Saturn’s auroral/polar H\textsuperscript{3+} infrared emission
II. A comparison with plasma flow models

Tom Stallard\textsuperscript{a,*}, Chris Smith\textsuperscript{b}, Steve Miller\textsuperscript{b}, Henrik Melin\textsuperscript{c}, Makenzie Lystrup\textsuperscript{b}, Alan Aylward\textsuperscript{b}, Nick Achilleos\textsuperscript{b}, Michele Dougherty\textsuperscript{d}

\textsuperscript{a} Radio and Space Plasma Physics Group, Department of Physics and Astronomy, University of Leicester, University Road, Leicester LE1 7RH, UK
\textsuperscript{b} Atmospheric Physics Laboratory, Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK
\textsuperscript{c} Space Environment Technologies, Planetary and Space Science Division, 320 N. Halstead St, Suite 170, Pasadena, CA 91107, USA
\textsuperscript{d} Space and Atmospheric Physics Group, Department of Physics, Imperial College of Science, Technology and Medicine, South Kensington Campus, London SW7 2AZ, UK

Received 16 September 2006; revised 17 May 2007
Available online 4 July 2007

Abstract

We present a detailed analysis of the H\textsuperscript{3+} intensity and velocity profiles crossing Saturn’s auroral/polar region, as described by Stallard et al. [Stallard, T., Miller, S., Melin, H., Lystrup, M., Dougherty, M., Achilleos, N., 2007. Icarus 189, 1–13], with a view to understanding the magnetospheric processes with which they are connected. The data are not consistent with the theory that Saturn’s main auroral oval is associated with corotation enforcement currents in the middle magnetosphere. This implies that the main auroral oval can be associated with the open–closed field line boundary [Cowley, S.W.H., Bunce, E.J., O’Rourke, J.M., 2004. J. Geophys. Res. 109. A05212]; a third model, by Sittler et al. [Sittler, E.C., Blanc, M.F., Richardson, J.D., 2006. J. Geophys. Res. 111. A06208] associates the main oval with centrifugal instabilities in the outer magnetosphere, but does not make predictions about ionospheric plasma flows with which we can compare our data. We do, however, tentatively identify emission at latitudes lower than the main auroral oval which may be associated with the corotation enforcement currents in the middle magnetosphere. We also find that at latitudes higher than the main auroral oval there is often a region of the ionosphere that is in rigid corotation with the planet. We suggest that this region corresponds to field lines embedded in the centre of the magnetotail which are shielded from the solar wind such that their rotation is controlled only by the neutral atmosphere.

Keywords: Aurora; Ionospheres; Infrared observations; Saturn, magnetosphere; Saturn, atmosphere

1. Introduction

The processes by which the saturnian aurorae are formed are an issue of intense current interest and debate. With the influx of new in situ data following Cassini’s arrival at Saturn (Dougherty et al., 2005; Gurnett et al., 2005; Krimigis et al., 2005; Young et al., 2005) and the supporting UV images that show the morphology of the aurora in detail for the first time (Gérard et al., 2004; Clarke et al., 2005; Crary et al., 2005; Grodent et al., 2005; Kurth et al., 2005), it has been possible for detailed theories to be developed (Cowley et al., 2004; Hill, 2005; Sittler et al., 2006).

In the case of Jupiter, there is at present a reasonable consensus that the main auroral oval is associated with sub-corotation of plasma in the jovian middle magnetosphere (Hill, 2001; Cowley and Bunce, 2001). Polewards of the main oval there are more complicated structures (Pallier and Prangé, 2001; see Clarke et al., 2004, for a review) that have yet to be fully explained, but are likely to be associated with solar wind coupling (Cowley et al., 2003b). Infrared data (Rego et al., 1999; Stallard et al., 2001, 2002, 2003) has been important in our emerging understanding of these phenomena. The principal purpose of this paper is to use similar IR data acquired for Saturn (Stallard et al., 2007) to assess the existing models of the saturnian aurorae. We are also able to tentatively identify features in our data that correlate with structures in Saturn’s magnetotail, and discuss
the possible implications of these structures for the conditions within the thermosphere.

In Section 2 we briefly discuss our present understanding of the magnetosphere of Jupiter and its relation to that planet’s aurorae. In this context we then discuss the extant models of Saturn’s main auroral oval and describe the plasma flows that these models predict will exist in the polar regions of the planet’s ionosphere. In Section 3 we review the observations presented in Stallard et al. (2007), and in Section 4 we assess their consistency with the predictions of Section 2. In Section 5 we discuss the velocity structure of the polar cap within our data, in Section 6 we calculate the energy the measured velocity structure deposits into the upper atmosphere, and in Section 7 we present our conclusions.

2. Models for the formation of giant planet aurorae

2.1. Jovian auroral models

The basis of our understanding of the saturnian aurorae is more robust—but still developing—knowledge of the jovian aurorae. The jovian aurorae are dominated by a bright and stable ‘main oval,’ present in both the UV and IR emissions. The present consensus is that this main oval is associated with the system of currents that flow between the polar regions of the planet and the middle magnetosphere (Hill, 2001; Cowley and Bunce, 2001). This system of currents was first described by Hill (1979) as the mechanism by which planetary angular momentum is transferred to the magnetosphere. The currents in the upper atmosphere flow towards the equator, while those in the middle magnetosphere flow away from the planet. These two regions are linked by field-aligned currents that close the circuit.

The angular momentum transfer mediated by these currents is necessary because fresh plasma is continually supplied to the jovian inner magnetosphere by volcanism on the moon Io. In the inner magnetosphere the Hill currents spin up the plasma rapidly into rigid corotation with the planet, as collisions between ions and neutrals in the atmosphere provide sufficient torque to keep the plasma rigidly corotating. Close to the planet, the Hill currents required to maintain corotation are relatively weak. However, the plasma injected into the inner magnetosphere by Io gradually diffuses outwards, forming a vast plasma sheet in the equatorial plane of the middle magnetosphere. At a critical distance from the planet, the required angular momentum to maintain rigid corotation in the plasma sheet is greater than can be provided by collisions between ions and neutrals within the atmosphere, and so the plasma beyond this radius therefore substantially sub-corotates. In this region the Hill currents are considerably larger than in the inner magnetosphere as the differential rotation velocity of the planet and the plasma, which drives the currents, is much greater. Thus, at the inner edge of the sub-corotating region, the magnitude of the Hill currents increases greatly. Since in the middle magnetosphere the current is flowing away from the planet, there must be strong upwards currents on field lines mapping to the inner edge of this region. At the planet, these upwards currents are of too great an intensity to be carried by the ambient plasma; it is thus necessary for them to be carried by the downwards acceleration of magnetospheric electrons. It is these electrons—with energies of a few kiloelectron Volts (keV) to over 100 keV—that are believed to be responsible for exciting the main auroral oval emission seen in the UV, optical and IR.

The key point of this discussion is that the jovian main auroral oval lies at the inner edge of the sub-corotating region of the middle magnetosphere. The self-consistent theoretical treatment of the jovian middle magnetosphere presented by Nichols and Cowley (2004) further supports this insight. Nichols and Cowley took into account variations in the ionospheric conductivity induced by the auroral electrons. Since the impact of these electrons increases the density of the ionosphere in the region of upwards currents (the main oval), they also tend to increase the intensity of the upwards currents at the equatorwards edge of the main oval. The peak upwards currents is then at a lower latitude; thus the main oval itself has been pushed to lower latitudes (corresponding, in the magnetosphere, to regions closer to the planet). This process ensures that the field lines mapping to the main auroral oval are concentrated at the inner edge of the region of sub-corotation. Plasma on field lines at slightly lower latitudes (closer to the planet) than those corresponding to the main oval are very nearly in rigid corotation with the planet. Auroral emissions polewards of the jovian main oval are less well understood.

As well as a wealth of information derived from UV images of the jovian auroral polar regions (e.g., Clarke et al., 1998, 2004; Pallier and Prangé, 2001), the understanding of Jupiter’s auroral features has greatly benefited from infrared imaging (e.g., Baron et al., 1991; Connerney et al., 1993, 1998) and spectroscopy (e.g., Drossart et al., 1989; Lam et al., 1997; Miller et al., 2000). For Jupiter, there is close correspondence between UV and IR images, indicating a related source for both UV and IR aurorae. But there are also differences: in particular, there is significant infrared emission across Jupiter’s polar cap in regions where the UV emission is low, a situation that is still not fully explained. Measurements of ion velocities in the upper atmosphere have been used to identify the presence of a westward (in the planetary reference frame, i.e., counter to the rotation of the planet) wind associated with the main auroral oval (Rego et al., 1999), and to delineate distinct flow regions within the polar cap (Stallard et al., 2003). Modelling has shown that this ion drift engenders a strong neutral wind (Millward et al., 2005), with important consequences for energy inputs due to Joule heating and ion drag (Smith et al., 2005, 2007; Smith, 2006).

To demonstrate how IR data can be used to support theories of the formation of the jovian aurorae we show in Fig. 1 an example of jovian auroral structure first published in Stallard et al. (2003). The thin line shows $ \text{H}_3^+ $ emission intensity in the fundamental $ v_2 \ Q(1,0^{-}) $ line, at 3.953 microns, across the northern auroral/polar region. The bold line shows line-of-sight velocities in an inertial frame. In this figure, we have taken the reference frame as that which rigidly corotates with the planet’s (North) magnetic pole, correcting for the small velocity change caused by it being tilted with respect to the rotational
pole by $\sim 10^\circ$. The dashed line shows the line-of-sight velocity expected if the H$_3^+$ in the auroral/polar region is in rigid corotation with the planet. The main regions of interest here are the two bright peaks on either side of the profile, which correspond to the main auroral oval, on the dawn (left) and dusk (right) side of the planet. Looking in particular at the dawn sector of the plot we can see that polewards of the main oval the H$_3^+$ substantially sub-corotates; however, just equatorwards of the main oval it rapidly returns to near-corotation. This is the behaviour predicted by the corotation breakdown model of the jovian main oval, represented particularly by the model of Nichols and Cowley (2004).

Polewards of the main oval are two regions, labelled in Fig. 1 as the dark and bright polar regions (DPR, BPR). Broadly speaking, Cowley et al. (2003b) identified the BPR with processes related to the Vasyliunas cycle outflow on the planet’s dusk flank, and the DPR with a region of magnetic flux open to the solar wind, connecting to the planet’s magnetotail. If this interpretation is correct, then the best theoretical model of the flow in the open field region is that of Isbell et al. (1984). Cowley et al. (2005) showed that if the effective Pedersen conductivity of the polar ionosphere is $\sim 0.2$ mho or less then the theory of Isbell et al. (1984) predicts approximately zero corotation of the open field region. This is exactly what is shown in Fig. 1; thus the IR data (Stallard et al., 2003), the qualitative model (Cowley et al., 2003b) and the theory (Isbell et al., 1984) are in excellent agreement. The IR data is valuable because it provides an instantaneous ‘big picture’ to the plasma flows that in situ spacecraft data cannot.

2.2. Saturnian aurora models

The processes controlling Saturn’s aurorae are less well understood. In particular, there is no consensus as to the mechanism responsible for the main auroral oval. There are at present three principal models: the corotation-breakdown model of Hill (2005); the ‘reconnection model’ of Cowley et al. (2004) and the ‘centrifugal instability model’ of Sittler et al. (2006). We now describe each of these models in turn.

The Hill model supposes that the saturnian main auroral oval is formed by the same process as the jovian main auroral oval, namely the breakdown of rigid corotation in the middle magnetosphere and the associated current systems. Cowley et al. (2003a) have modelled these currents using Voyager data, calculating the expected magnitude and location of the upward currents in the ionosphere that might be associated with aurorae. They found, firstly, that these currents were located at too low a latitude to correspond to the observed main auroral oval and, secondly, that the strength of the currents was insufficient to produce the observed auroral emission intensity. However, they did conclude that some field-aligned acceleration of electrons would occur: this implies that there may be faint auroral emissions associated with corotation breakdown that have yet to be discovered. (It should be emphasised that these predictions are not definitive, being dependent almost entirely upon plasma flow and magnetic field data collected by the Voyager missions.) If the Hill model were responsible for the main auroral oval then we would predict the polar plasma flows to exhibit similar behaviour to that observed at Jupiter (Fig. 1), specifically that equatorwards of the main auroral oval the plasma flow should return rapidly to near-corotation.

Cowley et al.’s (2004) model proposes that the main auroral oval at $\sim 15^\circ$ colatitude corresponds to the boundary between open and closed field lines. Elements of this model have been supported by independent observations (Stallard et al., 2004; Kurth et al., 2005). This model predicts that the main auroral oval is associated with a velocity shear at the open–closed field-line boundary. There is no direct evidence for this velocity shear, since the Voyager plasma flow data only exists for closed field lines. Thus the success of the Cowley model lies in
Saturn’s $H_3^+$ auroral/polar emission compared with plasma flow models

Fig. 2. Dataset-averaged intensity (thin line) and velocity (bold line) profiles for the subset of the IRTF/Saturn dataset for which symmetric auroral ovals are observed. The frame of reference is the Sun–Saturn inertial frame (dashed line) and the diagonally hatched regions on the edge of the plot mark the calculated limb of the planet.

inferring a velocity shear of the scale necessary to generate the observed auroral emissions. If the Cowley model is responsible for the main auroral oval, then we would expect to observe a significant shear in the plasma flow velocity corresponding to the location of the main auroral oval at $\sim 15^\circ$ colatitude, such that the plasma velocity on the equatorwards side of the main auroral oval is closer to rigid corotation than that on the polewards side. Crucially, though, the plasma does not need to return to rigid corotation with the planet. The Cowley et al. (2004) model specifically proposes that it only returns to $\sim 80\%$ of rigid corotation. At higher colatitudes the degree of corotation is then predicted to decrease in regions that map to the middle magnetosphere, before eventually returning to rigid corotation at colatitudes of $\sim 25^\circ$.

The third and final model, proposed by Sittler et al. (2006), claims that the aurorae are associated with centrifugal instabilities in the outer magnetosphere. This model predicts that the aurorae map to $L \sim 15$. It does not, however, make any specific predictions concerning the morphology of plasma flows in the auroral/polar regions.

This paper aims to distinguish between these models—particularly the first two—using IR data. We now briefly describe this data, before comparing it to the predictions of the models described above.

3. Observations

3.1. Characterising the IRTF/Saturn dataset

In Stallard et al. (2007) we presented results from an extensive dataset of observations of the auroral/polar regions of Saturn using the high-resolution spectrometer CSHELL on the NASA Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii. The IRTF/Saturn dataset consists of measurements of emission from the $H_3^+ v_2 Q(1, 0^-)$ line at 3.953 microns. Further details of the observing processes used can be found in Stallard et al. (2007). For all the data in our dataset we used a long-slit spectrometer aligned West–East on the planet, with the slit cutting through the centre of the auroral region.

Fig. 2 shows the dataset averaged intensity and velocity profiles from dawn to dusk across the auroral oval, for those data sets that have approximately symmetric emission about the pole. Using Saturn’s rings as a guide of position, the limb of the planet is marked by the diagonally hatched regions on the edge of the plot. The $H_3^+$ emission intensity is shown (thin line) along with the associated line-of-sight velocity (bold line) displayed as a Doppler shift derived from the wavelength of the $Q(1, 0^-)$ line. In this figure, the frame of reference is the Sun–Saturn inertial frame and so, for reference, the rotation of the planet is marked (dashed line). The velocity has been set to zero at the centre of the planet, since it is not possible, using standard arc lines, to calibrate the wavelength of the spectroscope sufficiently accurately in the $Q(1, 0^-)$ spectral region. This limits us to discussing relative velocities, with the implicit assumption that the predominant winds are zonal, rather than meridional, an assumption that is borne out by modelling studies (Smith, 2006; Smith et al., 2007). Positive values represent a velocity towards the observer. In addition to this, vertical dotted lines demarcate selected sub-regions within the data. We use these conventions on all subsequent plots, whether observed or modelled.

Fig. 3 shows $H_3^+$ profiles taken on a single night, December 24, 2004, typical of many we have observed within the IRTF/Saturn dataset. Stallard et al. (2007) and Stallard et al. (2001, 2004) discuss errors associated with the derivation of ion velocities, and examples of pixel-to-pixel variation and the effects of boxcar smoothing are given in Appendix A. Further discussion of the profiles in Figs. 2 and 3 is given in Sections 3.3 and 3.4.
3.2. Interpreting velocity profiles

It is important to clarify exactly what these velocity profiles represent. The H$_3^+$ molecules in the ionosphere are in continual random motion at or around the characteristic thermal velocity: for a temperature of 400 K (Melin et al., 2007) this velocity is \( \sim 2 \text{ km/s} \). This random motion contributes to the width of the \( Q(1, 0^-) \) line, but not to the central wavelength. The observed Doppler shift represents the mean bulk velocity of the H$_3^+$ molecules along the line-of-sight. This bulk velocity is related both to the plasma drift velocity of the connected magnetosphere and to the local bulk neutral velocity. The parameter that determines this relationship is the ratio \( r = v_{\text{in}}/\omega_i \) between the ion-neutral collision frequency \( v_{\text{in}} \) and the ion gyrofrequency \( \omega_i \). The behaviour is best interpreted in a frame in which the bulk neutral velocity is zero. In this case there is a non-zero plasma drift velocity associated with a perpendicular electric field. If \( r \ll 1 \), then collisions are negligible and the ions will move at the plasma drift velocity. At lower altitudes, when \( r \approx 1 \), collisions with neutrals begin to liberate the ions to move in the direction of the electric field. Their motion is then a combination of motion in the direction of the plasma drift and motion in the direction of the electric field. At sufficiently low altitudes, where \( r \gg 1 \), the ions are fully coupled to the neutrals by collisions: in a general frame they thus move with the bulk velocity of the neutrals.

To interpret our profiles we need to know the value of \( r \) in the region of the ionosphere where the majority of the H$_3^+$ emission originates. We can state with reasonable confidence that most of the H$_3^+$ in the ionosphere exists at altitudes greater than 1000 km above the 1 bar level. This is the approximate location of the homopause, below which H$_3^+$ is destroyed efficiently by charge exchange with hydrocarbons. The value of \( r \) at 1000 km (calculated using the empirical model of Moses et al., 2000) is \( \sim 0.2 \). Thus we expect the vast majority of H$_3^+$ emission to originate in the region where \( r \ll 1 \). So our observed ion velocity profiles correspond to the plasma drift velocity, and are therefore a signature of the flows in the connected regions of the magnetosphere.

Our data show consistently that the ions within the auroral oval generally lag behind corotation with the planet, in agreement with the preliminary results of Stallard et al. (2004). To represent the magnitude of this sub-corotation, Stallard et al. (2007) introduced the parameter \( \Gamma_{\text{ion}} \). Assuming that the line-of-sight velocity at the centre of the planet is zero, this parameter then measures the average lag of the ions with respect to rigid corotation, defined as

\[
\Gamma_{\text{ion}} = \frac{\Omega_{\text{ion}}}{\Omega_{\text{Saturn}}},
\]

where \( \Omega_{\text{ion}} \) and \( \Omega_{\text{Saturn}} \) are the angular velocities of the ions and Saturn respectively \( (\Omega_{\text{Saturn}} = 1.638 \times 10^{-4} \text{ rad s}^{-1}) \). Fig. 2 shows that \( \Gamma_{\text{ion}} \) is a useful parameter for the averaged dataset. Fig. 3 shows that while it is possible to use a single-valued \( \Gamma_{\text{ion}} \) for this data, as in Stallard et al. (2004), it is not necessarily the best representation of the measured velocity profile for single nights. So Stallard et al. (2007) also introduced a further parameter \( \gamma_{\text{ion}}(\alpha) \), given by

\[
\gamma_{\text{ion}}(\alpha) = \frac{[\text{dv}_{\text{ion}}(\alpha)/d\alpha]}{[\text{dv}_{\text{ion}}(\alpha)/d\alpha]},
\]

where \( \alpha \) is the distance from the North–South centre line of the planet in arcseconds, i.e., the perpendicular distance from the projected planetary rotation axis along the CSHELL slit;
v\text{ion} is the ion velocity and \[\frac{[dv\text{ion}(\alpha)/d\alpha]^0}{d\alpha}\] is the value of \([dv\text{ion}(\alpha)/d\alpha]\) expected if the ions were rigidly corotating with the planet. Thus \(\gamma_{\text{ion}}(\alpha)\) provides a way of characterising sub-regions across the auroral/polar region itself, when a single value of \(\Gamma_{\text{ion}}\) will not suffice; Fig. 3 makes use of this characterisation. Note that \(\gamma_{\text{ion}}(\alpha)\) is a purely empirical, phenomenological parameter, introduced to simplify the characterisation of our data and to enable us—as we shall show later—to make simple calculations of energy inputs due to Joule heating and ion drag.

Fig. 2 shows that the general morphology of the infrared emission intensities that we observe correlates well with a roughly symmetric auroral oval as seen in UV data. However, in comparing these datasets caution must be observed. The only infrared images of Saturn’s aurorae, taken by Cassini, are not of high enough resolution to properly compare with the UV. No infrared images from the Earth exist, because the auroral emission from Saturn is too weak in intensity. However, in the absence of better information it seems reasonable to assume that both sets of emissions are related to the same auroral processes. We now discuss the profiles given in Figs. 2 and 3 in more detail.

3.3. Dataset-averaged profiles

Firstly, we look at the average behaviour of the plasma flows. Fig. 2 shows the intensity and velocity profiles averaged over the subset of the dataset for which approximately symmetric auroral ovals are observed. [This figure is taken from Fig. 5 of Stallard et al. (2007).] The main auroral oval peaks in intensity around 1.0” to 1.5” about the centre of the planet. But there is still 25% or more of the peak intensity at 4” from the centre of the planet. Over the dataset, the equatorial diameter of Saturn ranged from 17” to 21 “, with an average of 19”. Data from separate nights may also be from differing slit positions, and cover varying auroral morphology. As such, a specific colatitudinal range cannot be given for this plot. However, Saturn’s equatorial diameter is 120,536 km, so 1” is equivalent to an average of \(\sim6000\) km across our dataset. These considerations mean that the dataset-averaged intensity profile begins to fall off at a colatitude of \(\sim7.5^\circ\), about half the 15° colatitude value normally taken to represent the main auroral oval as seen in UV images (Cowley et al., 2003a). Furthermore, the ‘flanks’ of the IR auroral oval extend at least to a colatitude of 25°, considerably equatorward of the UV reference oval. This means that our averaged intensity and velocity profile sample the whole of the auroral/polar region discussed by Cowley et al. (2003a). It is thus appropriate to use it to distinguish between flow signatures predicted by the Hill and Cowley models. A single value of \(\Gamma_{\text{ion}}\) is a good fit to the ion velocity over the entire region that this averaged profile samples, extending beyond a colatitude of 25°.

3.4. December 24, 2004 profile

In this paper, we will concentrate on the intensity and velocity profile averaged over the entire night’s data obtained on December 24, 2004, shown in Fig. 3. This profile is typical of the symmetric auroral ovals observed in our dataset. The profile was fitted previously by a single-valued \(\Gamma_{\text{ion}}\) parameter, to show the lag to corotation across the entire saturnian auroral/polar region. The value obtained for \(\Gamma_{\text{ion}}\) was 38% (Stallard et al., 2007), matching reasonably well with the prediction by Cowley et al. (2004) that the plasma drifts in this region would correspond to a \(\Gamma_{\text{ion}}\) of 25%. Our effective seeing—made up of the actual atmospheric seeing conditions and the effects of any drift in the telescope tracking and pointing—was 1.4”. Our best fit to the observed ring intensity then placed the CSHELL slit \(\sim0.3^\circ\) ‘below’ the southern rotational pole, i.e., slightly displaced towards midnight. Note that this amount is only 60% of the actual slit width of 0.5”.

On December 24, 2004, the equatorial diameter of Saturn spanned 20.4” on the sky, making 1” equivalent to 5910 km. The oval—indicated by the intensity peaks—extends 1.8” on either side of the pole, corresponding to a colatitude of \(\sim10^\circ\), comparable to the UV reference oval, if somewhat compressed. In this example, the duskside peak of the auroral oval is about 25% brighter than the dusk. The dawn flank at colatitude 25° (\(\alpha = -4^\circ\) on the figure) is >20% of the dawnside auroral peak intensity; the dusk flank is even brighter. So while we classify this auroral oval as ‘symmetric’ within the range of our overall dataset, it is clear that there remains a degree of asymmetry.

4. Model–data comparison

We now use the data we have presented to assess the validity of the Hill and Cowley models of the main auroral oval. The Sittler model does not make sufficiently detailed predictions to be testable using our data.

4.1. Hill model

As discussed in Section 2, the characteristic flow signature of the Hill model is a rapid return to almost rigid corotation immediately equatorwards of the main auroral oval. This signature is not observed in any of the data presented above. In the case of the symmetric, averaged profile (Fig. 2) and the symmetric profile from December 2004 (Fig. 3), typical of the majority of profiles across our dataset, the flow does not return to rigid corotation at all within the range of colatitudes that we observe. We believe that this represents strong evidence that the Hill model is not responsible for the generation of the main auroral oval at Saturn.

4.2. Cowley model

The characteristic signature of the Cowley model is a significant velocity shear in the region of the main auroral oval, corresponding to the open–closed field line boundary. The plasma on the equatorwards side of this velocity shear must be closer to rigid corotation than that on the polewards side. Crucially, though, the velocity does not need to fully return to rigid corotation to support the Cowley model.

Such a signature is not present in any of the data presented here. We would not expect to see this signature in the averaged data, because the open–closed field line boundary is expected to move in latitude depending upon the quantity of open flux.
Fig. 4. The auroral velocity predicted by the Cowley et al. (2004) mechanism and the intensity, modelled as a thin, bright oval located at 15° colatitude, which corresponds to the boundary of open and closed field lines. Both are shown as they would appear from Earth, with the slit positioning (0.3″ below the South pole) and effective seeing (1.4″) calculated for December 24, 2004.

present in the system. However, we may expect to observe the signature in the individual night profiles—and we do not.

At first this appears to rule out the Cowley model. However, the resolution of our data is limited by the seeing of ~1″, which corresponds to distances of ~6000 km on the surface of the planet. The region of enhanced rotation equatorwards of the main auroral oval in the Cowley model is predicted to be only of the order of 3000 km, which subtends just 0.5″ at the distance to Saturn, so it is possible that this flow region exists, but is spatially unresolved in our data. The Cowley model also includes plasma flows that we can compare to the overall structure of our data. This model provides an axi-symmetric representation of the velocity structure in the polar cap, using Voyager PLS data (Richardson, 1986) as a guide to the degree of sub-corotation on closed field lines, and our own preliminary results (Stallard et al., 2004), as a guide to the degree of sub-corotation in the polar cap, which in the Cowley model corresponds to open field lines. We do not address subsequent modifications of this model that take into account local time asymmetries (Jackman and Cowley, 2006) and the variable rotation of the neutral upper atmosphere (Smith, 2006).

Fig. 4 shows the intensity and velocity profiles predicted by Cowley et al. (2004), as they would appear if measured as part of the infrared database presented in (Stallard et al., 2007), with the slit positioning (0.3″ ‘below’ the South pole) and effective seeing (1.4″) calculated for December 24, 2004. For the Cowley et al. (2004) model, the main auroral oval, which maps to the open–closed field line boundary, can be clearly seen in the intensity profile—the centres of the UV oval on the dawn and dusk sides are marked by the inner two dashed lines in Fig. 4. Poleward of this, in the polar cap, is a region of open field lines associated with no emission and velocities that are set, before accounting the effect of seeing, to correspond to 30% of corotation; the polar cap emission produced in this profile results solely from the modelled effects of seeing. Equatorward of the main oval—between the inner and outer dashed lines on the dawn and dusk side—is a smaller region where the ion velocities return towards 80% of corotation. This is associated with the Dungey cycle return flow and Vasyliunas cycle flow regions in the outer closed field magnetosphere. Beyond this, extending down to a colatitude of ~25°, is a region which exhibits a greater departure from rigid corotation of ~50%, associated with the breakdown in rigid corotation within the middle magnetosphere.

In Fig. 5, we compare this predicted intensity and velocity structure with the data from December 24, 2004. So that the effects on the planet can be better understood, we have transposed both velocity profiles into the frame of reference that corotates with the planet. The intensity structure of these two profiles appears similar, but the observed intensity has two major differences:

1. The observed high-latitude region in the polar cap has a considerably higher level of H_3^+ emission than can be modelled by convolving the UV oval geometry with seeing effects.
2. The intensity falls off much more slowly at colatitudes greater than 15°. While UV images of the aurora generally show a discrete auroral oval that lies over a dark planet, early observations of Saturn’s IR aurora have shown some emission at mid-high colatitudes, tailing off from the main auroral oval (Stallard et al., 1999). These observations confirm this finding.
Saturn’s $H_3^+$ auroral/polar emission compared with plasma flow models

Fig. 5. Intensity and velocity profiles shown in Figs. 3 and 4, transposed into the frame of reference that corotates with Saturn. Top: Profiles based on the Cowley et al. (2004) model. Bottom: December 24, 2004 profiles.

The modelled (top) and observed (bottom) velocity profiles in Fig. 5 are also broadly similar. We note the following differences, however:

1. In the central polar cap the observed profile shows rigid corotation with the planet, whereas the modelled profile shows sub-corotation of 30%. The observed rigidly corotating region extends more towards the dawnside than the duskside.

2. On the duskside, the observed profile sub-corotates significantly more than the model across the region of the main auroral oval and at higher colatitudes. Whereas the modelled profile begins to return towards rigid corotation at the edge of the plot, the observed profile does not.

3. On the dawnside, the observed profile matches the model well at the location of the main auroral oval. At higher colatitudes, the observed profile again shows no return towards rigid corotation, as on the duskside.

So, while our data broadly supports the Cowley et al. (2004) model, the detailed flow structures do not match exactly. The most intriguing of these anomalies is the corotation in the central polar cap. It is to this that we now turn.
5. Corotation in the central polar cap

5.1. Model of the open field region

None of the models of Saturn’s main auroral oval make any detailed predictions concerning the plasma flows occurring on field lines inside the main auroral oval. If we assume that either the Cowley or Sittler model is correct, as the above discussion strongly indicates, then this region corresponds mostly to open field lines. The expected behaviour of these field lines is then described by the theoretical treatment of Isbell et al. (1984).

This treatment supposes that field lines open to the solar wind are constrained at the solar wind end to move steadily anti-sunwards, while at the planetary end they are in partial corotation with the planet. Thus the field lines become twisted. The field-aligned tail currents necessary to generate the twist in the field lines must close as Pedersen currents in the ionosphere. These Pedersen currents are themselves generated by the differential rotation velocities of the plasma and neutrals in the polar cap. This situation leads to a simple relationship between the solar wind velocity, the effective ionospheric Pedersen conductivity, and the degree of corotation of the plasma in the polar cap.

This theory was used by Cowley et al. (2003a, 2004) to predict that, if the effective Pedersen conductivity of the ionosphere in the polar cap were ~1 mho, the ionosphere should rotate with ~30% of the planetary angular velocity. As previously mentioned, this value is broadly consistent with our \(\Gamma_{\text{ion}}\) values. However, for near-corotation of the plasma in the central polar cap to be observed, the effective Pedersen conductivity in this region must be much higher—90% corotation requires an effective Pedersen conductivity \(\Sigma_{P} \sim 20\) mho and 95% corotation requires \(\Sigma_{P} \sim 40\) mho. For this simple theory to describe the region of corotation observed in the central polar cap, there would have to be a region of considerably enhanced ionospheric conductivity at these latitudes. There seems no obvious mechanism that could generate such a highly localised enhancement. An alternative is that the rotation of this region of the polar cap is not determined by the processes described by Isbell et al. (1984). We now explore such a scenario.

5.2. Structure of the magnetotail

A possible explanation of our data is suggested in Milan et al. (2005). This study pointed out that the twisting of the tail field lines described by Isbell et al. (1984) would result in a ‘core’ of field lines at the centre of each of the magnetotail lobes that is shielded from tail reconnection by the surrounding field lines. This situation is shown schematically in Fig. 6. The core field lines might thus only undergo tail reconnection occasionally, perhaps during the passage of large compressions in the solar wind.

The postulated existence of this central core to the magnetotail offers an explanation of our ‘three-tiered’ velocity structure. We propose that the corotating region at the centre of the December 2004 data corresponds to this core of field lines. To justify this proposition, we must consider in more detail the behaviour of this core of field lines. As already mentioned, these field lines may remain open for long periods of time, perhaps until a major compression in the solar wind leads to reconnection penetrating throughout the twisted magnetotail. Such compressions occur approximately every 30 days at Saturn (Jackman et al., 2004). If the open field lines in the core increase in length at the velocity of the solar wind (~600 km/s) then 30 days is sufficient for them to extend \(1.5 \times 10^9\) km, or roughly to the orbit of Uranus. They thus extend out to much greater distances in the tail than the open field lines in the younger outer layer of the magnetotail. We contend, for reasons to be discussed further below, that the length of the ‘core’ is so great that the solar wind velocity ceases to be an important influence on the rotation velocity of the ionosphere connected to these field lines. If so, there is nothing to prevent the ionosphere and near magnetotail from being driven into corotation with the neutral upper atmosphere. The central region of corotating ionosphere in our data is then easily identified with the core of corotating magnetotail flux tubes.

We now present a simple argument to justify our assertion that the solar wind does not control the rotation of the core. As mentioned above, the rotation velocity of open field lines is jointly determined both by the solar wind velocity and by conditions in the ionosphere. In the Isbell et al. (1984) formulation, the system of field-aligned currents that mediate this interaction must simultaneously satisfy related conditions in the
ionosphere and in the far tail. It is the simultaneous satisfaction of these conditions that determines the rotation velocity of the ionosphere. In order for this to occur it is clear that the ionosphere and the far tail must be able to exchange information about their respective states on a timescale that is short compared with any changes in these states.

In the case of newly opened flux, it seems reasonable to assume that this is the case, since the distances involved are only of a few tens of planetary radii. However, in the case of a 30-day-old core of open flux the assumption is worth questioning. The maximum speed at which information may propagate along the tail is given by the Alfvén speed. A robust upper limit to the Alfvén speed is, of course, the speed of light, \( c = 300,000 \text{ km/s} \). If the core extends for \( 1.5 \times 10^9 \text{ km} \), as discussed above, then the one-way light propagation time is \( \sim 1 \text{ h} \). It must, therefore, take at least two hours for the ionosphere and the far tail to perform the necessary information exchange. This is an absolute lower limit. For Alfvén speeds a few times slower than \( c \), the information exchange time is comparable to the time required for one planetary rotation. We contend that under these circumstances the rotation of the ionosphere connected to the core flux tubes must be controlled by short timescale in situ processes—namely collisions between ions and neutrals—rather than by the exchange of Alfvén waves with regions of the solar wind located at or beyond the orbit of Uranus.

We have reached this conclusion using a somewhat general argument, but we feel that it captures the essence of the issue. It is evident, however, that the theory of the twisted magnetic field lines associated with newly opened flux on Saturn’s polar upper atmosphere from Joule heating and ion drag \( H_{\text{elec}} \), using the expression given by Miller et al. (2005):

\[
H_{\text{elec}} = 2\pi \Sigma_\text{P} B^2_{\text{aur}} \int_0^{v_i^2} \frac{r}{\Omega_{\text{Sat}}} dr,
\]  

Fig. 7. The annulus model of sub-corotation in the polar cap. The ion velocity in the inertial frame (solid line) is plotted as a function of distance from the pole, \( r \). This can be contrasted against the velocity of rigid corotation (dashed line). The ion velocity in the corotating frame, \( v_i \), is the difference between the two velocity profiles shown, as indicated by the arrow.

where \( \Sigma_\text{P} \) is the effective Pedersen conductivity (which we take to be \( 1 \text{ mho} \)), \( B_{\text{aur}} \) is the magnetic flux density (for which we take a representative value of \( 6.5 \times 10^{-5} \text{ T} \)); \( v_i \) is the corotation lag of the ions—i.e., the velocity of the ions in the frame corotating with the planet; and \( r \) is the distance from the spin axis.

Assuming that the polar ionospheric flows are well represented by a constant \( \Gamma_{\text{ion}} \), the corotation lag of the ions is given simply by

\[
v_i = \Omega_{\text{Sat}}(1 - \Gamma_{\text{ion}}) r,
\]  

where \( \Omega_{\text{Sat}} \) is the angular velocity of Saturn, \( 1.638 \times 10^{-4} \text{ radian s}^{-1} \), and we then find, integrating Eq. (3) across the auroral/polar region from the pole at \( r = 0 \) to the main oval (which we take to lie at \( R_{\text{oval}} = 1.56 \times 10^7 \text{ m} \)):

\[
H_{\text{elec}} = \pi / 2 \Sigma_\text{P} B^2_{\text{aur}} \Omega_{\text{Sat}}^2 [1 - \gamma_{\text{ion}}]^2 R_{\text{oval}}^4 = H_0 [1 - \Gamma_{\text{ion}}]^2.
\]  

6. Energy inputs to the upper atmosphere

We now use our data to estimate the probable electromagnetic energy inputs into the polar upper atmosphere associated with our measured ion velocity profiles. In particular, we extend the analysis of Stallard et al., 2007 to include the effects of the structure observed in the velocity profiles close to the pole.

We also simplify the calculation by taking the auroral/polar region to be flat, ignoring the small but complicated correction that would be necessary to take into account the curvature of the planet.

6.1. Theory

In Stallard et al. (2007), we calculated the total energy input to Saturn’s polar upper atmosphere from Joule heating and ion drag \( H_{\text{elec}} \), using the expression given by Miller et al. (2005):

\[
H_{\text{elec}} = \pi / 2 \Sigma_\text{P} B^2_{\text{aur}} \Omega_{\text{Sat}}^2 [1 - \gamma_{\text{ion}}]^2 R_{\text{oval}}^4 = H_0 [1 - \Gamma_{\text{ion}}]^2,
\]

where \( H_0 = 10.57 \text{ TW} \). \( H_0 \) represents the total heating if \( \Gamma_{\text{ion}} = 0 \), i.e., if there is zero corotation of the plasma in the polar cap.

In practice, \( \Gamma_{\text{ion}} \) is observed to be non-zero. In Stallard et al. (2007) we took a value of \( \Gamma_{\text{ion}} = 0.43 \), implying \( H_{\text{elec}} = 3.44 \text{ TW} \).

However, the foregoing discussion indicates that assuming a single value \( \Gamma_{\text{ion}} \) is often not a good approximation. To re-evaluate \( H_{\text{elec}} \) taking into account the structure in the auroral/polar region, we adopt an annulus model (Fig. 7) in which a central region \( 0 < r < r_1 \) is characterised by \( \gamma_{\text{ion}} = \gamma_{\text{inner}} \), and an outer annulus \( r_1 < r < R_{\text{oval}} \) by a different \( \gamma_{\text{ion}} = \gamma_{\text{annulus}} \). Thus the ion velocity is given by

\[
v_i = \Omega_{\text{Sat}}(1 - \gamma_{\text{inner}}), \quad \text{for } 0 < r < r_1,
\]

\[
v_i = \Omega_{\text{Sat}} r(1 - \gamma_{\text{inner}}) + (r - r_1)(\gamma_{\text{inner}} - \gamma_{\text{annulus}}),
\]

\[
\text{for } r_1 < r < R_{\text{oval}}.
\]
Integrating Eq. (3) using these values yields the following formula for $H_{\text{elec}}$:

$$H_{\text{elec}} = H_0 (\gamma_{\text{inner}} - \gamma_{\text{annulus}})^2 F(\beta, \Delta),$$

(7)

where

$$\beta = r_i / R_{\text{oval}},$$

(8a)

$$\Delta = (1 - \gamma_{\text{inner}}) / (\gamma_{\text{inner}} - \gamma_{\text{annulus}}),$$

(8b)

and

$$F(\beta, \Delta) = (1 + \Delta)^2 - 8\beta(1 + \Delta)/3 + 2\beta^2 - \beta^4(1 - 2\Delta)/3.$$  

(9)

Equation (7) of course reduces to Eq. (5) if we set $\beta = 0$, $\gamma_{\text{annulus}} = \Gamma_{\text{ion}}$ or $\beta = 1$, $\gamma_{\text{inner}} = \Gamma_{\text{ion}}$. We can estimate $\beta$ by noting that $\beta = r_i / R_{\text{oval}}$, where $r_i$ and $R_{\text{oval}}$ are the distances taken from the regions as delineated in Fig. 3 and are expressed in arcseconds.

6.2. Energy inputs for the different profiles

Using Eq. (7) we can now calculate the energy inputs for the profile shown in Fig. 2, for the published $\Gamma_{\text{ion}}$ value of 38% for December 24, 2004, and for the asymmetric profile shown in Fig. 3. The results of this calculation are shown in Table 1. We have calculated dawn and dusk values separately, in order to take into account the velocity asymmetry in the profiles. To calculate each of the dawn and dusk values we use Eq. (7), but halve the result. Thus we are assuming that the ion velocity values that we measure are representative of the ion velocities at all longitudes within the dawn and dusk portions of the polar cap, respectively.

The total energy input due to the average symmetric profile of 3.32 TW is, unsurprisingly, essentially identical to the value of 3.44 TW calculated in Stallard et al. (2007). The energy input calculated for December 24, 2004 using a single sub-corotation value is 4.06 TW. This is significantly larger than the average profile because the ions are sub-corotating, suggests that there must be significant day-to-day variation in the energy inputs to the polar cap given the 0.3–0.5 range of $\Gamma_{\text{ion}}$ values published in Stallard et al. (2007).

The effect of the structures in the central polar cap is to significantly decrease the total energy input to 2.92 TW. This is a ~10% decrease compared to the average case and a ~30% decreases to the energy input calculated using a single $\Gamma_{\text{ion}}$ value.

Comparing the dawn and dusk energy inputs, we can see that the dusk value is three times the dawn value. This is a clear consequence of the near-corotating region being concentrated on the dawn side of the polar cap, reducing the heating in that region. Thus while the total difference in energy input between the symmetric and asymmetric profiles is large, almost all of this difference is due to a drop in energy input on the dawn side.

6.3. Consequences for thermospheric dynamics

This imbalance in the energy inputs within the polar cap may have significant implications for the dynamics of the upper atmosphere in this region. Some of the characteristics of the thermospheric winds in the polar cap have recently been discussed by Smith et al. (2007). They showed that the net effect of the electromagnetic energy inputs on the thermosphere is to produce a concentrated ‘hottspot’ at the pole, while cooling subauroral latitudes. However, their model is axially symmetric, so does not take into account the possible effect of asymmetries in the energy inputs such as we have calculated above. If the greater energy input on the dusk side is a persistent phenomenon, then we would expect a thermally driven wind across the polar cap from the dusk side to the dawn side.

Additionally, if there is a substantial region of ionosphere surrounding the pole with which the plasma rigidly corotates, then we expect the sub-corotational ion drag in this region to be considerably reduced. We would then expect that in this region the polewards flows and corresponding compressional heating will also be reduced. This may significantly alter the flows described by Smith et al. (2007), with important consequences for the thermal structure of the upper atmosphere. However, accurately determining these effects would require careful numerical modelling of the thermosphere that is beyond the scope of this study.

7. Conclusions

In this paper we have carried out a more detailed analysis of some of the $\text{H}_3^+$ intensity and velocity profiles contained in the IRTF/Saturn dataset, with a view to understanding the magnetospheric processes with which they are connected. This paper has extended the observation made in Stallard et al. (2007) of the need to interpret velocity profiles in terms of regions with varying lags to corotation, making use of the $\gamma_{\text{ion}}(\alpha)$ parameter instead of the single value $\Gamma_{\text{ion}}$. This detailed examination of the intensity and velocity profiles has given considerable insight into the mechanisms at work producing the observed emission and plasma flows in the auroral polar region.

Table 1
The electromagnetic energy inputs into the polar upper atmosphere associated with our measured ion velocity profiles (Figs. 2–3) calculated using Eq. (7)

<table>
<thead>
<tr>
<th>$\gamma_{\text{inner}}$</th>
<th>$\gamma_{\text{annulus}}$</th>
<th>$\alpha_i$</th>
<th>$\beta$ = $\alpha_i / R_{\text{oval}}$</th>
<th>$H_{\text{elec}}$ (TW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average dawn</td>
<td>0.44</td>
<td>–</td>
<td>3.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Average dusk</td>
<td>0.44</td>
<td>–</td>
<td>3.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Average total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dec constant dawn</td>
<td>0.38</td>
<td>–</td>
<td>3.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Dec constant dusk</td>
<td>0.38</td>
<td>–</td>
<td>3.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Dec constant total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dec annulus dawn</td>
<td>0.91</td>
<td>0.3</td>
<td>1.4</td>
<td>0.44</td>
</tr>
<tr>
<td>Dec annulus dusk</td>
<td>0.91</td>
<td>0.3</td>
<td>0.2</td>
<td>0.06</td>
</tr>
<tr>
<td>Dec annulus total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes. For December 24, 2004 we have used both a constant rate of sub-corotation and the varying regions of sub-corotation shown in Fig. 3. We have calculated dawn and dusk values separately, in order to take into account the velocity asymmetry in the profiles.
Saturn’s $H_3^+$ auroral/polar emission compared with plasma flow models

Fig. 8. Intensity and velocity profiles from December 24, 2004, showing the effect of various boxcar smoothing. (a) No smoothing; (b) 3-pixel smoothing; (c) 5-pixel smoothing; (d) 7-pixel smoothing. Note that 1 pixel is 0.2′′, equivalent to ~1200 km at Saturn.

In particular, we have been able to show:

- That the $H_3^+$ intensity and velocity profiles are incompatible with the Hill model of the main auroral oval, in which it is associated with middle magnetosphere corotation enforcement currents.
- That it is possible, sometimes, to find additional auroral emission at lower latitudes than the main oval that is compatible with the Hill model.
- That there is often a region of the ionosphere in the central polar cap in rigid corotation with the planet; we suggest that this may represent the ionospheric footprint of the ‘core’ of the southern magnetotail lobe.

It is clear that these conclusions point to the further need to correlate $H_3^+$ (and UV) measurements of Saturn’s auroral/polar regions with conditions in the magnetosphere and in the solar wind, if we are to further develop our understanding of the important coupling processes at work. Cassini’s magnetometer and plasma instruments have been providing information on these conditions at Saturn since 2004, and we will look at correlations between the spacecraft’s measurements and the IRTF/Saturn dataset in forthcoming publications.

Acknowledgments

This work was supported by the UK Particle Physics and Astronomy Research Council, with postdoctoral fellowships for T.S. and N.A., a CASE studentship for C.S., and a senior fellowship for M.D. H.M. was supported by a postgraduate studentship from the UK Engineering and Physical Sciences Research Council. T.S., S.M., H.M. and M.L. were visiting astronomers at the NASA Infrared Telescope Facility which is run on behalf of NASA by the Institute for Astronomy, University of Hawaii. The IRTF telescope operators Dave Griep, Bill Golisch and Paul Sears are warmly thanked for their continued support and expert advice in making these observations possible. The team reporting here is part of the Europlanet European planetary science network, which is support by the European Union’s Framework 6 programme. Europlanet colleagues are thanked for their very helpful discussions during the preparation of this paper. We would also thank the referees for their detailed comments on our work.

Appendix A. Pixel-to-pixel variability of ion velocity profiles, and the effects of smoothing

The errors in deriving ion velocities from CSHELL have been discussed by Stallard and co-workers on previous occasions (Stallard et al., 2001, 2004, 2007). These may be as much as ±600 m/s for an individual pixel, but are considerably reduced by the process of boxcar smoothing. This process, however, results in a loss of detailed spatial information. In papers concerning the ion velocity structure in the auroral/polar upper atmosphere of Jupiter and Saturn, we have therefore concentrated on regions that behave in a relatively uniform fashion—the auroral oval peaks and the Dark Polar Region for Jupiter, for example, and the regions characterised either by $I_{ion}$ or $v_{ion}(\alpha)$ for Saturn. In Fig. 8 we show the raw velocity (and intensity profiles) for the data collected on December 24, 2004 and the effects of smoothing by 3, 5 and 7 pixels, respectively. Fig. 8a shows that there is considerable pixel-to-pixel variation, particularly at sub-auroral oval latitudes, for both the intensity and velocity profiles. But smoothing by a 3-pixel average, a typical value of the seeing on Mauna Kea, and corresponding to 0.6′′ or ~3600 km on Saturn, makes the $v_{ion}(\alpha)$ regions in the velocity profile clearly distinguishable. This paper uses 5-pixel smoothing, equivalent to 1.0′′ or ~6000 km on Saturn.
to allow for the additional ‘smearing’ of the data due to drift in the telescope pointing; 7-pixel smoothing essentially results in no appreciable difference from the 5-pixel case, except at the lowest latitudes for which we can measure appreciable H$_3^+$ emission.

References


