position of the telescope was fixed at Jupiter's equator, and so no offset information was available. During all the measurements the slit was aligned East–West and centred on Jupiter's rotational axis.

Using these high spectral resolution observations we will determine the line-of-sight (LOS) velocity from Doppler shifted H_3^+ emission lines using the method originally discussed in Stallard et al. (2001) and adapted for use at mid-to-low latitudes.

Initially the Doppler shift of the H_3^+ emission line is measured in the observer reference frame, which includes the LOS component of Jupiter's rotation. As stated previously, velocities derived by Stallard et al. (2001) and Chaufray et al. (2011) are in the planetary reference frame, where the rotation rate of the planet has been removed. By removing the LOS component of Jupiter's rotation, we are transforming from the observer reference frame to the planetary reference frame which corotates with System III.

Fig. 1b shows a comparison of the LOS velocity in the planetary and the observer reference frame. When H_3^+ is measured in the observer reference frame, the Doppler shift of the H_3^+ emission line includes a large component due to the rotation of Jupiter, which is represented by the dotted blue line in Fig. 1b. This line also represents corotation in the observer reference frame. The black dot-dash black line in Fig. 1b represents the LOS velocity of the H_3^+ ions in the observer reference frame. The component of rotation can easily be calculated using the circumference, rotation rate and apparent size of Jupiter in the sky and varies linearly across the disc of the planet, as described by Stallard et al. (2001). Jupiter's rotation is then removed from the spectral slit image by shifting each spatial position (row) by the appropriate amount. The solid black line in Fig. 1b shows the LOS velocity of the H_3^+ ions in the planetary reference frame. A value of zero, once transformed to the planetary reference frame, means that the ions are rotating at the planetary rotation rate, hence the solid red line represents corotation in the planetary reference frame.

The emission of H_3^+ is weaker at the equator than in the auroral regions. In addition, at these latitudes the methane in Jupiter's atmosphere becomes less efficient at absorbing sunlight at the wavelength at which H_3^+ emission is observed, causing increased noise in the data. To enhance the signal, the spectral slit images across 1 year were coadded to study the bulk flows of H_3^+ . Before coadding we must remove the component Jupiter's rotation as the apparent size of Jupiter in the sky varies across the 3 years of data (Fig. 1a), and so the change in rotational velocity per pixel also

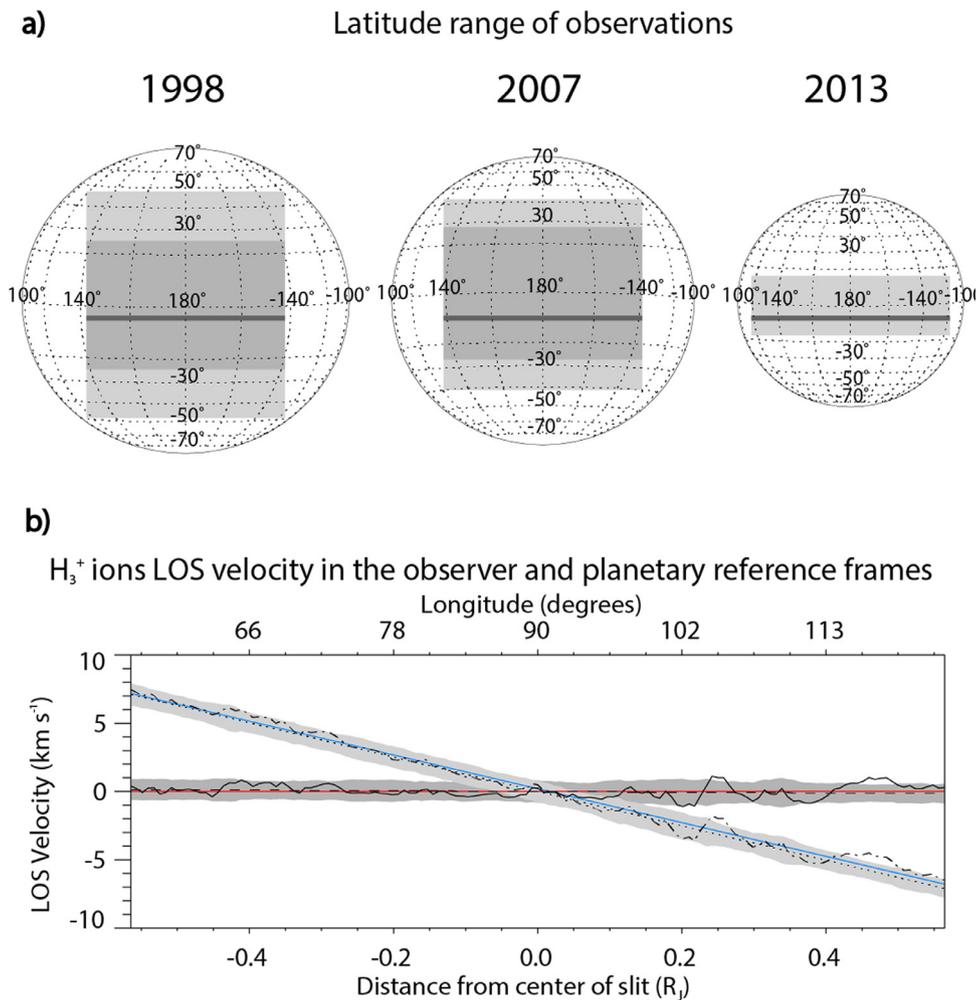


Fig. 1. (a) The latitude ranges of the collated mid-to-low latitude H_3^+ emission data taken in 1998, 2007 and 2013. The light grey region is the maximum range of latitudes of the data: $\sim 48.3^\circ$, $\sim 43.3^\circ$ and $\sim 15.0^\circ$ colatitudes respectively. The dark grey region represents the refined latitude range: $\sim 25.8^\circ$ and $\sim 27.1^\circ$ colatitudes for 1998 and 2007 respectively. This schematic is to scale except for the slit width. In creating this schematic, the sub-Earth latitude of the observer and the flattening of Jupiter have been taken into account. (b) Two mid-to-low latitude LOS velocity profiles, derived from mid-to-low-latitude H_3^+ emission CSHELL data, taken on 7th September 1998. The first LOS velocity profile is in the observer reference frame and is indicated by the dot-dash black line. This reference frame includes the LOS component of Jupiter's rotation, which is represented by the dotted blue line. If the H_3^+ ions are corotating, then their LOS velocity will match the dotted blue line. The dotted black line is the 1D polynomial fitted to the derived LOS velocities and the light grey shaded region represents the associated errors. The second LOS velocity profile is in the planetary reference frame and is indicated by the bold black line. In this reference frame the LOS component of Jupiter's rotation has been removed and the H_3^+ ions that are corotating will have a velocity of zero, represented by the bold red line. The dashed black line is the 1D polynomial fitted to the derived LOS velocities and the dark grey shaded region represents the associated errors. The x-axis is the spatial axis in Jupiter radii ($R_J = 71492$ km), where the centre of the rotational axis is assumed to be at the centre of the slit. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

changes. Undertaking a summation prior to removing the component of Jupiter's rotation would result in meaningless LOS velocities.

In keeping with the method described in Stallard et al. (2001), a Gaussian was fitted to the H_3^+ emission line at every spatial position. The relative peak position of this Gaussian provides a Doppler shifted LOS velocity. The main adaptation of the method used in Stallard et al. (2001) was the exclusion of the spatial correction, as this is not required at mid-to-low latitudes since the slit is evenly illuminated in this region. To correct for the relative motion of Earth and Jupiter, a zero velocity must be subtracted from the derived LOS velocities. By subtracting the zero velocity from the derived LOS velocities, the LOS velocity at the centre of the planet becomes zero as seen in Fig. 1b. Ideally we would use the LOS velocity at the central meridian longitude (CML) as an arbitrary zero point, however, since the limbs of the planet are not visible in the slit we cannot accurately identify the centre of the planet. Hence, we approximate an absolute velocity by subtracting the median value of the LOS velocity.

Emerich et al. (1996) measured turbulent velocity from the spectra of the H Ly- α emission to be ± 7 km s^{-1} at the location of the H Ly- α bulge. They believe this turbulence could be caused by the collision of supersonic jets as described by Sommeria et al. (1995). However, CSHELL introduces broadening into the measured emission line and therefore cannot be used to study this turbulence. Situated inside the instrument, arc lamps emit light at known wavelengths and from the emission lines of the arc lamps the half width at full maximum can be calculated. For 1998, 2007 and 2013 the standard deviation of the half width at half maximum was found to be ~ 1.59 pixels. This means that CSHELL can only detect turbulence greater than ± 5 km s^{-1} and the attenuated signal of H_3^+ at the equator increases this error further. As such, this data cannot be used to measure the spectral broadening caused by turbulence within the H Ly- α region, and so this study concentrates on bulk velocities.

Unlike the auroral regions, no literature has reported on H_3^+ LOS velocities in the mid-to-low latitude region of Jupiter's ionosphere. Investigations by Tao et al. (2014) have shown that the

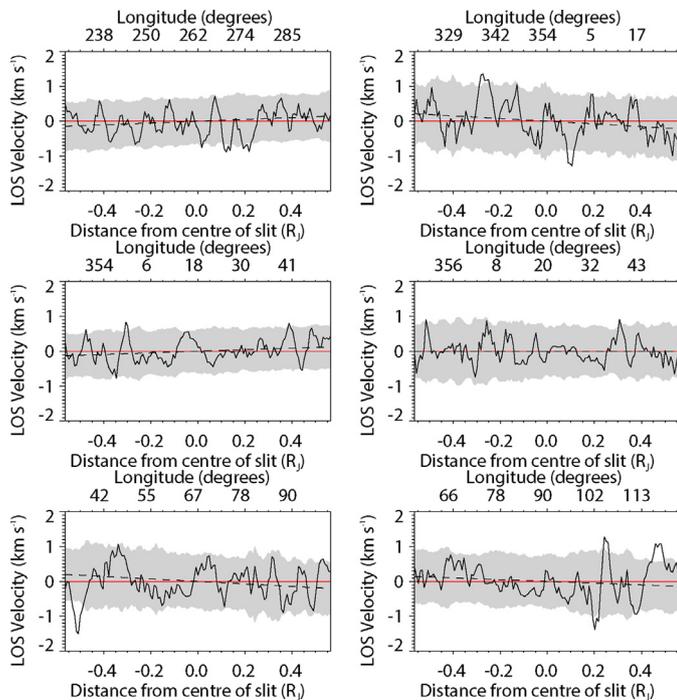


Fig. 2. Mid-to-low latitude LOS velocity profiles in the planetary reference frame, derived from mid-to-low-latitude H_3^+ emission CSHELL data, taken on 7th September 1998. The data covers a wide range of central meridian lines (CML). The solid black line is the derived LOS velocity of the H_3^+ ions. The dashed black line is a 1D polynomial fitted to the derived LOS velocity values. In this reference frame, a zero velocity implies corotation and is represented by the solid red line. The grey shaded region represents the errors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

maximum thermospheric neutral wind velocity, generated by solar EUV flux and auroral energy inputs, at latitudes less than 30° is 6.54 m s^{-1} . However these winds remain below the sensitivity of CSHELL ($>100 \text{ m s}^{-1}$) and so we cannot measure the effect of the velocity increase of the thermospheric neutral winds on the H_3^+ ions. As we cannot detect these winds using CSHELL data, we do not expect to measure any deviations from corotation due to coupling with the thermospheric neutral wind.

As outlined in Stallard et al. (2001) a correction was applied to the data since there is a distortion in the H_3^+ emission line introduced by the cross-disperser component of CSHELL. The difficulty in applying this correction introduces a significant error into the final velocity calculation. In addition to the instrumentation error, errors were accumulated through fitting Gaussians to the H_3^+ emission line and fitting a 1D polynomial to the derived LOS velocities. Through propagation of these errors, a final error at each spatial position along the slit was produced, and is indicated in the figures, where appropriate.

3. Results and discussion

An example of six mid-to-low latitude H_3^+ LOS velocity profiles from the 7th September 1998 is shown in Fig. 2. The solid black line is the calculated LOS velocity of the H_3^+ ions in the planetary reference frame, derived from individual spectral slit images. The dashed black line is a 1D polynomial fitted to the data. In the planetary frame of reference, a LOS velocity of zero infers that the H_3^+ ions are corotating. In Fig. 2, corotation is represented by the solid red line, which remains constant at a zero velocity. Departures from this zero line would be indicative of a magnetosphere-ionosphere coupling interaction. The 1D polynomial has a gradient very close to zero in the six plots in Fig. 2, showing that the bulk

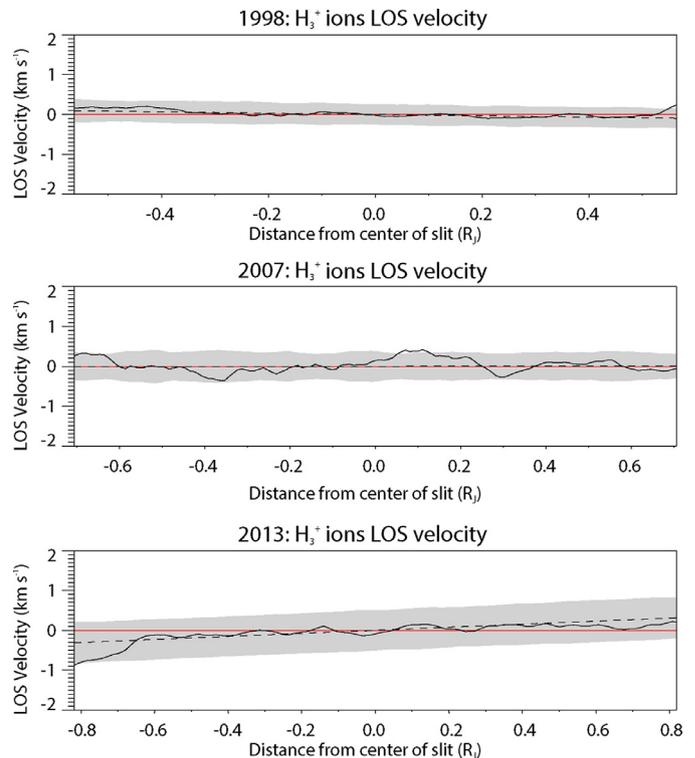


Fig. 3. Three mid-to-low latitude LOS velocity profiles in the planetary reference frame, for 1998, 2007 and 2013. The LOS velocity values were calculated from summation of the mid-to-low-latitude H_3^+ emission lines in a particular year.

flow of the equatorial H_3^+ is corotating during these observations. The LOS velocity of the H_3^+ ions in Fig. 2 shows some variability, which may indicate small scale flows in this region but these velocities remain inside the $\sim 0.5 \text{ km s}^{-1}$ error.

Flows in the circulatory pattern described by Sommeria et al. (1995) would appear in the LOS velocity profiles as deviations from corotation at fixed longitudes. Since the H Ly- α bulge is fixed in magnetic System III longitude, as Jupiter rotates, the localised deviation from corotation will be observed to move along the slit. Fig. 2 shows the LOS velocity profile for a range of CML; covering approximately half a jovian rotation and explores the longitude location of the H Ly- α bulge, which is fixed at $\sim 100^\circ$ longitude. If the localised deviations from corotation predicted by Sommeria et al. (1995) exist, then they would be observed as a prominent returning feature in Fig. 2, with the strongest flows expected in the centre of the H Ly- α bulge which would be observed in the first two plots. There is no evidence of returning features associated with the H Ly- α bulge outside the mean error of $\pm 0.51 \text{ km s}^{-1}$ and any observed variation in the LOS velocity are likely to be the result of noise.

Fig. 2 is an example of the LOS velocity profiles from the 7th September 1998 observations; a total of 124 measurements of mid-to-low latitude H_3^+ emission lines were investigated. Where the signal was adequate to derive the LOS velocity, it was found that the H_3^+ ions are corotating. No returning features were identified during these observations. This is in agreement with the results shown in Fig. 2.

In addition to small scale flows, Sommeria et al. (1995) modelled circulatory patterns include an Eastward and Westward jet, emerging from the position of the bulge. The Eastward jet dominates the Westward jet and therefore if the circulatory pattern from Sommeria et al. (1995) exists, it would be seen in Fig. 3 as a general sub-rotational trend due to the main flows in the model being mainly against rotation. The LOS velocities in Fig. 3 were de-

rived from the coadded spectral slit image. This prevents evidence of longitudinal variability being observed, but allows a greater accuracy of measurement of the rotation rate of the mid-to-low latitude region.

If the apparent coupling discussed by [Chaufray et al. \(2010\)](#) in the auroral region continues to the equator, then we would expect to observe the dominating Eastward electrojet as a LOS velocity deviation from corotation by several km s^{-1} . To determine the bulk flow of the H_3^+ ions, we refer to the 1D polynomial which was fitted to the derived LOS velocities. If the gradient of this line deviates from zero, then this will imply a departure from corotation. The gradient of the 1D polynomial is $-0.0013 \pm 1.4 \times 10^{-4}$, $6.8 \times 10^{-5} \pm 3.6 \times 10^{-4}$ and $0.0045 \pm 3.0 \times 10^{-4}$ for 1998, 2007 and 2013 respectively. Although the gradient of the 1D polynomial for 1998 and 2013 show slight departures from corotation, the maximum deviation of the 1D polynomial from corotation for 1998, 2007 and 2013 is $0.091 \pm 0.25 \text{ km s}^{-1}$, $0.0082 \pm 0.30 \text{ km s}^{-1}$ and $0.31 \pm 0.51 \text{ km s}^{-1}$ respectively. These are not significant deviations from corotation and a zero value means that the ions are rigidly corotating within the bound of our experimental errors.

Since the H_3^+ ions in Jupiter's mid-to-low latitude ionosphere have been found to be corotating with the neutrals, there will be no joule heating or ion drag in this region. This is because the velocity of the neutrals approximately matches that of the H_3^+ ions, and therefore collisions between them will be severely limited. The remaining energy inputs in the equatorial region are heating by atmospheric waves from lower altitudes ([Tao et al., 2009](#)), redistribution of polar auroral energy ([Bougher et al., 2005](#); [Majeed et al., 2005, 2009](#)), and a small contribution to heating by solar photons. Energy losses will be due to downward conduction and H_3^+ radiation to space ([Yelle and Miller, 2004](#)). It remains unclear if and how this limited set of energy terms can produce the observed high thermospheric temperatures at the equator (e.g. [Yates et al., 2014](#)). There is also disagreement over the mechanisms through which the energy is transported in the jovian ionosphere. Through meridional advection, the model by [Smith and Aylwood \(2009\)](#) describes poleward flow of heat raising the temperature of the polar region and cooling the mid-to-low latitudes. However, the models by [Bougher et al. \(2005\)](#) and [Majeed et al. \(2005, 2009\)](#) discuss how heat transported from the auroral regions through meridional advection heats the mid-to-low latitude region. It is the hope of the authors that the LOS velocity measurements in this study will go some way to constraining the equatorial conditions and hence work towards a unified model.

4. Conclusions

This study is the first to measure the LOS velocity of the H_3^+ ions in Jupiter's mid-to-low latitude ionosphere. The LOS velocity derived from the Doppler shifted H_3^+ emission line shows that the H_3^+ ions in Jupiter's ionosphere are rigidly corotating. No evidence that the H_3^+ ions are sub- or super-rotational, has been found in this data. This confirms that the ionosphere rigidly corotates at mid-to-low latitudes, such that the departures observed by e.g. [Stallard et al. \(2001\)](#) are confined to the polar region and are therefore likely to be due to magnetosphere-ionosphere coupling at those latitudes, as is often asserted.

No returning features were observed in the individual H_3^+ emission lines taken over a wide range of CML and no general trends were identified in the summation of H_3^+ emission lines. Therefore there is no evidence of strong flows at the equator, which the circulation pattern in the model by [Sommeria et al. \(1995\)](#) implies. This lack of evidence suggests that the H Ly- α bulge is produced through a different process than that modelled by [Sommeria et al. \(1995\)](#). However, the model may be referring to higher altitudes

than the H_3^+ emission and therefore it may not be possible to observe the proposed flow in H_3^+ measurements.

The spectral resolution of CSHELL is insufficient to test whether the thermosphere corotates as a result of vertical viscous transport, which could result in up to a 0.1 km s^{-1} super rotation at the equator due to Jupiter's tropospheric jets, or meridional advection which would smooth thermospheric flows globally. In future work it will be important to test whether the angular momentum is transferred by meridional advection as suggested by [Smith and Aylwood \(2009\)](#), [Bougher et al. \(2005\)](#) and [Majeed et al. \(2005, 2009\)](#), or by vertical transport similar to the coupling of the altitudes in the auroral regions discussed in [Chaufray et al. \(2010\)](#). The result presented here highlights the need for simultaneous measurements of both H_3^+ and H Ly- α emissions, as well as other thermospheric components in both the auroral and equatorial region. Such measurements would allow us to better understand how this region couples to both the lower atmosphere and the surrounding magnetosphere.

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