Simultaneous multi-scale and multi-instrument observations of Saturn's aurorae during the 2013 observing campaign

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Abstract

On 21 April 2013, during a co-ordinated Saturn auroral observing campaign, the northern and southern poles of the planet were observed from the NASA Infrared Telescope Facility (IRTF), Keck, and Hubble Space Telescope (HST) simultaneously with the Cassini infrared, visible, and ultraviolet remote sensing instruments. We present simultaneous multi-scale and multi-wavelength analysis of the morphology of auroral emissions at Saturn. There is variability on every spatial and temporal scale analysed, and high spatial resolution observations distinguish variable features with sizes tens of km on the planet. The fine scale temporal and spatial features seen in the main oval itself show that complex structures present even during quiet solar wind conditions. We observe diffuse ultraviolet emissions southward of the southern midnight main oval that are not seen in the infrared. This implies a steep temperature gradient, ~ 60 K over $2\text{--}4^\circ$ latitude equatorward of the main oval. Lower spatial resolution observations reveal broad-scale dynamics at both poles, variable over minutes to hours, the morphology of which is only partly consistent with a overlapping local-time fixed and co-rotating current systems. We also present the

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Figure 1: The UT intervals on 21 April 2013 (2013-111) during which a particular instrument was acquiring data. The arrow in the illustration of Saturn at the bottom indicates the azimuth of the effective southern PPO dipole direction ($\phi_S = 85^\circ$ at 07:00 UT, as measured duskward from noon). The arrow shows the rotation of the planet as seen from above the northern pole, with the Sun towards the bottom. Note that 10:00 UT corresponds to midnight in Hawaii Standard Time, the time-zone of the IRTF and Keck telescopes.

first direct comparison of simultaneous infrared, visible, and ultraviolet auroral emissions at Saturn. These emissions are co-located, even though the spatial scale and operational mode of each instrument are very different.

Keywords: Saturn, Atmosphere, Magnetosphere, Aeronomy

1. Introduction

The upper atmosphere of Saturn is mostly composed of atomic and molecular hydrogen. The ionised part of the upper atmosphere, the ionosphere, is dominated by H^+ (protons) and H_3^+ . When energetic electrons enter the upper atmosphere of a giant planet, by way of precipitation delivered along the magnetic field lines, they can either excite or ionise the constituents therein. Badman et al. (2014) reviews the auroral process in detail.

Auroral emission in the ultraviolet is the result of the interaction between the atmosphere and precipitating electrons. The secondary electrons resulting from this interaction excite the molecular hydrogen which produce photons in the 70-180 nm range (Gérard and Singh, 1982; Tao et al., 2011). A part of this emission, mainly below 135 nm, is attenuated by the hydrocarbon layer situated at or above the aurora. The level of absorption, mea-

Instrument	Start Time	End Time	Exposures
NASA IRTF CSHELL	06:55	13:50	75×120 s
Keck NIRSPEC	09:26	12:29	57×60 s
HST ACS Orbit 1	11:38	13:14	2 groups of 5×100 s
HST ACS Orbit 2	12:21	13:56	2 groups of 5×100 s
Cassini VIMS	08:38	12:19	3 groups of $64 \times 64 \times 1$ s
Cassini UVIS	08:40	14:53	373×60 s
Cassini ISS	08:40	09:41	37×180 s

Table 1: The simultaneous remote sensing observations of Saturn analysed in this study for 2013-111. This is presented as a time-line in Figure 1. The times of the IRTF, Keck, and HST observations are adjusted to be equivalent to UT at time of emission from the planet’s ‘surface’.

12 sured by the color ratio $CR=I(155\text{-}162\text{ nm})/I(123\text{-}130\text{ nm})$, where I is the brightness in a
13 certain spectral range, is directly correlated to the penetration depth of the precipitating
14 electrons. When no absorption is observed, the CR of the emergent emission is 1.1 (Gustin
15 et al., 2013, and references therein). Atomic hydrogen is also excited in a similar way,
16 producing H Ly- α in the ultraviolet and H Ba- α in the visible, amongst other emissions.

17 When molecular hydrogen undergoes ionisation, it is rapidly converted to H_3^+ by the
18 exothermic reaction

19 where the energy required to produce H_2^+ is delivered either via energetic particles or solar
20 extreme ultraviolet (EUV) photons. The infrared intensity of the H_3^+ emission is both an
21 exponential function of ionospheric temperature (Neale et al., 1996; Miller et al., 2013)
22 and a linear function of the ionisation rate of H_2 , which quickly leads to the formation of
23 H_3^+ . The emission rate of H_3^+ is given by

$$I = N \frac{K^i}{Q(T)} \exp\left(-\frac{hc\omega_u^i}{kT}\right), \quad (2)$$

24 where N is the number of H_3^+ ions that are emitting thermal emission at temperature T , k
25 is Boltzmann’s constant, ω_u^i is the wavenumber of the upper energy level of the transition
26 i , $Q(T)$ is the temperature dependent partition function given by Miller et al. (2013),

27 and K^i is a composite constant determined by the properties of the transition i we are
28 considering – for more information see e.g. McCall (2001).

29 The analysis of auroral emissions in each wavelength band tells us about different
30 aspects of the precipitation process and how this injection of energy affects the makeup
31 of the upper atmosphere. The morphology tell us about where in the magnetosphere the
32 precipitation originates from, and via analysis of spectra, both infrared and ultraviolet, one
33 can monitor physical parameters like ion density, thermospheric temperature, precipitation
34 flux, and precipitation energy of the auroral primaries.

35 The time between photon impact and UV emission of H and H₂ is very short, about
36 10^{-2} s (Menager et al., 2010; Badman et al., 2014), giving an instantaneous view of the
37 precipitation process. In contrast, H₃⁺ radiates thermally and can have lifetimes of up to
38 500 s (Melin et al., 2011a), producing a temporally averaged view of the auroral emission
39 during the lifetime of the ion. Therefore, both integration times of the instrumentation and
40 the chemical lifetimes of the species concerned become important factors when comparing
41 simultaneous infrared and ultraviolet/visible auroral emissions.

42 For example, Melin et al. (2011a) analysed simultaneous infrared and ultraviolet ob-
43 servations of Saturn’s southern aurora at a high spatial resolution, and noted that outside
44 of the main oval emission, the intensity of H₃⁺ did not necessarily map well to that of
45 either H or H₂, with a diffuse equatorward oval being most prominent in H Ly- α . These
46 differences are likely attributable to both the fact that the intensity of emission of the H₃⁺
47 ion is strongly dependent on temperature, and that it has lifetimes of up to 500 s.

48 One of the most intriguing features of the Saturn system is the presence of rotating
49 period phenomena near the planetary rotation period, but with two separate periods that
50 slowly evolve with time, one associated with the northern hemisphere and the other with
51 the southern (Galoiseau and Lecacheux, 2000; Espinosa and Dougherty, 2000; Gurnett
52 et al., 2009; Provan et al., 2009; Andrews et al., 2010; Southwood and Cowley, 2014; Provan
53 et al., 2014) The signatures of these period phenomena, known as the planetary period
54 oscillations (PPO), are present in many observations, e.g. Saturn kilometric radiation
55 (SKR, Gurnett et al., 2009; Lamy et al., 2011), the infrared H₃⁺ aurora (Badman et al.,
56 2012b; Lamy et al., 2013), the ultraviolet H₂ aurora (Lamy et al., 2009; Nichols et al.,

2010a; Lamy et al., 2013; Bunce et al., 2014), the magnetospheric energetic electrons (Carbary et al., 2009), and the magnetospheric magnetic field (Provan et al., 2009), to mention but a few. Badman et al. (2012b) observed the intensity of the auroral H_3^+ emission in each hemisphere to be dependent on both local-time and the appropriate PPO phase. This is consistent with the superposition of two current systems, one fixed in the Sun-Saturn frame, the other rotating at the PPO period. The ultimate origin of the rotating current systems has been proposed to be driven by either the magnetosphere (Goldstein et al., 2014) or the atmosphere (Smith, 2006; Jia et al., 2012; Southwood and Cowley, 2014). In the latter case, it remains an open question what mechanism could provide the required relatively stable and sustained atmospheric vorticities (Smith, 2014).

The main auroral oval of Saturn maps near to the boundary between open and closed field-line (Cowley et al., 2004; Bunce et al., 2008; Carbary et al., 2008; Belenkaya et al., 2011). On, or close to this oval, there are a number of specific features that are attributed to separate processes. These include dawn brightened signatures of Dungey cycle plasma convection (Cowley et al., 2005), interactions between Saturn’s magnetosphere and the solar wind at the magnetopause (Gérard et al., 2005; Radioti et al., 2011; Badman et al., 2013; Meredith et al., 2014), and signatures of injections from the hot plasma populations in the night-side magnetosphere (Grodent et al., 2010).

H_3^+ was first detected at Saturn by Geballe et al. (1993) using the United Kingdom Infrared Telescope (UKIRT), whereas the ultraviolet emission was first discovered by a rocket-borne spectrograph in 1975 (Weiser et al., 1977). It was not until the arrival of the Cassini spacecraft that visible auroral emissions were discovered (Kurth et al., 2009).

The infrared, visible, and ultraviolet auroral emissions have been used in multiple studies as a diagnostic for the ionosphere–magnetosphere–thermosphere interaction but also as an in-situ diagnostic of the physical conditions in the thermosphere. See Bhardwaj and Gladstone (2000), Kurth et al. (2009), and Badman et al. (2014) for excellent overviews.

Lamy et al. (2013) analysed a set of radio, infrared, ultraviolet, and energetic neutral atom (ENA) Cassini observations over the duration of a full Saturn rotation. This set of observations coincided with an injection event in the magnetotail, producing dawn intensifications of the auroral oval, seen in both the infrared and ultraviolet remote sensing

87 data. They also noted features in the auroral emissions compatible with two superimposed
88 current systems, one fixed in local-time and one rotating at the PPO phase, as outlined
89 above.

90 Most remote sensing studies of Saturn’s aurora have used observations from a single
91 vantage point, obtained from either the surface of the Earth, low altitude Earth orbit, or
92 from the Cassini spacecraft in orbit at Saturn. By definition, such observations cannot get
93 a complete view of the northern and southern auroral ovals, since at least one portion of the
94 system is hidden from view. Ground-based observations are limited by always observing
95 the sunlit hemisphere, such that the effects of solar-related emissions cannot easily be
96 disentangled from those created by auroral processes. Gérard et al. (2013) analyzed near
97 simultaneous HST and Cassini auroral observations of the northern pole, deriving the
98 vertical column of methane, which required primary electron energies in the range 3 keV
99 to 20 keV. These energetic electrons would produce a peak auroral emission altitude of
100 just 640 km, lower than the 900 to 1300 km derived from HST images (Gérard et al.,
101 2009) and the 1100 km derived from infrared Cassini observations (Stallard et al., 2012).

102 Here, we compare the morphology of simultaneous remote sensing auroral observations
103 from the 2013 Saturn auroral observing campaign of both the dayside and nightside of
104 the planet. This is achieved by combining observations using ground-based infrared tele-
105 scopes, the Hubble Space Telescope, and infrared, visible, and ultraviolet remote sensing
106 instruments onboard the Cassini spacecraft.

107 **2. Observations**

108 The co-ordinated Saturn Auroral Observing campaign took place in April and May
109 2013, involving Cassini (remote sensing and in-situ instruments), the Hubble Space Tele-
110 scope (HST), the NASA Infrared Telescope Facility (IRTF), the W. M. Keck II, and the
111 Very Large Telescope (VLT). During these two months there was a variety of temporal
112 overlaps between observations using these instruments, but the 21 April 2013 (day-of-year
113 111, hereafter 2013-111) stands out as particularly interesting. On this day all but one
114 remote sensing instrument involved with this campaign observed over a period of 8 hours.
115 The missing facility is the VLT, which only acquired data on day 2013-131. Each instru-

a) view from Cassini

b) view from the Earth

Figure 2: Saturn as seen from a) the Cassini spacecraft and b) the Earth on 21 April 2013 (day-of-year 111) at 10:00 UT. Cassini is viewing the nightside, whereas the Earth views the sunlit hemisphere. During this interval the angular equatorial diameter of Saturn is $18.8''$ as seen from the Earth and 12.8° as seen from Cassini. Indicated in a) is the field-of-view FOV of the Cassini remote sensing instruments, shown in greater detail in Figure 3. Panel b) shows the FOV of the Keck NIRSPEC slit ($2.23 \mu\text{rad}$ or $0.46''$ wide), the IRTF CSHELL slit ($2.42 \mu\text{rad}$ or $0.5''$ wide), and the HST ACS (covering $35 \times 31''$ or $170 \times 150 \mu\text{rad}$). The dotted arrow shows the direction of Cassini.

Figure 3: The latitude and local-time projection of the Cassini VIMS infrared channel, the ISS Narrow Angle Camera (NAC), and the UVIS Far Ultraviolet (FUV) channel field-of-views as seen at 10:00 UT 2013-111, covering the midnight sector of the southern pole of Saturn. The view is through the planet from the north pole. For both VIMS and UVIS, each pixel is shown, whereas for ISS, each square contains 128×128 actual pixels. The grid has a spacing of 5° in latitude and 1 h in local-time. The spatial resolutions of these three remote sensing instruments are very different indeed, with the mean resolutions on the planet being 720, 280, and 14 km/pixel for UVIS, VIMS, and ISS respectively.

116 ment involved in this campaign has unique capabilities, revealing different aspects of the
 117 auroral process.

118 During 2013-111, the Earth-based platforms (IRTF, Keck, and HST) were observing
 119 the dayside of Saturn at the same time as Cassini was observing the nightside, providing an
 120 opportunity to measure simultaneous dayside and nightside auroral emissions in multiple
 121 wavelength bands. The time-line of the observations can be seen in Figure 1, with the
 122 geometry being shown in Figures 2 and Figure 3.

123 Table 1 details the observations analyzed in this study and Table 2 summarises the
 124 capabilities of each instrument. Granular details on how the instruments operate and

the data reduction can be seen in Appendix A. It is important to note that none of the instrument offers the same capability, each having slightly different operational modes and angular resolutions. As we shall see, this imposes limits on the comparative science that can be achieved.

On figures detailing the observations, where it is appropriate, the azimuth of the northern and southern PPO phase, ϕ_N and ϕ_S respectively, are shown at various times in a view looking down onto the north pole with noon at the bottom. These vectors show the direction of the quasi-uniform equatorial perturbation magnetic fields associated with the PPOs at these times, as well as the direction of the effective transverse dipole associated with the corresponding polar field perturbation (e.g. Andrews et al., 2010). They rotate at the corresponding PPO period in the sense as planetary rotation. The specific phases employed here were derived from concurrent Cassini magnetic field data by Provan et al. (2014). The rotation periods are 10.641 h for the northern system and 10.694h for the southern. The maximum upward field-aligned current (FAC) associated with these rotating magnetic fields is located at $\phi_S + 90^\circ$ in the south and $\phi_N - 90^\circ$ in the north (Andrews et al., 2010). We define the PPO longitude, $\Phi_{N,S}$, to be the angle between a point on the planet and the azimuth of the PPO phase, $\phi_{N,S}$, with the positive sense being the same as that of IAU System III longitudes.

Since auroral emission is expected to be driven by the upward FACs (e.g. Bunce et al., 2008), these are also locations of increased auroral brightness (Badman et al., 2012b; Nichols et al., 2010a). A comparison between the expected enhancement in brightness, governed by the phase of $\phi_{N,S}$, and the observed auroral brightness, as seen in both the infrared and the ultraviolet, is explored in Section 3.3.

In the following sections we describe the morphology of the auroral emission as observed through each instrument’s FOV. Table 3 summarizes the key findings of each observation.

2.1. Cassini VIMS

Figure 4 shows the latitude and local-time projected VIMS observations of H_3^+ emission, with the grid having a spacing of 1 h in local-time and 5° in latitude. During this interval, the mean spatial resolution of a VIMS pixel on the planet is 280 km/pixel, pro-

Figure 4: Latitude and local-time projection of the auroral H_3^+ emissions observed by Cassini VIMS at the southern pole of Saturn on 2013-111. Dawn is towards the left, midnight towards the top, and dusk towards the right. The illustrations of Saturn at the bottom show the planet as viewed from above the north pole, with the sun towards the bottom. The grid spacing is 1 h in local-time and 5 degrees in latitude. The arrows indicate the azimuth of the PPO phase, where N and S indicate ϕ_N and ϕ_S respectively. Lines orthogonal to the arrows are the expected locations of the peak upward FACs, i.e. $\phi_S - 90^\circ$ for the north and $\phi_N + 90^\circ$ for the south. The dashed line in the projections show ϕ_S .

154 viding a detailed view of the southern midnight auroral oval, covering about 6 hours of
 155 local-time, centred about two hours post-midnight. The dashed line indicates ϕ_S PPO
 156 phase, with the illustrations of Saturn showing both the northern and southern PPO
 157 phase, together with the location of the expected peak upward FAC. The auroral emission
 158 is confined to a thin band of emission located between -72° and -75° latitude, consistent
 159 with the mean auroral location of -74° of Badman et al. (2011). There is a discontinuity
 160 at about midnight in Figure 4a, which rotates into the morning sector, appearing approx-
 161 imately fixed in PPO longitude. There is also a kink apparent at midnight at Figure 4b,
 162 which is also seen rotated in Figure 4c. Most of these H_3^+ emission features appear fixed
 163 in PPO longitude. For example, the discontinuity remains leading ϕ_S in both Figure 4a
 164 and 4b.

165 2.2. Cassini UVIS

166 Figure 5a shows the brightness of a) H₂ Lyman and Werner bands and b) H Ly- α as
 167 observed by UVIS, projected to latitude and UT, between 08:00 and 1500 UT. The two
 168 color-bars show the brightness and the calculated electron energy flux. To convert the H₂
 169 brightness to precipitating power, we assumed that 10 kR are produced by an electron
 170 energy flux of 1 mW/m² (Gustin et al., 2012, and references therein). Because the Cassini
 171 pointing was approximately fixed at $\sim$ 01:00 LT, shown in Figure 3, the UVIS emissions
 172 in Figure 5 shows how the brightness changes along the spectrograph slit as the planet
 173 rotates underneath it. This means that the spatial information is limited, and looking at
 174 the UVIS data in isolation renders us unable to disentangle spatial and temporal effects.
 175 However, the infrared VIMS observation provides a 2D view of the morphology, indicating
 176 that the emission is approximately fixed with rotation. Both VIMS and UVIS sees the
 177 discontinuity, and the poleward motion of the main oval, with UVIS seeing a subsequent
 178 equator-ward movement after 12:00 UT, after which there are no more VIMS images.

179 Figure 5a and b shows main oval emission at about -74° , consistent with the dayside
 180 statistical UV oval of Badman et al. (2006). There is also weaker and diffuse equatorward
 181 emission at about -70° latitude. The auroral brightens weakens significant at 10:00 UT,
 182 consistent with the discontinuity seen by VIMS in Figure 4. There is bright emission in
 183 both H and H₂ at 09:30 and at 11:00 UT. After this time the main oval dims and brightens
 184 slightly at about 13:30 UT.

185 2.3. Cassini ISS

186 The visible ISS observations offer a very narrow field of view of auroral emission at
 187 the southern pole, covering only a few degrees of latitude. The latitude and local-time
 188 projected ISS observations can be seen in Figure 6, with the dashed line showing lines
 189 of constant PPO longitude, indicating the rotation of the planet. There is a clear arc of
 190 emission rotating into the dawn sector, which appears to be moving at a rate close to
 191 that of co-rotation, as the lines that indicates rotation intersect the main oval at approxi-
 192 mately constant latitudes. There is significant background emission in these images, with
 193 a brightness of about $\sim$ 5 kR, which is a similar level to that of the main oval itself.

Figure 5: UVIS data showing brightness of a) H₂ Lyman and Werner bands and b) H Ly- α emissions projected to latitude and UT, between 08:00 and 15:00 on 2013-111. These observations are approximately fixed in local-time, $\sim$ 01:00, as illustrated in Figure 3. The top right scale shows the calculated electron energy flux required to produce the observed H₂ brightness (Gustin et al., 2012). The top x axis shows the Φ_S PPO longitude under the UVIS slit. The equator is towards the top, and the pole towards the bottom. The main emissions are located between -72° and -74° latitude, with significant equatorward emission being present near -70° .

Figure 6 shows structure within the main oval, with bright spots and dark bands appearing and disappearing between exposures, in particular Figure 6c, j, and k. These features are as small as a few tens of km. There is significant short-term variability in brightness, with Figure 6j showing a bright spot on the main oval that dims over timescales of minutes. As indicated by the arrows, there is evolving filamentary structures in Figures 6h and 6i, which also show highly variable behavior, both spatial and temporal.

2.4. *HST ACS*

Shown in Figure 7 are the four sets of HST observations obtained during the interval considered here, projected to latitude and local-time. On the small illustrations of Saturn below the HST images, the northern and southern PPO phase are shown, in addition to the location of the peak FAC. The viewing geometry is shown in Figure 2b.

The images in Figure 7 show relatively quiet auroras. They are similar to those observed by Gérard et al. (2006) during quiet magnetospheric conditions, and very much unlike those observed by Nichols et al. (2014) on 2013-95 and 2013-140, which were active. There is a dawn-side enhancement in the first two images, which has dimmed completely in the last two. The last image shows a brightening of the dusk side oval. All images in Figure 7 show diffuse emission poleward of the main auroral oval at local noon – most clearly shown in c), appearing static in local-time. Note that the midnight sector is not visible with this viewing geometry.

The total emitted UV power has been estimated for each image using by converting the observed brightness in the F125LP filter to the emitted power of unabsorbed H₂ auroral emission in 700-1800 Å, as given in Table 2 of Gustin et al. (2012), assuming a CR of 1.1. This conversion is obtained by applying hydrocarbon absorption and total HST throughput to an unabsorbed H₂ spectrum to obtain a simulated observed spectrum. The ratio between the integrated spectra provides conversion from counts to kR. The total emitted power is then calculated assuming a mean H₂ photon energy of 10 eV and a HST-Saturn distance of 1.32×10^9 km. The total powers for the four images in Figure 7 are 28, 28, 28, and 27 (± 1) GW respectively. Despite the differences present in the individual HST images in Figure 7, there is very little actual change in power output.

Figure 6: The latitude and local-time projected ISS observations of auroral H Balmer- α emission at the southern pole of Saturn on day 2013-111. The grid spacing is 1° in latitude, equivalent to ~ 1000 km on the planet, and 20 minutes in local-time. Subfigures a) through t) shows the first 20 images in a sequence of 37, with these being the only ones that show clear evidence of auroral emission. The dashed line indicate meridians of constant PPO longitude (arbitrary), showing the rotation of the planet. The fact that the projected ISS frames migrate slowly towards dawn indicates that the pointing of Cassini is slowly drifting towards later local-times. The schematics of Saturn on the left show the PPO phase for the leftmost of the ISS observations (see Figure 4 for description of the layout).

Figure 7: The HST ACS observations of Saturn’s northern pole on 2011-111 projected to latitude and local-time, showing emission in the F125LP filter containing H_2 Lyman and Werner band emissions. The grid spacing is 45° in latitude and 3 h local-time (arbitrary). The schematics of Saturn shows the PPO Phase during these observations, as per Figure 4. Note that the midnight sector is not observable by the HST.

2.5. NASA IRTF CSHELL

Figure 8 show 8 spectral images, each integrated for ~ 40 minutes, and the summed total, with the spatial dimension along x and spectral dimension along y . The spectral dimension covers 1.65 nm , and is centered at $3.953\text{ }\mu\text{m}$. This displays the $\text{H}_3^+ \text{ Q}(1, 0^-)$ intensity across Saturn’s northern polar cap, with the dawn region towards the left, eastward on the sky. The motions of the ions, as they flow towards us at dawn and away at dusk, produce a wavelength Doppler shift that can be measured using CSHELL. This can be seen as a slight negative slope in the summed $\text{H}_3^+ \text{ Q}(1, 0^-)$ emission line in Figure 8i.

Whilst the signal-to-noise is low in Figure 8, there is clear variability over the entire interval from 07:14 to 13:14 UT. This interval starts of with the auroral H_3^+ emission being weak, barely visible over the noise floor of the observations. After almost disappearing at 09:18 UT, it brightens considerable between 10:09 UT and 12:14 UT, initially noon-brightened, then dusk brightened at 11:18 UT. After 12:14 UT, the emission dims significantly, and is not readily seen at all at 13:14 UT. The summed intensity over this interval, seen in Figure 8i, is relatively evenly distributed across the polar cap.

238 As described in Section Appendix A.3, there were significant telescope guiding prob-
 239 lems during this interval, imposing significant uncertainties on both intensity and the
 240 derived ion velocities.

241 2.6. Keck NIRSPEC

242 Figure 9 shows the intensity of the $Q(1, 0^-) H_3^+$ spectral line at $3.953 \mu m$ across the
 243 entire slit, traversing both the midnight and noon part of the northern oval, followed by
 244 reflected sunlight from the rings, and finally, at the bottom, is the noon part of the southern
 245 auroral oval. In this wavelength range, the brightest emission is the ring reflection, seen
 246 here as a bright red band at about -14° , as the image has been thresholded to show
 247 the brightest H_3^+ emissions. The northern noon part of the oval is seen early in this
 248 set of observations between 09:30 and 10:30 UT, and it appears to undergo a poleward
 249 contraction up between 10:00 and $\sim 10:30$ UT, after which the noon oval is not readily
 250 seen. The southern noon oval is weak early in this interval, intensifying around noon.
 251 The intensity of both the southern and northern main ovals vary significantly over the ~ 3
 252 hours of observations analyzed here, up to 50%. The H_3^+ emissions do not display any
 253 obvious north-south conjugate behavior in intensity.

254 The pole-to-pole H_3^+ emission in Figure 9 show structures in intensity at northern low-
 255 to mid-latitudes, some of which span are persistent over ~ 30 minutes. These emissions
 256 have been reported by O'Donoghue et al. (2013) as being produced by the inflow of material
 257 from the rings along magnetic field lines that alter the chemical makeup of Saturn's upper
 258 atmosphere (Connerney and Waite, 1984; Prangé et al., 2006). The variable but relatively
 259 long-lived horizontal low-latitude structures seen in Figure 9 warrant further investigation,
 260 but falls outside the scope of this study.

261 3. Results & Discussion

262 The individual remote sensing observations described in the previous Section, seen in
 263 Figures 4 to 9, show emissions observed from different platforms, at different spatial scales,
 264 and in different wavelength bands. Each of these tell us something different about the
 265 auroral phenomenon, and by comparing these observations we can gain a more complete

Figure 8: NASA IRTF CSHELL spectral images of the $\text{H}_3^+ \text{ Q}(1, 0^-)$ line at $3.953 \mu\text{m}$, showing the intensity of Saturn's auroral emission across the polar cap, as indicated in Figure 2b. The times are the center times of the co-added observations. The horizontal direction is spatial, while the vertical dimension is spectral, covering 1.65 nm , centered at the $\text{H}_3^+ \text{ Q}(1, 0^-)$ transition at $3.953 \mu\text{m}$. The intensity of this spectral line is shown in Figure 9. Westerly angular offsets are toward dusk, with the dashed lines are separated by an angular distance of $0.15 R_S$ (i.e. $6''$) from the centre of the planet. Note that the total profile i) is not on the intensity scale indicated.

Instrument	Wavelength	FOV (spatial pixels)	t_{exp}	Notes
Cassini VIMS	IR, 0.8 - 5.2 μm	32×32 mrad (64×64)	1 s pixel ⁻¹	Integrates one pixel at a time. Has 256 spectral elements.
Cassini UVIS	UV, 90 - 190 nm	1.5×64 mrad (1×64)	60 s	Has 1024 spectral elements.
Cassini ISS	VIS, 0.2 - 1.1 μm	6.1×6.1 mad (1024×1024)	3 min	Using the clear filter.
HST ACS	UV, ~ 130 nm	170×150 μrad (1024×1024)	8 min	Using the F125LP filter.
Keck NIRSPEC	IR, 3.9 - 4.1 μm	2.2×116 μrad (3×167)	1 min	Has 1024 spectral elements.
IRTF CSHELL	IR, ~ 4.0 μm	2.4×145 μrad (2.5×150)	~ 40 min	Has 256 spectral elements.

Table 2: Summary of the basic characteristics of the remote sensing instruments analyzed in this study, with wavelengths given in the infrared (IR), visible (VIS), and ultraviolet (UV). The angular field of view (FOV) is given in the second column, with the number of pixel that this area subtends within the brackets. The total exposure time required to produce the figures presented in this paper are give by t_{exp} , governed principally by S/N. All the instruments are described in greater detail in Appendix A.

Instrument	Fig.	§	N/S	Key features
Cassini VIMS	4	2.1	S	a) Thin main auroral oval, with no other auroral emission present b) Distinct discontinuity present at about $\Phi_S = 0$
Cassini UVIS	5	2.2	S	a) Main oval, varying in intensity and location at a constant local-time b) Diffuse equatorward emission at about 70°
Cassini ISS	6	2.3	S	a) Fine structure within the main oval b) High degree of spatial and temporal variability
HST ACS	7	2.4	N	a) Thin main auroral oval indicating quiet conditions c) Diffuse equatorward oval seen in UVIS data is not present
IRTF CSHELL	8	2.5	N	a) Low signal to noise and guiding problems a) Northern oval varies over time-scales of hours
Keck NIRSPEC	9	2.6	N, S	a) Total northern intensity intensifies over time. b) Northern noon main oval fades away over time. c) Southern noon oval becomes brighter over the same interval

Table 3: Summary of the key features seen in each instrument during the interval on 2013-111 considered here, described in more detail in Section 2. References to Figures and Sections (§) are listed in the table, along with which hemisphere is observed, north (N) or south (S).

Figure 9: The infrared intensity over a narrow wavelength band centered on the $Q(1, 0^-) H_3^+$ spectral line along the north-south aligned Keck NIRSPEC slit as a function of time on day 2013-111. The y-axis shows the angular distance in Saturn radii (R_S) and the corresponding latitude, with the northern aurora, southern aurora and the solar reflection of the rings indicated. Note that the emission seen at the rings is reflected sunlight and not H_3^+ . The sub-Earth latitude of Saturn at the time of these observations was 18.2° , and the latitude in parantheses denotes that this latitude is on the far-side of the planet.

266 picture of these processes. Below, these observations are discussed from a simultaneous
 267 multi-scale and multi-platform perspective.

268 3.1. Multi-Scale Behaviour of the Main Aurora Oval

269 Since we have a set of infrared, visible, and ultraviolet observations obtained at the
 270 same time, we can compare auroral emissions at the southern pole of Saturn in the three
 271 wavelength bands simultaneously. Figure 10 shows these emission projected to latitude
 272 and southern PPO longitude. The figure covers 70° of rotation, focusing on the small
 273 region for which there are ISS observations.

274 Figure 10 was constructed by projecting the observations onto a square grid with
 275 PPO longitude on the x -axis and planeto-centric latitude on the y -axis. Both VIMS and

Figure 10: The a) ultraviolet UVIS H Ly- α series, b) infrared VIMS H_3^+ and c) visible ISS H Ba- α observations obtained on 2013-111 projected to latitude and PPO longitude. In b) the outline of each VIMS exposure is shown: 09:14 UT (dashed), 10:28 UT (dot-dashed), and 11:42 UT (dot-dot-dashed). The UVIS and VIMS observations can be seen plotted over a longer latitude and longitude range in Figure 11.

ISS produces a sequence of images that are spatially overlapping, and in such instances the projection routine averages the emission from all the images that occupy a particular latitude–PPO longitude location. The effect of this averaging is most clearly seen in Figure 10c, where the projection process produces a smooth auroral arc, seen between 310° and 340° , with none of the short-term temporal features seen in Figure 6. This tells us that over time-scales of greater than an hour, the temporal variability seen in a set of individual ISS frames averages out into a smooth main auroral oval. Figure 10b combines three VIMS images, and the edges of each are marked as dashed, dot-dashed and dot-dot-dot dashed lines. There are abrupt continuities at these edges, particularly at a PPO longitude of 0° , indicating that there is some variability in the morphology as a function of longitude.

This projection assumes that the structure of the aurora is, in this case, only dependent on longitude, and any time variations are then conflated in longitude variations. It is worth noting that auroral features have been observed to rotate at both slower and faster angular speeds than that of the PPO phase (Meredith et al., 2013; Nichols et al., 2014). However, as seen in Figure 4, the emission does appear relatively fixed in longitude. The VIMS and UVIS variability is similar to that seen by Lamy et al. (2013). Here, the inclusion of the simultaneous visible data enables us to assess how the very fine scale visible structures relates to the broad scale features in infrared and ultraviolet wavelengths.

Figure 10a shows the emission derived from the H Ly- α component of the FUV spectrum, which is dominated by H₂ Lyman and Werner bands. This was chosen as to enable a like-for-like comparison with the visible emission, which is dominated by H Ba- α emissions.

The three panels in Figure 10 show that the UVIS, VIMS, and ISS instruments have very different spatial resolutions: 720, 280, and 14 km/pixel on the planet, respectively. This is also illustrated by Figure 3. These differences enable us to compare the large-scale morphology to that of the small scale at the same time. The high spatial resolution ISS observations in Figure 6 show that there is significant structure within the oval itself, with spatial features as small as tens of km and with spatial variability occurring over time-scales of minutes. The UVIS observations, shown in Figure 5, show slight variability in the first hour of observations, whilst there is dramatic variability in the ISS images, shown in Figure 6, both in terms of where the peak brightness occurs along the main oval

306 and the structure of it. Since the fine-scale variability seen with ISS is expected to have
307 a one-to-one correspondence with the variability present in the field-aligned currents, the
308 high resolutions ISS observations reveal auroral processes that are not visible to the higher
309 resolution UVIS and VIMS instruments.

310 The HST observations seen in Figure 7 show an aurora that is thin and stable, indi-
311 cating that during this interval the solar wind conditions were quiet (Crary et al., 2005;
312 Gérard et al., 2006; Clarke et al., 2009). During intervals of active aurora, fine structures
313 within or adjacent to the main oval have been observed (Badman et al., 2012a; Lamy
314 et al., 2013; Nichols et al., 2014), albeit at much lower spatial resolutions. Here, Figure 6
315 show that even during quiet solar wind conditions conditions, when the main oval appears
316 thin and relatively unchanging, there are highly variable structure inside the main oval
317 itself. These features cannot be captured by larger resolution instruments; the width of
318 the UVIS slit overlaps with about a third of the entire ISS FOV, as seen in Figure 3.

319 Given these results, we expect Cassini’s in-situ observations of the upward FACs to be
320 variable over similarly small distances, with fine structures expected to have a separation
321 of a fraction of a degree on the planet. Provided that in-situ instruments have sufficient
322 cadence, these small scale structures may be visible in the FAC signatures (e.g. Talboys
323 et al., 2009). Whilst outside the scope of this paper, we recognise that there is an op-
324 portunity to understand these small and variable structures as Alfvén wave interactions,
325 a mechanism often attributed to small scale variability at the Earth (e.g. Knudsen and
326 Wahlund, 1998), Jupiter (Hess et al., 2011), and Saturn (Meredith et al., 2013).

327 The set of multi-scale Cassini observations analysed in this study show that Saturn’s
328 aurora displays significant variability on all time-scales, from minutes to hours, and on all
329 spatial scales, from tens of km to several thousands of km, even during quite solar wind
330 conditions. Therefore, as is the case with Earth’s aurora (Uritsky et al., 2010; Klimas
331 et al., 2010), we are at Saturn also likely to find spatial and temporal variability on as
332 small a spatial scale we can observe. The fact that variability is also observed over long
333 time-scales, shows that the short-term variability is not merely stochastic, but forms part
334 of an intricate and evolving system.

3.2. Multi-Spectral Comparisons

Figure 10 shows a small section of the southern main auroral oval. The emissions are co-located in all three wavelength bands, to a very good approximation. This oval is curved poleward from -72° to -74° latitude and appears brightest between $\Phi_S = 320^\circ$ and 330° in both the infrared and the ultraviolet. The two-dimensional distribution of the infrared auroral oval can be seen in Figure 4. The visible main oval appears more uniform in brightness, which is due to the fact that the projection averages about an hour's worth of visible images, as described in the previous section.

The spatial overlap of the main oval seen in the ultraviolet, infrared, and visible in Figure 10 is not perfect. For example, the infrared appears to have a slightly steeper latitude-longitude slope than the ultraviolet and the visible. In Figure 10b the dashed, dot-dashed, and dot-dot-dashed lines indicate the edge of the FOV of each of the VIMS images seen in Figure 4, corresponding to Figure 4a, 4b, and 4c respectively. Across these edges, at 330° and 5° PPO longitude, there are distinct discontinuities in the H_3^+ emission. There is also emission at $\Phi_S = 355^\circ$, which is not seen in either the visible or the ultraviolet. These differences are not physical, and can be attributed to differences in the operational mode of the instruments, capturing glimpses of temporal and spatial variability at different times and locations. VIMS integrates a square FOV one pixel at a time, UVIS observes a single slit of emission at a time, and ISS integrates an entire square FOV at one time. Consequently, it becomes non-trivial to disentangle the spatial and temporal variability, especially when comparing morphology over a limited latitude and longitude region.

At southern PPO longitudes of 0° to 20° there is H Ly- α emission in the ultraviolet that is not seen in the visible H Ba- α emission. The majority of these emissions are produced when H_2 is excited to its dissociative triplet state, producing excited states of atomic hydrogen. Therefore, we do not expect H Ly- α and H Ba- α emissions to exhibit any difference in morphology. It would appear that the ISS instrument is only able to capture the very brightest of the atomic hydrogen emission. This is corroborated by the relatively low S/N of the ISS images seen in Figure 6 and 10c. Additionally, the bright H Ly- α emission at $\Phi_S = 20^\circ$ longitude may not be contained within the ISS FOV or may

365 not be simultaneous with the ISS observation.

366 The VIMS and UVIS instruments were acquiring data for a longer interval than ISS,
367 and therefore they can be compared over a larger PPO longitude range. These are seen
368 in Figure 11, covering 160° of PPO longitude, or about half of the PPO system, and 23°
369 in latitude. These projections were constructed in the same manner as Figure 10. The
370 two main auroral emission are at similar latitudes in the two wavelength bands, both
371 undergoing equatorward and poleward motion, with both showing the discontinuity at
372 about $\Phi_S \approx 330^\circ$ and the kink at about 10° . As noted, it is difficult to disentangle
373 spatial and temporal variability due to differences in how these instruments operate. The
374 brightest H_2 emission occurs at a longitude of $\sim 10^\circ$, which has no clear counterpart in
375 the infrared H_3^+ intensity. The brightest H_3^+ intensity occurs at about $\Phi_S = 320^\circ$ PPO
376 longitude, which agrees well with the second brightest H_2 emission.

377 The ultraviolet brightness scale in Figure 11a is exponential, whereas the infrared in-
378 tensity scale in Figure 11b is linear. Therefore, the main oval is much more variable as
379 seen in the ultraviolet, varying from a few kR to several tens of kR over spatial scales of a
380 few of degrees longitude. The infrared main oval displays very limited variability, varying
381 at the most by about 50% in intensity over the same spatial scales. The estimated energy
382 flux of the precipitation is shown in Figure 5a. If one assumes that the ionospheric tem-
383 perature does not vary over time-scales of hours, as noted for the noon oval (O'Donoghue
384 et al., 2014), the variability seen in Figure 11 is driven mainly by changes in the H_3^+ den-
385 sity. Thus, these observations broadly agree with the first order approximation that the
386 number density of H_3^+ is proportional to the square root of the precipitation energy flux
387 (Tao et al., 2011), producing only a modest change in H_3^+ intensity.

388 The FOV of the HST observations, seen in Figure 7, does also include Saturn's southern
389 pole. However, there is very little ultraviolet H_2 brightness present there, having a S/N
390 much too low to render them meaningful. In contrast, H_3^+ emission from the south is easily
391 observed, as seen in Figure 9. This results from the fundamental difference between the
392 type of emission that these species produce in response to an injection of energy into the
393 upper atmosphere (i.e. energetic electrons or solar photons). H_2 emits almost immediately
394 after excitation, and is therefore an instantaneous view of the incoming source of energy.

Figure 11: The a) ultraviolet UVIS H₂ Lyman and Werner bands and b) infrared VIMS H₃⁺ auroral emissions at Saturn's southern pole on 2013-111, projected to latitude and longitude. The outline of each of the VIMS FOVs is shown as per Figure 10.

395 H_3^+ on the other hand is produced by the chemical reaction described in Equation 1,
 396 becoming collisionally thermalised with the neutral atmosphere over the H_3^+ life-time of
 397 ~ 500 s (Melin et al., 2011a). This means that the H_3^+ emission maps the energy injection
 398 into the upper atmosphere over the duration of its lifetime, making it impossible to resolve
 399 temporal variability on time-scales shorter than the H_3^+ life-time. This also means that we
 400 are likely unable to observe very fine-scale variability, like that seen in the ISS observations
 401 in Figure 6, even if an infrared observation were to have a spatial resolution of tens of
 402 km and very short integration times, the long life-time of the ion would act as to produce
 403 a temporally averaged view over the life-time of the ion. In contrast, the only effective
 404 limit on ultraviolet and visible emissions is the integration time of the instrumentation in
 405 question.

406 Figure 12 shows the dayside northern and southern intensity of the H_3^+ $\text{Q}(1, 0^-)$ tran-
 407 sition derived from Keck and IRTF observations plotted versus UT time. Also indicated
 408 is the total power emitted at the northern pole in the UV as observed by HST. At the top
 409 of Figure 12 is the northern (green) and southern (blue) PPO phase, indicated as arrows,
 410 with the expected locations of the maximum upward FAC indicated as an orthogonal solid
 411 line (as in Figure 4). Over the entire interval, between 09:00 UT and 13:00 UT, the infrared
 412 emissions observed with IRTF and Keck are boardly consistent. The differences between
 413 the east-west aligned IRTF observations and the north-south aligned Keck observations
 414 (see Figure 2), are produced when auroral emission that is not symmetric about the pole,
 415 which is clearly seen in the HST images in Figure 7 as a asymmetric auroral oval.

416 The HST power, remains very steady about noon whereas both IRTF and Keck sees
 417 fading H_3^+ intensity at the same time. This inconsistency becomes difficult to explain.
 418 Either there is emission that is outside the FOV of both Keck and IRTF that brightens
 419 in the same interval. The emission would have to be located at 09:00 LT or 15:00 LT,
 420 outside of the east-west and north-south slits. The HST images in Figure 7a and 7b
 421 show that there is emission at 09:00 LT, which appears to be fading slightly during the
 422 24 minute period. Since the intensity of the H_3^+ is dependent on temperature, the polar
 423 atmosphere could cool, becoming less intense, whilst still being subject almost the same
 424 levels of particle precipitation. This requires a decrease in the energy injected into the

Figure 12: A qualitative comparison of the H_3^+ intensity of the northern and southern auroral polar regions as observed by Keck (solid and dotted lines, respectively, with the uncertainties shaded), the northern H_3^+ intensity as observed by the IRTF (stars), and the total power emitted in the ultraviolet as seen by HST in the north (diamonds). The schematics of Saturn along the top indicate the PPO phase, as in Figure 4. The northern and southern PPO phase are also given at the top axis.

upper atmosphere via Joule heating.

In comparing the set of multispectral observations presented here, we must conclude that comparing like-for-like morphology of different wavelength bands is very challenging. The limitations created by the differences in how these instruments operate mean that, even though these observations were obtained during the same interval, only a very small fraction show represent emissions emitted from the same location at the same time.

3.3. Auroral Brightness as a Function of PPO Phase

The correlation between the brightness of auroral emission and PPO Phase has been noted by Nichols et al. (2010b), Badman et al. (2012b), and Lamy et al. (2013). Here, we investigate if there is a relationship present in the observation obtained in the interval

435 considered here.

436 By comparing the northern and southern PPO phase, $\phi_{N,S}$, to the emissions detailed
437 in this study (Figure 12, and others), we note the following for the emission observed
438 through each instrument:

- 439 1. **HST:** There is poor correspondence between the high intensities observed in the HST
440 observations of Figure 7a and 7b and the expected location of the northern upward
441 FAC. The dusk brightening observed in Figure 7c and 7d, however, is approximately
442 along the azimuth of the peak FAC.
- 443 2. **Keck:** In Figure 12, the peak northern upward FAC occurs at noon between 09:00
444 and 10:00 UT, as indicated by the green lines on the Saturn schematics. During
445 this interval, the most intense northern H_3^+ emission is observed by Keck, the slit
446 of which is aligned along the rotational axis of the planet. Figure 9 shows an in-
447 tensification of the noon oval during this interval, which diminishes after 10:00 UT.
448 The southern Keck H_3^+ intensity shows a minimum during this interval. The IRTF
449 observations, which measure integrated intensity across the main oval, i.e. in the
450 east-west direction, show a slight increase in intensity just before 10:00 UT, although
451 this variability remains within the error bars. The peak southern upward FAC is
452 expected to occur at local noon between 12:00 and 13:00 UT. The southern H_3^+ in-
453 tensity peaks just before 12:00 UT, in broad agreement with the peak FAC passing
454 the noon meridian.
- 455 3. **IRTF:** The maximum IRTF CSHELL H_3^+ intensity in Figure 12 occurs at 11:18.
456 This occurs about 2 hours after peak FAC is at noon. However, the IRTF slit does
457 not see the northern noon, as the slit cuts east-west across the pole. Figure ??f
458 is the spectral image at 11:18, and is seen to be slightly dusk brightened. This is
459 consistent with the max FAC rotating from noon into the afternoon sector, where
460 it becomes visible by the IRTF. Note that the dusk brightening is absent in the
461 subsequent IRTF spectral image, seen in Figure ??g.
- 462 4. **VIMS:** In the LT projection in Figure 4 the FOV only overlaps with the direction
463 of the azimuth of the southern PPO Phase, with the location of the maximum FAC
464 entering the FOV of the soon after the sequence of integration ends. Interestingly,

the oval discontinuity seen in Figure 4 is approximately aligned with the southern PPO longitude $\Phi_S = 0$. However, we are unable to discern if the azimuth of the effective dipole direction of the rotating electric field is responsible for such a feature.

5. **UVIS:** Figure ?? shows the ultraviolet emission observed as the planet rotates underneath the slit. The maximum FAC occurs in the south at $\Phi_S = -90^\circ = 270^\circ$. There is a poleward movement of the main oval and a equatorward movement of the diffuse oval. It is unclear, however, that these movements are directly associated with the passing of the maximum FAC.

6. **ISS:** The very narrow field of view of ISS renders us unable to perform any fruitful comparison between emission brightness and PPO phase.

It is apparent that whilst the azimuth of the northern and southern maximum upward FAC associated with the PPO aligns well with some auroral brightness features observed in this study, there are distinct features that do not. Yet, in statistical studies, there are distinct intensity features associated with the PPO phase, both in the northern and southern hemisphere (Nichols et al., 2010b; Badman et al., 2012b; Lamy et al., 2013). This means that whilst there is variability contained within individual observations, these short-term changes are not ordered by the PPO phase.

3.4. *Diffuse Equatorward Emissions*

The UVIS observations in Figure 11a clearly shows diffuse emission equatorward of the main oval, at around -70° . This is broadly consistent with the equatorward emission observed by Grodent et al. (2010), which was associated with suprathermal electrons located between 4 and 11 R_S . It is also consistent with the arc seen in H_3^+ emission on the dawn and dusk side of the southern oval (Stallard et al., 2008), and with extended bands of H_3^+ emission seen on the southern nightside (Lamy et al., 2013). However, this equatorward ultraviolet emission seen by UVIS is notably not present in the infrared VIMS H_3^+ observations in Figure 11b. This was previously noted by Melin et al. (2011a).

If there was a linear relationship between the H_2 and H_3^+ emission rates, then the equatorward emission would be visible in the infrared. Since this feature is completely absent in Figure 11b, Equation 2 tells us that the differences in emission must be driven by

494 temperature differences, producing exponential emission rate changes, and not differences
 495 in density, which result in linear changes. Assuming that the altitude of the peak emission
 496 rates of both H_3^+ and H_2 are the very similar, as per Gérard et al. (2009) and Stallard
 497 et al. (2012), this suggests a steep decreasing temperature gradient towards the equator.

498 We now calculate what difference in ionospheric temperature is needed to produce the
 499 observed results. Firstly, we assume that the excitation and ionization rate of H_2 are
 500 linearly proportional. With the eqatorward H_2 emission being ~ 4 times weaker than the
 501 main oval, we infer a ~ 4 times difference in the H_3^+ production rate, and subsequently
 502 the H_3^+ density. Secondly, if we consider Equation 2 for the H_3^+ $\text{Q}(1, 0^-)$ transition, and
 503 assume that the auroral oval is at a temperature of about 500 K (Melin et al., 2007, 2011a;
 504 Lamy et al., 2013; O'Donoghue et al., 2014), then the diffuse equatorward auroral oval,
 505 separated by only a few degrees of latitude from the main oval, needs to be at a temperature
 506 of ~ 440 K for it not to be observable, given a $\text{S/N} \sim 10$ of the observations in Figure 4. This
 507 rapid decrease in temperature with latitude, 40 K over $2-4^\circ$, is inconsistent with the UVIS
 508 occultation analysis of Koskinen et al. (2013), at least in the auroral region. In addition,
 509 note that Lamy et al. (2013) observed equatorward emissions in both the infrared and the
 510 ultraviolet at the same time. This does not require the invocation of a step temperature
 511 gradient equatorward of the main oval. This indicates that the Joule heating at the main
 512 oval is substantially larger than that at the equatorward oval. This in turn suggests
 513 that the amount of Joule heating injected at sub-auroral latitudes is variably over time.
 514 The origin of the auroral signatures observed here is discussed below.

515 The IRTF velocity profiles in Figure 13 we show the same types of H_3^+ intensity profiles
 516 and line-of-sight Doppler velocities as presented by Stallard et al. (2008), obtained by the
 517 same instrument, i.e. CSHELL. They found that after subtracting the modeled main
 518 oval emission at the southern pole, a band of equatorward emission was readily apparent.
 519 The distinct extended flanks on the dusk and dawn ansae that were seen by Stallard
 520 et al. (2008) are not seen in Figure 13. Hence, there is no evidence of dawn and dusk
 521 equatorward emission at the sunlit northern polar ionosphere, whereas it is seen in the
 522 southern emission near midnight. Additionally, in the HST images shown in Figure 7
 523 there is no evidence of diffuse emission on the dayside about 74° latitude, indicating that

524 this is not a feature that is present at all local-times.

525 If the low latitude emission seen at the southern pole is related to the suprathermal
526 population of electrons in the inner magnetosphere (Grodent et al., 2010), then we would
527 expect this emission feature to be both conjugate and independent of local-time, since the
528 inner regions of the magnetospheric plasma distribution is symmetric. These emissions
529 are also unlikely to be associated with a secondary auroral oval (Stallard et al., 2008), as
530 this also requires conjugacy and local-time independence. Mitchell et al. (2009) suggested
531 that field-aligned currents can be produced via the production of energetic neutral atoms.
532 These emissions can be highly dependent on local-time, but they do require conjugacy.
533 Within the set of observations analyzed here, there are no observations of the region
534 equatorward of the main oval at local midnight.

535 3.5. H_3^+ Ion Velocities

536 Figure 13 shows the H_3^+ intensity (solid) and velocity (dotted) for the intervals ap-
537 proximately coinciding with the HST images, derived using the CSHELL observations. In
538 order to build up sufficient S/N, about two hours worth of data is co-added, averaging
539 out any shorter term variability present on those time-scales. The observations of Figure
540 13 are discussed in Section 3.5, where they are analyzed with the context of the to the
541 simultaneous HST images.

542 As indicated above, Figure 13 shows the intensity and line-of-sight velocity of the H_3^+
543 emission at similar times to the first two and last two of the HST observations shown in
544 Figure 7. The solid line in Figure 13 is the intensity, the dotted is the line-of-sight velocity,
545 and the dashed is the line corresponding to rigid co-rotation assuming a period of 10.7 h .
546 The shaded area indicates the region beyond the limb of the planet. The velocities are
547 anchored at noon, where it is assumed to be zero.

548 The integration time-scales of the HST and IRTF observations are very different. In
549 order to build up a good enough S/N in the velocity profile under the quiet conditions
550 observed here, a rolling average of ~ 2 hours of observations needs to be co-added. The HST
551 observations, on the other hand, are only 500 s long. Therefore, any short-term variability
552 evidenced in HST imaging is averaged out in the longer IRTF observations. However, over

the interval of HST observations, the emission does not undergo any dramatic changes, remaining relatively quiet.

In addition, the ion velocities derived from the IRTF CSHELL data can be affected by the extent to which accurate guiding of the telescope on the planet can be maintained. If the telescope moves significantly during the interval in question, velocities from different regions will be superimposed, and the resulting structure becomes hard to interpret. Here, the extent to which the telescope was able to maintain accurate guiding and track the planet across the sky is unclear. However, it may be estimated to be up to $2''$, introducing significant errors in the spatial location of the observed velocity structures.

The observations of Stallard et al. (2007a) suggests that a symmetric distribution of H_3^+ intensity across the polar cap, such as that shown in Figure 13, is associated with a three-region velocity structure. Here, the region just pre-noon that Stallard et al. (2007b) sees as co-rotating is being held at a $\sim 0 \text{ km s}^{-1}$ velocity relative to rigid rotation (indicated as line 2 in Figure 13), and the sub-corotating region at dawn is here approximately co-rotating (line 1). The sub-corotating region post-noon seen as line 3 in Figure 13a agrees well with the same region of Stallard et al. (2007b).

The east-west intensity profile of Figure 13a bears little resemblance to the dawn brightened morphology the HST observations in Figure 7 a) and b). This means that either the CHSELL slit cuts along the line just above this brightening and thus misses it, or over a period of two hours the mean east west profile averages out into something that is approximately symmetric about the pole. The pre-noon region of zero co-rotation in Figure 13a may be associated with a region linked to the solar wind, i.e. it is held in the inertial frame of the Sun. If the main auroral oval is associated with the open-closed field-line boundary (Bunce et al., 2008), then regions poleward of this are on field lines connecting to the solar wind.

Given the high degree of blending of velocities from different spatial regions across the pole, the velocities in Figure 13a are broadly consistent with a main oval that is sub-corotating, and a polar region that is being held by the solar wind at zero velocity.

Figure 13b shows the velocity structure some 2 hours later, corresponding to the HST images of Figure 7c & d. Once again the large averaging produces a symmetric oval, with

583 the bulk of the H_3^+ ions flowing at a co-rotation velocity. With the ions and neutrals
 584 flowing at a similar bulk velocity, we expect the collisional energy transferred between
 585 them to be at a minimum. However, this is inconsistent with the HST observations that
 586 change very little over this interval: the total power only varies by a few percent. We
 587 attribute this discrepancy to the significant guiding error experience at the IRTF.

588 *3.6. Lessons for future Saturn auroral campaigns*

589 Co-ordinating spacecraft and ground based telescopes to observe the same object at
 590 the same time is notoriously hard. This is mainly because of scheduling issues, but as
 591 shown in this paper, the different temporal and spatial scales of different instruments
 592 introduce complexities that are difficult to disentangle. Each instrument has the potential
 593 to contribute a different story-line to the scientific narrative, and comparative studies can
 594 produce fruitful science (e.g. Lamy et al., 2013; Gérard et al., 2013). Hence, comparisons
 595 are possible, but care needs to be taken to understand the capabilities and limitations
 596 of each set of observations. If truly simultaneous comparisons between the VIMS and
 597 UVIS instruments are to be undertaken, and compared like for like, a more detail analysis
 598 is available (Melin et al., 2011a), but this comes at the price of loosing any 2D spatial
 599 information.

600 Here, we have only compared auroral morphologies observed in different wavelength
 601 bands obtained from different vantage points. This is but one of many ways in which
 602 to study this data. For example, no spectral analysis has been undertaken, which pro-
 603 vides, amongst other things, a measure of the amount of energy injected into the upper
 604 atmosphere. This study also only uses infrared, visible, and ultraviolet remote sensing in-
 605 struments. Cassini carries a whole host of others instruments with which comparisons can
 606 be made, including in-situ particle and fields instruments, radio, and ion/neutral imaging.
 607 This is to say that whilst it is nontrivial to compare simultaneous multi-wavelength mor-
 608 phologies, which can produce results that are inconsistent between data-sets, these types
 609 of observing campaigns facilitate science that is not possible with any one instrument.
 610 Therefore, the limitations in the analysis of morphology noted here does not mean that
 611 all types of comparisons will suffer in the same manner.

Figure 13: The H_3^+ ion intensity (solid) and velocity (dotted) derived from the NASA CSHELL observations in Figure 8, for the intervals approximately centred on the times of the HST observations of Figure 7. The dashed line indicates the co-rotation velocity assuming a rotation period of 10.7 h, and the gray shaded areas indicate where the spectrograph slit is nominally outside the planet disk. Dusk is towards the right and dawn is towards the left. The three lines labelled 1, 2, and 3 show the distinct velocity regions discussed in Section 3.5.

612 The observations analysed here were obtained during quiet solar wind conditions, re-
 613 sulting in a faint auroral oval. Therefore, the comparisons undertaken here are at times
 614 limited by the S/N. The 2013 campaign covered about two months worth of observations,
 615 during which there were both active and quiet periods. It is imperative that future cam-
 616 paigns cover a similarly lengthy time-span, enabling us to observe a range of solar wind
 617 conditions, and how these relate to the observed emissions.

618 Observing campaigns that include ground-based data needs to schedule enough of them
 619 as to increase the probability of getting usable data, given the auroral S/N, weather, and
 620 telescope issues. These facilities are limited to observing during night-time hours at the
 621 Earth, and the other platforms, such as space telescopes and spacecraft, must take this
 622 into account.

623 4. Summary

624 We have compared the morphology of Saturn’s aurora from six remote sensing instru-
 625 ments all obtained on 21 April 2013, between 07:00 UT and 15:00 UT. These observations
 626 covered the infrared, visible, and ultraviolet, and included the NASA IRTF and Keck
 627 telescopes on the ground, the Hubble Space Telescope, and the Cassini spacecraft. The
 628 findings of these comparison can be summarised as follows:

- 629 1. These observations provide simultaneous multi-scale and multi-vantage point views
 630 of the morphology of Saturn’s auroral emissions. High spatial resolution Cassini ISS
 631 observations reveal spatial variability on several tens of km and brightness variability
 632 on timescales of minutes. Variability on larger spatial scales show that the total
 633 intensity of the oval varies not only over these short periods, but also over much
 634 longer timescales. This fine-structure variability seen inside the main oval is likely
 635 to be present at all times, as they are here clearly seen during a period of quiet
 636 auroral activity.
- 637 2. We directly compare the morphology of simultaneous infrared, visible, and ultravio-
 638 let auroral emissions. These main auroral emissions are broadly co-located, although
 639 there are differences. These differences can be attributed to differences in how the

instruments acquire their data, but may also be indicative of the fundamentally different emission mechanisms of excitation (H , H_2) and thermal emission via ionisation of H_2 (H_3^+).

3. There are instances where the infrared and ultraviolet emissions coincide with the location of the expected peak in upward FAC associated with the PPO current system, but there are also instances at which there is no correspondence. In addition, there are features in the north, observed by HST, that appear at the southern peak upward FAC location, which may indicate a presence of the southern PPO phase in the northern hemisphere.
4. Diffuse emissions, equatorward of the main oval is only observed at the southern midnight sector in the ultraviolet using UVIS. The absence of these in the infrared H_3^+ emission suggests that this region is significantly cooler than the main auroral oval. We calculate that this is of the order of 60 K over 2-4° latitude. This emission is also not observed on the northern dayside by HST, showing that it is confined in local-time. This suggests that the mechanism for producing this emission is driven by the ENA production process (Mitchell et al., 2009).
5. Our ability to perform like-for-like comparisons of multi-wavelength and multi-vantage point observations of Saturn's aurora is limited by a number of factors, such as auroral activity at Saturn, spacecraft instrument operational modes, weather on Earth, and accuracy of telescope guiding. With no ability to effect all of those factors, future co-ordinated observing campaigns should aim to cover a long enough period, as not to rely on a single interval or a single set of conditions.

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Appendix A. Instrumentation & Observations

The period of interest spans between 07:00 and 15:00 Universal Time (UT), which covers about three quarters of a Saturn rotation (indicated by the rotational phase diagram in Figure 2). This figure shows when each of the instruments were acquiring data. There is no period during which all of the six instruments that were observing during this day were acquiring data, but between about 09:00 and 12:00 UT there are up to five instruments observing.

During the interval shown in Figure 1, Saturn was at a distance of 8.8 AU from the Earth (9.8 AU from the Sun), giving a light travel time of 4,403 s (1h 13m 23s). All the times in Figure 1 are adjusted to be UT at the time of emission at Saturn. This means that observations from the Earth based platforms are shifted backwards in time by the Earth-Saturn light travel time.

The observational geometry is shown in Figures 2 and 3. As viewed from the Earth, Saturn subtended $17''$ pole-to-pole, having a right-ascension of $\alpha=14^{\text{h}} 28^{\text{m}} 09^{\text{s}}$ and a declination $\delta=-11^{\circ} 48' 18''$. The planet reached a maximum elevation of 58° above the horizon (i.e. an airmass of 1.175) at 11:00 UT in Hawaii. Opposition of the Sun-Earth-Saturn system occurred on the 28 April 2013.

What follows are brief outlines of the six instruments and a description of the auroral emission that each of them observes.

697 *Appendix A.1. Cassini Remote Sensing*

698 The Visual and Infrared Mapping Spectrometer (VIMS, Brown et al., 2004), the Imag-
 699 ing Sub System Narrow Angle Camera (ISS, Porco et al., 2004), and the Ultraviolet
 700 Imaging Spectrograph (UVIS, Esposito et al., 2004) are mounted on the Cassini Remote
 701 Sensing Palette (RSP). These instruments share a common boresight, pointing along the
 702 $-y$ direction, where the $+x$ direction is along the stellar reference units, and $+z$ is along the
 703 long axis that runs from the High Gain Antenna (HGA) towards the main rocket engines
 704 (Henry, 2002). The latitude and local time projection of each of the Cassini instruments
 705 at 10:00 UT on 2013-111 can be seen in Figure 3.

706 During the observations considered here, Cassini was at a radial distance of 7 to 10 R_S
 707 from Saturn, in a 9.6 day orbit about the planet (orbit #187) with an orbital inclination
 708 of 62° from the equatorial plane. The spacecraft was located in the pre-midnight sector
 709 with a mean local-time of 22:49 h , and with a varying sub-Cassini latitude of -54° at
 710 2013-111 07:00 UT to -34° at 2013-111 15:00 UT. The view of Saturn from Cassini during
 711 this interval can be seen in Figure 2a.

712 The pointing geometry of Cassini and its instrument boresights are derived from
 713 NASA’s Navigation and Ancillary Information Facility (NAIF, Acton, 1996) in the usual
 714 manner. All the projections in latitude along one axis and either local-time, UT, or longi-
 715 tude on the other axis are calculated at an altitude of 1100 km above the 1 bar reference
 716 surface. This is the altitude measured for both the peak intensity H_3^+ emission in the in-
 717 frared (Stallard et al., 2012) and the peak brightness of the H_2 emission in the ultraviolet
 718 (Gérard et al., 2009). All latitudes are kronocentric and local-times are as given by NAIF,
 719 and the PPO phase is given by Provan et al. (2014). One degree of latitude represents
 720 ~ 1000 km on the planet.

721 The Cassini pointing during this interval was approximately fixed in local-time, the
 722 geometry being shown in Figure 3. There is a slight drift in spacecraft pointing during this
 723 interval towards dawn, only readily apparent in the high spatial resolution observations
 724 of ISS (see Figure 6).

725 A single UVIS pixel contains 3×2 VIMS pixels, and a single VIMS pixel contains 83
 726 $\times 83$ ISS pixels. Because of the design and operational considerations of each instrument,

combining these into truly simultaneous (i.e. emissions from the same place recorded at the same cadence) is non-trivial. Melin et al. (2011a) outline how simultaneous UVIS and VIMS observations can be combined to analyse auroral emissions at Saturn.

A brief outline of each of the Cassini instruments considered in this study follows below.

Appendix A.1.1. Cassini VIMS

VIMS has a field of view of 32×32 mrad, covering 64×64 pixels, with the instrument integrating each spatial pixel in sequence, so that no VIMS pixel is temporally simultaneous with any other. The spectral resolution is $R = \lambda/\Delta\lambda \sim 200$, and the total wavelength coverage is 0.8 to 5.1 μm , dispersed over 256 spectral pixels. This region includes discrete line emission of R and Q branch H_3^+ between 3.5 and 4.1 μm .¹

We used the infrared bins 153, 155, 160, 165, 168, and 200 at 3.41, 3.44, 3.53, 3.61, 3.67, and 4.20 μm respectively. The width of each wavelength bin is ~ 0.017 μm . A background subtraction of the reflected solar light component is performed by subtracting the scaled intensity in wavelength bin 150 at 3.37 μm , in addition to subtraction of both the mean vertical and horizontal intensity profiles. This latter process acts as to remove some of the systematic effects present in some wavelength bins. The integration time per pixel is 1 s, giving a total exposure time of 4160 s (including 64 dark current exposures). The diagonal bands seen at the top of the VIMS FOV in Figure 4c are due to instrumental effects sometimes present in a subset of wavelength bins.

Appendix A.1.2. Cassini UVIS

The UVIS set of instruments has telescopes sensitive to both EUV and FUV wavelengths. Here, the FUV channel was used, which has a wavelength range of 112 to 191 nm dispersed over 1024 spectral elements and 64 spatial pixels along the slit, with a spectral resolution of $R \sim 500$. A spectral compression was used producing a spectral image with 128 wavelength elements. Each individual spectrum was integrated for 60 s. The slit is 64 mrad long, and 1.5 pixels wide, with each pixel having a FOV of 1.5×1 mrad using

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¹See §2.9 in McCall (2001) for details of the H_3^+ spectroscopic notation used here.

754 the low-resolution slit, producing a mean spatial resolution on the planet of 720 km/pixel.
755 The standard time-dependent University of Colorado calibration was applied to the UVIS
756 data. The wavelength region of the UVIS FUV channel includes the Lyman and Werner
757 H₂ band emissions between 90 and 160 nm, in addition to the H Ly- α emission at 122 nm.

758 The UVIS FUV instrument has a relatively broad and complex line spread function
759 (LSF) that disperses UV photons of a particular energy across the detector. This has to
760 be accounted for when extracting the emission brightness of H and H₂. The H Ly- α LSF
761 is derived from observations of interplanetary hydrogen (IPH, i.e. a source of only Ly- α)
762 obtained during intervals when Cassini transfers data to the Earth via the Deep Space
763 Network (DSN).

764 *Appendix A.1.3. Cassini ISS*

765 The ISS NAC is a $f/10.5$ Ritchey-Chretien telescope that has a square FOV with each
766 side subtending 6.1 mrad, contains 1024×1024 pixels. It has a wavelength range of 0.2 to
767 1.05 μm , covering the visible part of the electromagnetic spectrum. In these observations
768 the clear filter was used, covering 200 to 1050 nm, capturing auroral emission from H
769 Balmer- α at 0.66 μm , in addition to emission at other visible wavelengths (see the visible
770 spectrum in Dyudina et al., this issue). 37 ISS images were obtained between 08:40 and
771 10:38, each 180 s long. A 4×4 spatial binning was used, giving a resolution per pixel on
772 the planet of 14 km.

773 Observations of aurora in the visible wavelength region at Saturn are limited to night-
774 side observations at a high phase angle, which makes the number of opportunities at which
775 these observations are possible low, compared to auroral observations in the infrared or
776 ultraviolet. These opportunities are strongly dependent on the spacecraft orbit.

777 *Appendix A.2. Hubble Space Telescope ACS*

778 The Advanced Camera for Surveys (ACS, Ford et al., 1998) is an ultraviolet-sensitive
779 wide field $35 \times 31''$ (1024×1024 pixels) camera, installed on HST during Servicing Mission
780 3B in 2002. This spacecraft orbits with a period of ~ 100 minutes, at a low altitude Earth
781 orbit.

Figure 7 shows four HST images, projected to latitude and local-time. Each exposure is 500 s, containing five co-adds of 100 s. The F125LP (CaF₂) filter was used, which has a maximum throughput at 130 nm, which excludes the bright H Ly- α line. Hence, these observations purposefully exclude emissions that are associated with the geocorona of the Earth, a source of significant photon contamination. These observations were obtained on two consecutive HST Earth orbits, and a) and b) were obtained at the beginning and at the end of a single orbit (and similarly for c and d). The noise floor in the HST images shown in Figure 7 is ~ 2 kR.

Appendix A.3. NASA IRTF CSHELL

Located near the summit of Mauna Kea, Hawaii, at an altitude of 4,205 m above sea level, the IRTF is a 3 m telescope equipped with the Cryogenic Echelle Spectrograph (CSHELL, Greene et al., 1993). This instrument provides a high spectral resolution of $R = \lambda/\Delta\lambda \sim 35000$, providing a theoretical velocity resolution of $3 \text{ km s}^{-1}\text{pixel}^{-1}$. The spatial extent along the slit is $30''$, and the width is $0.5''$. The spectral window was centered at the H₃⁺ Q(1, 0⁻) transition at $3.953 \mu\text{m}$, and covered the region between 3.984 and $3.958 \mu\text{m}$. The spectrograph slit was aligned east-west across the northern pole of Saturn, as indicated in Figure 2b. The observations presented here were reduced in the usual manner, using krypton and argon arc-lamps for wavelength calibration across the detector array. Half of the total integration time was spent measurements of the prevailing Earth sky emissions (sky frames, or B frames), with the other half observing the polar region of Saturn (object frames, or A frames).

The largest source of uncertainty for the intensity shown in Figure 8 is inaccurate guiding of the telescope, which occurs from time to time. For these observations the guiding was particularly problematic, and the telescope could veer up off the planet, or down onto the planet. In the worst instances, telescope movements comparable to the size of the auroral region can occur on time-scales of a single integration of 120 s. At the telescope, care is taken to note down the individual exposures subject to these movements as to remove them from any subsequent analysis. Smaller movements are harder to discern, and may therefore still be present in the data presented here. Therefore, the error on both

intensity, position, and derived velocities remain large, on the order of 30 %. Under normal circumstances, data that is obtained during intervals with problematic guiding is not considered reliable, and is not used. It is included here because it adds another view of the Saturn system, but throughout the following analysis, we remind the reader that the errors are considerable.

By fitting the position of the spectral line in Figure 8 as a function of spectral and spatial position, the H_3^+ ion velocity can be derived, since emission from the ions is subject to Doppler shifts as they flow away or towards the Earth. This method was first applied to Jupiter (Rego et al., 1999; Stallard et al., 2001) and subsequently to Saturn (Stallard et al., 2007a). The uncertainty in the ion velocities is governed principally by the S/N and the accuracy of the telescope guiding: the S/N determines the accuracy to which the exact wavelength of the H_3^+ emission line can be determined at each spatial position and telescope guiding drifts produce a blending of emissions from different spatial positions. This is discussed further in Section 3.5.

Appendix A.4. Keck NIRSPEC

The 10 m twin Keck telescopes are located 235 m due West of the IRTF. On Keck II, the northernmost of the two telescopes, the Near Infrared Spectrograph (NIRSPEC, McLean et al., 1998) is mounted at one of the Nasmyth foci, providing near-infrared cross-dispersed spectra at a resolution of $R \approx 25000$. When centred in the L band telluric atmospheric window, these emissions include both the R and Q branch of H_3^+ . NIRSPEC has previously been used to study the ionosphere of Jupiter (Lystrup et al., 2008), Saturn (e.g. O’Donoghue et al., 2013), Uranus (Melin et al., 2011c), and Neptune (Melin et al., 2011b).

On 2013-111 Keck NIRSPEC observed Saturn for ~ 3 h, as indicated in Figure 1. The 24'' long slit was aligned parallel to the rotational axis, cutting through both the northern and southern auroral oval, traversing the rings. This geometry is shown in Figure 2b. The width of the spectrograph slit is 0.46'', which is equivalent to about 1400 km on the planet.

Spectral order 1 (of 4) of the NIRSPEC cross dispersed spectrum covered 3.95 to 4.00

840 μm , which includes part of the Q branch emission of H_3^+ . Each exposure on the planet was
841 60 s and a sky exposure was obtained for each of these with equal exposure time. A total
842 of 57 Saturn exposures were obtained, with the data being reduced in the normal manner,
843 applying flat fields and dark frames. Flux calibration was achieved using observations of
844 the A0 star HR 5717 (K magnitude 6.3).

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