Exploring Key Characteristics in Saturn’s Infrared Auroral Emissions Using VLT-CRIRES: \( \text{H}_3^+ \) Intensities, Ion Line-of-Sight Velocities, and Rotational Temperatures

M. N. Chowdhury\(^1\), T. S. Stallard\(^1\), H. Melin\(^1\), and R. E. Johnson\(^2\)

\(^1\)Department of Physics and Astronomy, University of Leicester, Leicester, UK, \(^2\)Hotelli Korpikartano, Inari, Finland

Abstract

We present a study of Saturn’s \( \text{H}_3^+ \) northern auroral emission using data from 19 May 2013 from the Very Large Telescope’s long-slit spectrometer Cryogenic Infrared Echelle Spectrograph (VLT-CRIRES). Adaptive optics, combined with the spectral resolution of VLT-CRIRES (\( \Delta \lambda / \lambda \approx 100,000 \)), offers unprecedented spectrally resolved views of Saturn’s infrared aurora. Discrete \( \text{H}_3^+ \) emission lines—used to derive dawn-to-dusk profiles of auroral intensity, ion line-of-sight velocity, and thermospheric temperature—reveal a dawn-enhanced aurora with an average temperature of \( 361 \pm 48 \) K and a localized dark region in the emission co-located with a noon-to-midnight (and vice versa) flow in the ion velocity on the scale of \( \sim 1 \text{ km/s} \), resembling an ionospheric polar vortex. A temperature hotspot of \( 379 \pm 66 \) K may be driving an emission region, corresponding to a location where \( \text{H}_3^+ \) is failing to cool the thermosphere. Results presented here have implications for current understanding on the complex nature of Saturn’s thermosphere-ionosphere-magnetosphere interaction.

1. Introduction

Planetary aurorae result from interactions between the magnetosphere and upper atmosphere. Energetic particles from the magnetosphere are driven into the top of the atmosphere where they excite and ionize constituent atmospheric particles to produce emissions. Observations from ground-based facilities and spacecraft have revealed the highly dynamic nature of Saturn’s aurorae. The intensity and location of auroral emissions on a planet can be considered the signature of different processes and conditions in the magnetosphere and upper atmosphere. Studying the aurora provides valuable insights into the complexity of interactions between the magnetosphere, ionosphere, and thermosphere including the magnetospheric origins of particles, which induce auroral emissions (Bhardwaj & Gladstone, 2000; Stallard et al., 2018).

Saturn’s aurora form from the precipitation of charged particles produced by the ionization of neutral gases, which exist within the equatorial region of Saturn’s magnetosphere. These gases occur via sputtering and outgassing from the icy moons and rings of Saturn, for example, the geyers on Enceladus (Hansen et al., 2006). This neutral gas is then photoionized by solar extreme ultraviolet photons. Particles with sufficient energy can reach high planetary latitudes and precipitate into the atmosphere and subsequent high-energy excitation of atmospheric constituents releases energy in the form of the aurorae (Stallard et al., 2018).

Auroral studies at Saturn are primarily carried out in the ultraviolet (UV) and infrared (IR) wavelengths. UV studies characterize high-energy electron impacts on the upper atmosphere, which result in the excitation of atomic and molecular hydrogen and hence auroral emissions (e.g., Gustin et al., 2009). These have been used to characterize the auroral morphology of Saturn in detail, identifying typical components such as areas of cusp emission, small-scale spots and arcs, and others, all dominated by a main emission resembling an oval centered on the pole (Grodent, 2015; Stallard et al., 2018). Badman et al. (2011) showed using Cassini-VIMS data that the average location of the IR main oval was similar to the UV main emission; the IR main oval was observed to extend to co-latitudes of \( \sim 14–20^\circ \). The discrete nature of the main oval (as observed in the UV) suggests that this feature is likely generated at the open-closed field line boundary by downward accelerated precipitating electrons found in regions of oppositely upward directed field-aligned currents (Cowley et al., 2004). Solar wind compression events influence auroral morphology with the degree of compression having an impact on dawn-brightening (Stallard, Masters, et al., 2012). Relatively small and
moderate compressions in the solar wind result in a brightening of the dawnside aurora and poleward movement of the main emission; large compressions can result in the entire dawn half of the polar cap being filled with bright emission (Clarke et al., 2009; Grodent et al., 2005).

Ground-based IR studies of Saturn have developed our understanding of mechanisms governing the production and behavior of Saturn’s IR aurorae. Studies can make use of discrete ro-vibrational emission lines of the tri-hydrogen cation (henceforth H$_3^+$) to probe interactions between the ionosphere and the local space environment, including physical conditions of the surrounding neutral atmosphere (Miller et al., 2010; O’Donoghue et al., 2014). H$_3^+$ is a molecular ion found in the upper atmosphere of Saturn (Geballe et al., 1993) and has two primary pathways of production: photoionization of neutral molecular hydrogen in the upper atmosphere by solar extreme ultraviolet (EUV) photons, providing a uniform ionization source across the entire sunlit portion of the planet, and electron impact ionization, where energetic electrons and ions primarily originating in the magnetosphere accelerate along high-latitude magnetic field lines and precipitate into the polar/auroral regions. Both processes ionize molecular hydrogen in the upper atmosphere producing H$_2^+$, which quickly reacts with H$_2$ to produce H$_3^+$. The H$_3^+$ density peaks at an altitude of ~1,155 km above the 1-bar pressure level in the polar regions at Saturn (Stallard, Melin, et al., 2012), but it can be produced over a much larger altitudinal range between 900 and 4,000 km (Tao et al., 2011).

H$_3^+$ is a dominant ion in the ionosphere, and its high radiative efficiency makes H$_3^+$ emission a major cooling mechanism in both polar and non-polar upper atmospheric regions of giant planets (Miller et al., 2010). H$_3^+$ is widely referred to as the “thermospheric thermostat” in the context of giant planetary upper atmospheres for its effective ability to re-radiate heat into space (Miller et al., 2000; Rego et al., 2000; Satoh & Connerney, 1999), although Müller-Wodarg et al. (2012) suggest that this plays only a minor role at Saturn.

Stallard et al. (2007) have shown significant dawn-to-dusk polar emission across the southern auroral region. Dawn enhancements in the aurora result from solar wind compressions and have been observed in the UV (e.g., Clarke et al., 2009). Dawn enhancements are also linked to the effect of the rotating current system as described by planetary period oscillations (PPOs; e.g., Kinrade et al., 2018). This current system possesses a layer of both downward and upward currents on either side of a pole, and the latter can drive energetic electrons into the atmosphere to produce periodic dawn-enhanced UV and IR auroral emission (Bader et al., 2018; Stallard et al., 2018).

The line-of-sight velocity of H$_3^+$ ions can be derived from the Doppler shift of the H$_3^+$ emission lines (e.g., Rego et al., 1999; Stallard et al., 2007) enabling a measure of their angular velocities with respect to the planetary rotation rate. Stallard et al. (2007) used high spectral resolution data ($R = \lambda/\Delta \lambda \sim 40,000$) from Saturn’s southern auroral region to derive ion line-of-sight velocity profiles, revealing a three-tier structure with a central area near the pole where ions move with velocities close to planetary corotation, flanked on either side by areas of strong sub-corotation. Stallard, Masters, et al. (2012) later showed that this was a non-permanent feature and a breakdown in the structure was detected during periods of solar wind compression events at Saturn.

The rotational temperature of H$_3^+$ can be derived by taking the ratio of the spectral radiiplies of the $v_2$ Q(1,0$^-$) and Q(3,0$^-$) fundamental emission lines. Average measurements and observation dates of previous ground-based studies that derived temperature profiles for Saturn’s auroral regions are summarized in Table 1. O’Donoghue et al. (2014) used simultaneous Keck observations of Saturn’s northern and southern aurorae from April 2011 to obtain average thermospheric temperatures of 527 ($\pm$18) K and 583 ($\pm$13) K for each polar region, respectively. They suggested that this disparity was a product of the offset magnetic dipole at Saturn and the result of an inversely proportional relationship between the total thermospheric heating rate—due to Joule heating and ion drag mechanisms—and the magnetic field strength. This study noted a higher H$_3^+$ column density in the northern hemisphere compared with the southern due to the value of the observer sublatitude (8.2$^\circ$) of Saturn at the time; more of the northern aurora was illuminated by sunlight, with a greater rate of H$_3^+$ production in that hemisphere. Further, ground-based observations of the southern polar region, as detailed by Melin et al. (2007), have shown that the southern aurora exhibited a much wider range of H$_3^+$ temperatures. Using data taken from three separate observing campaigns, they found average values of 380 ($\pm$70) K across the aurora in a noon-to-midnight cut of the pole and 420 ($\pm$70) K in a dawn-to-dusk profile.
Only two ground-based studies have derived thermospheric temperature profiles from the northern polar region, showing an overall noon-to-midnight variation between 416 (±18) K and 527 (±18) K (O’Donoghue et al., 2014, 2016). The data sets used in these were limited in both the spectral and spatial realms of resolution. This study presents a data set at a higher spectral and spatial resolution compared to all previous ground-based studies of Saturn’s IR auroral emissions. Using these observations, we derive dawn-to-dusk auroral emission intensity, ion line-of-sight velocity, H$_3^+$ rotational temperature, column density, and total emission profiles.

### 2. Observations and Data Analysis

Spectroscopic data were collected using the European Southern Observatory’s Very Large Telescope (VLT) facility situated at Cerro Paranal in Chile. Observations of Saturn’s northern auroral region were made on the night of 19 May 2013 through to the early hours of 20 May 2013 (Universal Time, UT) spanning the period from 23:16 to 04:33 UT, with the Saturn airmass varying from 1.828 to 1.095 during this time. The Saturn observer sub-latitude was 21.28°, so the northern aurora was favorably displayed and, while the planet rotated, spectral data from Saturn was collected from ~230–61° Saturn System III Central Meridian Longitude.

The instrument used to collect data was the long-slit Echelle spectrometer Cryogenic Infrared Echelle Spectrograph (VLT-CRIRES), which has a slit width of 0.2′′—corresponding to a resolving power of ~100,000—and the data were collected on four Aladdin detector arrays with an overall plate scale of 0.089′′ per pixel (Käufl, 2008; Smoker, 2013). Instrument settings used for these observations allowed the detector arrays to cover a wavelength range of 3.884–3.986 μm, with a gap of 0.006 μm between each array. This instrument could also collect a large amount of spatial information due to its 40′′ slit length and the use of adaptive optics (AO) during the observations. The spectrometer slit was aligned at a single position on the planet cutting east-to-west along the northern polar cap at a latitude of 90° and perpendicular to the planetary rotational axis, as shown in Figure 1. With the slit positioned directly on the rotational pole, 100-s planetary exposures (A) were taken and interspersed with sky exposures (B) in an ABBA pattern as described in studies such as Stallard et al. (1999). Long-duration exposures were necessary to gather data that had a sufficient signal-to-noise ratio (SNR) to derive the data products. Saturn is a relatively faint object to observe at H$_3^+$ wavelengths, and the SNR of the raw data before reduction was ~27. The AO system used during our observing run was able to limit the majority of distortive effects due to atmospheric seeing by imposing a lower seeing limit of ~0.04′′ (seeing without AO varied between ~1″–1.5″ on the night), and this in turn aided the characterization of smaller-scale structures in the data products.

The methods used for data reduction involved the same standard flat-fielding and flux calibration techniques (using the star HR 5355 for this study) as those employed in studies such as Johnson et al. (2017), and references therein, and the reader is referred to this article, which used spectral data collected at Jupiter by VLT-CRIRES, for a narrative on data reduction and cleaning methods. We coadded all 65 spectral frames and divided by the total number to increase the signal, and the spectral data were further smoothed in the spatial direction to boost the SNR to ~41 before performing fits on the data. This 5-pixel boxcar smooth corresponds to an effective seeing of 0.43″ on the observation night.
Figure 1. (a) The Very Large Telescope’s long-slit spectrometer Cryogenic Infrared Echelle Spectrograph slit position on the planet—this image (taken using adaptive optics on 19 May 2013) shows that the slit (dashed line) was positioned across the north polar cap with the center of the slit at a latitude of $90^\circ$; (b) the auroral emission intensity profile derived from the Gaussian fit performed on the $\text{H}_3^+$ $v_2$ $Q(1,0^-$ $- 0^-)$ emission line; (c) two of the four detector arrays that contained the most prominent Q-branch $\text{H}_3^+$ emission lines, that is, the $v_2$ $Q(1,0^-)$ and $Q(3,0^-)$ lines; and (d) the line emission intensity profile derived from the Gaussian fit performed on the $\text{H}_3^+$ $v_2$ $Q(3,0^-)$ emission line.

A six-term Gaussian was fitted to every spatial position along the coadded $v_2$ $Q(1,0^-)$ and $Q(3,0^-)$ spectral lines returning the height of the Gaussian, the pixel position of the peak of each fit, the width of the Gaussian, and the coefficients of a quadratic fit to the background signal. These were then used to derive the auroral emission intensity, the ion line-of-sight velocity, the thermospheric temperature, the $\text{H}_3^+$ column density, and the total emission generated by $\text{H}_3^+$ ions in the upper atmosphere. Error propagation performed for each of the derived parameters resulted in $\pm 1$ standard deviation (1-sigma) bounds, which originate from the uncertainty in fitting Gaussian profiles to each of the spectral lines under consideration. All the profiles we derive in this current work (including column density and emission intensity but excepting the ion line-of-sight velocity) have been line-of-sight intensity corrected. The computational methods involved in calculating the parameters for this study are described extensively by Johnson et al. (2017, 2018), and the reader is referred to these works for further details.

3. Results

Figure 2 shows the auroral emission intensity and the ion line-of-sight velocity. These have been plotted as a function of co-latitude on the planet with the center of the pole corresponding to 0° co-latitude (or, 90° latitude), and the positions of the planetary limbs are indicated. The planetary rotation rate of 10.63 hr is assumed to be equivalent to the velocity of the corotating atmosphere and is plotted as a dashed line (Provan et al., 2018). The auroral emission intensity we have derived shows a dawnside enhancement in the strength of the emission. Figure 2 shows the main oval as the large peak at co-latitude 17° marked with an A on the dawnside. The symmetric duskside emission on the main oval (at position D) is absent. In our data, there are interesting features within this polar cap such as a localized region of weaker emission at B on the dawnside and a region of stronger emission (compared to the background level) at C on the duskside.

The ion line-of-sight velocity profile (also shown in Figure 2) shows the velocity of $\text{H}_3^+$ ions with respect to the planetary rotation rate in the reference frame of the observer. There are no small-scale structures seen at the main oval co-latitudes between 15° and 20° larger than our errors on both the dawnside and duskside of the planet. This suggests that changes in Saturn’s ionospheric currents are of a scale too small...
Figure 2. Auroral H\textsuperscript{+} Q(1,0)\textsuperscript{−} emission intensity and ion line-of-sight velocity profiles. The vertical dashed lines delineate regions of 10\textdegree co-latitude on the planet, and the vertical blue lines indicate the planetary limbs. Four main regions of interest have been identified and are labeled as follows: (A) the main oval peak seen between 15\textdegree and 20\textdegree co-latitude on the dawnside of the planet; (B) the region with a localized interaction between the ion line-of-sight velocity and the auroral emission intensity between 0\textdegree and 5\textdegree co-latitude on the dawnside; (C) the position of an intense polar auroral brightening between 5\textdegree and 10\textdegree co-latitude on the duskside of the planet; (D) is the region between 15\textdegree and 20\textdegree co-latitude on the duskside, which would nominally coincide with the position of the duskside main oval but is instead lacking an intense spike (equivalent to A on the dawnside). The direction of the flow of ions (noon-to-midnight and midnight-to-noon), as seen at (B) in the H\textsuperscript{+} line-of-sight velocity profile, is indicated using color-coded arrows and data points. N.B. wherever possible, the first instance in which any given derived profile is displayed, it is done so with individual data points in order to more clearly represent the spatial scale of the detector array pixels.

to be observed clearly, either at less than 2\textdegree co-latitude or at less than or equal to 0.5 km/s, which are the bounds representing the limit of our data set. We do not see any evidence of strong flow shears at these main oval positions (A and D), which would produce a notable increase in the velocity as ions move away from the observer followed by a sharp drop in the velocity as the ions move toward the observer. We thus cannot conclude that there are either Hall currents or the auroral electrojet present in our data, the latter of which would induce strong flow shears at the same positions as the main oval peaks as has been seen on the order of 0.5–1 km/s at Jupiter under normal auroral conditions (Stallard et al., 2001).

Away from the center of the pole, there is a breakdown in corotation in the line-of-sight velocity between about 5\textdegree and 25\textdegree co-latitude on both sides of the pole as the measured velocity sits between ~30% and 90% of corotation with the planetary atmosphere. Comparing the auroral emission intensity and ion line-of-sight velocity profiles in Figure 2 shows the presence of a very sharp velocity shear between 0\textdegree and 5\textdegree co-latitude at B on the dawnside, which corresponds to a region of weak emission intensity compared to the background level at adjacent locations. The sharp shift in velocity indicates that there is initially a noon-to-midnight flow (away from the observer, as shown by purple data points and arrow) of H\textsuperscript{+} ions in the ionosphere between approximately 5\textdegree and 2.5\textdegree co-latitude on the dawnside of the pole, which is followed immediately by an oppositely directed midnight-to-noon flow of ions (toward the observer, as shown by green data points and arrow) between around 2.5\textdegree and 0\textdegree co-latitude on the dawnside of the pole. The nature of the almost ~1 km/s swing in velocity over ~5\textdegree of latitude, as shown by the arrows in Figure 2, is very intriguing as it deviates from the otherwise nominal (but not uncomplicated) trend of ions, which are flowing in a direction going from dawn-to-dusk across the pole. This is the only strong reversal in the data although there are other small features present.
Figure 3. (a) Thermospheric temperature, $H_3^+$ column density, and normalized auroral emission intensity profiles; (b) thermospheric temperature profile with error bars; (c) $H_3^+$ column density with error bars and auroral emission intensity profile; (d) $H_3^+$ total emission and auroral emission intensity profiles; (e) $H_3^+$ column density and total emission profiles; and (f) thermospheric temperature and $H_3^+$ column density scatter plot. N.B where applicable, the vertical dashed lines delineate regions of $10^\circ$ colatitude on the planet and the vertical blue lines show the planetary limbs.
At position C on the duskside there is a region of constant velocity in the ion line-of-sight velocity profile with this value remaining close to around 0.5 km/s. Stallard et al. (2003) and Cowley et al. (2003) have proposed how, at Jupiter, this behavior can be the result of a slow convection of ions coupled to open magnetic field lines across the polar aurora, such that they are relatively stationary compared with corotational and sub-corotational closed magnetic field lines. If the velocity was exactly equal to 0 km/s, then it would suggest that this region could be connected to open-field lines in the outer magnetosphere. Once errors are accounted for in these data, the line-of-sight velocity in this region does fall very close to 0 km/s.

Our thermospheric temperature profile, shown as the red trace in Figures 3a and 3b, is plotted as a function of co-latitude on the planet and is displayed alongside the auroral emission intensity and H$_3^+$ column density. We have large error bounds on the temperature profile compared with other derived parameters and this is due to a marginally weaker and noisier signal from the H$_3^+$ Q(3,0) emission line. We see a subtle temperature gradient across the pole as the temperature increases from 350 (±73) K on the duskside of the planet to 389 (±126) K on the duskside. In a variable duskside compared to the dawnside, there are two hotspots at 9$°$ and 22$°$ co-latitude interspersed within a colder region between 13$°$ and 20$°$ co-latitude. The existence of these features could be down to a number of factors. For example, studies that derived H$_3^+$ temperatures have observed their temperatures to be the result of differences in altitude of where H$_3^+$ was produced (as seen at Jupiter by Lystrup et al., 2008) and enhanced heating associated with Joule heating through either the current system described in Stallard et al. (2008) or ring rain as discovered by O’Donoghue et al. (2013). The dawnside of the planet is cooler than the duskside and a hotspot at 9$°$ co-latitude on the duskside of the planet happens to loosely coincide with the emission intensity spike inside the polar cap at position C. This shows there is a possible link between the increased H$_3^+$ intensity at this position and the temperature hotspot, maybe resulting in a temperature-driven auroral emission due to localized Joule heating.

The H$_3^+$ column density profile is largely anticorrelated with the thermospheric temperature in Figure 3a, and we compute a Pearson correlation coefficient of −0.80 from our data set that can be seen in Figure 3f. There are regions between 5$°$ and 25$°$ co-latitude on the duskside where the column density does not appear to be as well anticorrelated as the rest of the profile is, although the error bounds on our temperatures are very large relative to other derived parameters. This anticorrelation could suggest that H$_3^+$ may be acting as a thermostat in a similar way to Jupiter with the column density thus being the primary driver of the H$_3^+$ cooling that we observe. Generally, the thermospheric temperature is low at points where the column density is high due to the re-radiating capability of H$_3^+$ (Miller et al., 2000). The H$_3^+$ total emission profile, showing the wavelength integrated radiated energy escaping the planet, is relatively well matched to both the column density and auroral emission intensity profiles: this property is highest where the column density is highest and is less effected by temperature.

4. Discussion

The dawnside enhancement in Saturn’s main auroral oval has been observed before in studies from both ground-based and in situ observations (e.g., Badman et al., 2011, Bunce et al., 2008). Badman et al. (2011) showed that their main oval emission could be found within the 20$°$ co-latitude region on the poles and the dawn-enhanced main oval that we observe in our data is centered around 17$°$ co-latitude and is therefore in good agreement. They also observed occasional emission inside the polar cap region, and we are able to do the same by noting features at B and C in Figure 2 where the emission intensity deviates from background levels. Bunce et al. (2008) suggested that the dawnside enhancement was linked to the magnetosphere-solar wind interaction across the open-closed field line boundary. A stronger than normal shear in rotational flow across this region could lead to asymmetries in the auroral emission intensity. Historically, ion line-of-sight velocity profiles observed at Saturn have produced relatively coarse views of ion flows. For example, Stallard et al. (2007) observed a three-tier velocity structure in their profiles but later found that this can be disrupted by solar wind compressions (Stallard, Masters, et al., Stallard et al., 2012). Our data set, with its spectral resolution of ~100,000 and collected using AO, has allowed us to pick out finer-scale structures than before. We do not see a prevalent three-tier structure but instead a central region dominated by the discrete small-scale flow shear at position B in Figure 2. This shear at the pole is colocated with a region of localized weak emission, and the velocity of the ions suggests the presence of a structure inside the polar cap. In particular, the direction of motion of the ions may indicate behavior consistent with that of a small H$_3^+$ ion vortex near the center of the northern pole. The sharp increase and immediate decrease in the velocity over ~5$°$ of latitude is evidence for a flow of ions away from and then back toward an observer.
The presence of any ionospheric $H_3^+$ polar vortices can only be confirmed using two-dimensional maps of the entire northern auroral region, collated together from scans of the planet. The current data set features a cut of the auroral emission from just one position, which happens to be directly along the northern pole going in an east-to-west direction, thus presenting difficulties in inferring the characteristics of surrounding auroral features and $H_3^+$ ion velocities.

In Figure 3a, a region of high temperature on the duskside of the pole culminates in a hotspot of 379 ($\pm$66) K. High $H_3^+$ temperatures are observed either due to increased heating (via mechanisms such as Joule heating) or due to a change in the energy of precipitating electrons, thus producing $H_3^+$ at different altitudes and sampling different parts of the vertical temperature curve. Tao et al. (2011) have shown that the $H_3^+$ temperature depends on the energy of incident electrons, since lower-energy electrons (0.1–1 keV vs. 10–100 keV) lead to $H_3^+$ being produced higher than 2,000 km above the 1-bar pressure level. The hotspot we observe could be the result of $H_3^+$ ions depositing their energy at high altitudes and sampling the hotter temperatures there. Natural altitudinal variations in our temperature profile make it likely that any observed changes are representative of the bulk atmosphere near the $H_3^+$ peak altitude, which is the dominant ion between 1,300 and 2,600 km above the Saturnian 1-bar pressure level (Tao et al., 2011).

What certainly adds to the intrigue surrounding this hotspot, which is closely colocated with point C in Figure 2, is that the spike in emission intensity is unrelated to any change in $H_3^+$ column density. The position of this emission peak inside the polar cap corresponds to the strong auroral hotspot in the thermospheric temperature at $\sim$9° co-latitude on the duskside, suggesting that the enhancement in $H_3^+$ brightness (e.g., Badman et al., 2011; Stallard et al., 2007) may be driven by a localized thermospheric hotspot. This may explain why comparable enhancements are not observed in the UV, which measures prompt emission from particle precipitation and could also potentially explain the presence of auroral features that are generally seen in IR in the polar cap (Stallard et al., 2008). The existence of localized thermospheric hotspots near Saturn’s pole could also relate to the poleward flow of energy predicted by the “thermospheric fridge” ion drag mechanism described by Smith et al. (2007) and may potentially be a detection of the predicted localized hotspot evoked to explain the thermospheric flows required to drive PPO (Jia et al., 2012; Smith, 2011). This temperature-driven auroral hot spot could be possible evidence of the thermospheric asymmetry as required by PPO, but such a conclusion cannot be made from this data given the very large error bounds on the derived temperature profile and the additional need for a robust and comprehensive time series analysis of the emissions to identify any periodicities.

A general anticorrelation exists between the observed $H_3^+$ temperature and column density; a property that has been noted as being an inherent degeneracy of the measurement technique (Melin et al., 2013). This anticorrelation has been observed from ground-based observations carried out before at Saturn (O’Donoghue et al., 2014, 2016) and helps to reaffirm the well-established finding that $H_3^+$ acts as a thermospheric thermostat in the upper atmospheres of gas giants due to its efficient radiative capabilities (Miller et al., 2000). However, the re-radiating capability of $H_3^+$ does not appear as effective at the thermospheric hotspot corresponding to the particularly bright emission inside the polar cap at point C on the duskside in Figure 2. This may suggest that $H_3^+$ is trying to cool the region but is failing to do so with the same efficiency as the rest of the auroral region.

5. Conclusions

This data set offers a higher spatially and spectrally resolved view of Saturn’s IR aurora than ever before, allowing us to detect features and structures in the derived auroral parameters on a smaller scale.

We observe a thermal hotspot that may be driving auroral emission inside the polar cap, corresponding to a region where the line-of-sight velocity of ions moving in the upper atmosphere is $\sim$0.5 km/s. Given that the temperature-driven auroral hot spot contributes to the overall asymmetry in the thermospheric temperature profile, this is also possibly evidence of the temperature asymmetry required by PPO although a detailed time series analysis of the data would be necessary to state this more conclusively. We also see evidence for vortex-type flows in the $H_3^+$ ion line-of-sight velocity profile, corresponding to a region of weaker emission in the auroral intensity. This could be the result of a localized vortical flow of $H_3^+$ ions driving a relatively larger ionospheric polar vortex inside the dawnside polar cap.
Acknowledgments
This study is based on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere under ESO program 091.C-0257(A). VLTP spectral data are available from the ESO Science Archive Facility. M. N. C. and R. E. J. were supported by UK Science and Technologies Facilities Council (STFC) studentships, ST/N504117/1 and ST/X42J3T/2, respectively. T. S. and H. M. were both supported by U.K. STFC Grant ST/N000749/1.

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