

# Saturn's northern aurorae at solstice from HST observations coordinated with Cassini's Grand Finale

L. Lamy<sup>1</sup>, R. Prangé<sup>1</sup>, C. Tao<sup>2</sup>, T. Kim<sup>3</sup>, S. V. Badman<sup>4</sup>, P. Zarka<sup>1</sup>, B. Cecconi<sup>1</sup>,  
W. S. Kurth<sup>5</sup>, W. Pryor<sup>6</sup>, E. Bunce<sup>7</sup>, A. Radioti<sup>8</sup>

<sup>1</sup>LESIA, Obs. de Paris, PSL, CNRS, UPMC, Univ. Paris Diderot, Meudon, France.

<sup>2</sup>National Institute of Information and Communications Technology, Tokyo, Japan.

<sup>3</sup>Center for Space Plasma and Aeronomic Research, University of Alabama, Huntsville, USA.

<sup>4</sup>Department of Physics, Lancaster University, Lancaster, UK.

<sup>5</sup>Department of Physics and Astronomy, University of Iowa, Iowa City, USA.

<sup>6</sup>Department of Science, Central Arizona College, Coolidge, USA.

<sup>7</sup>Department of Physics and Astronomy, University of Leicester, Leicester, UK.

<sup>8</sup>Space Science, Technologies and Astrophysics Research Institute, Liège, Belgium.

## Key Points:

- Saturn's northern UV aurorae at solstice were sampled from HST observations coordinated with Cassini's Grand Finale.
- The observed aurorae are highly variable with powerful events, radiating up to 120 GW, controlled by solar wind and planetary rotation.
- The average auroral brightness strongly varies with LT with two maxima at dawn (previously known) and pre-midnight (newly identified).

## Abstract

Saturn's northern far-ultraviolet aurorae have been regularly observed throughout 2017 with the Space Telescope Imaging Spectrograph (STIS) of the Hubble Space Telescope (HST), during northern summer solstice. These conditions provided the best achievable viewing of the northern kronian auroral region for an Earth-based telescope and a maximal solar illumination, expected to maximize the magnetosphere-ionosphere coupling. The HST observations were coordinated with *in situ* measurements along the path of the Cassini spacecraft across auroral field lines during the Grand Finale. In this study, we analyze 24 STIS images concurrently with quasi-continuous Cassini/RPWS measurements of Saturn's Kilometric Radiation and solar wind parameters derived from numerical MHD models. The observed northern aurorae display highly variable auroral components, **down to timescales of minutes**, with a total power ranging from 7 to  $124 \pm 11$  GW. They include a prominent main oval **poleward of  $72^\circ$  latitude and shifted by  $\sim 3^\circ$  toward the nightside**, which bears clear signatures of the solar wind and planetary rotation control, **unexpectedly frequent** cusp emissions near noon, including **the brightest ever reported event** which radiated  $13 \pm 1$  GW, and a dayside weak secondary oval **situated** around  $70^\circ$  latitude. On average, the northern aurorae display a strong LT dependence with two maxima at dawn and pre-midnight, the latter being attributed to regular nightside injections possibly associated with solstice conditions. **The average aurora also displays clues of a rotational control of the oval's average position, but not of its intensity.** These results provide a reference **frame** to analyze Cassini *in situ* and/or remote measurements, whether simultaneous or not.

## 1 Introduction

Saturn's aurorae have been intensively observed from Earth over the past decades with the Hubble Space Telescope (HST) in the far-ultraviolet (FUV) mainly using the Space Telescope Imaging Spectrograph (STIS) and the Advanced Camera for Surveys (ACS) [Grodent, 2015, and refs therein]. Many of these observations were coordinated with *in situ* and/or remote measurements from the Cassini spacecraft, including its Ultraviolet Imaging Spectrometer (UVIS), during its orbital tour from 2004 to 2017. Recent reviews summarize our current understanding of kronian auroral processes [Kurth *et al.*, 2009; Badman *et al.*, 2015; Stallard *et al.*, in press, and refs therein].

The UV aurorae are the neutral atmospheric response of the prominent H and H<sub>2</sub> species to precipitations of electrons energized in the magnetosphere. The energy of primary electrons, measured by various methods based on spectroscopic HST/STIS and Cassini/UVIS measurements ranges from a few keV to a few tens of keV [Gustin *et al.*, 2017]. The kronian aurorae decompose into a variety of components, tentatively listed by Grodent [2015], driven by different acceleration processes and underlying current systems. We hereafter restrict ourselves to four broad categories : **the so-called main oval, noon/post-noon high latitude emissions (polar cusp and bifurcations), the low-latitude secondary oval and the Enceladus footprint.**

The dominant auroral emission is a circumpolar main oval, whose intensity and location significantly vary with time. It was early found to be associated with Saturn's Kilometric Radiation (SKR) [Kurth *et al.*, 2005] and with strong upward field-aligned currents located slightly equatorward of the open-closed field line boundary [Bunce *et al.*, 2008; Belenkaya *et al.*, 2008; Hunt *et al.*, 2015]. It typically radiates a few tens of kilo-Rayleighs (kR, **local photon flux per pixel**) and a few tens of GW (**total power radiated by the whole auroral region**), although differing definitions of these quantities used in the literature prevent us from cross-comparing them **for the purpose of, for example, investigating** seasonal variations. The quiet main oval is a quasi-circular narrow faint ring of emission near  $72 - 75^\circ$  northern latitudes. By contrast, magnetospheric compressions driven by interplanetary shocks trigger bright auroral storms typically lasting for  $\sim 1.5$  planetary rota-

tions ( $1.5 \times \sim 10.7$  h), with a **significant part of the** main oval expanding toward high latitudes [Prangé et al., 2004; Clarke et al., 2005, 2009; Meredith et al., 2014a; Badman et al., 2016]. Longitudinally extended intensifications along the undisturbed oval phased with SKR were alternately related to rotationally-modulated nightside injections [Jackman et al., 2009; Mitchell et al., 2009; Nichols et al., 2010a; Lamy et al., 2013]. The main oval additionally hosts a variety of smaller-scale transient and/or sub-corotating hot spots [Radioti et al., 2009; Grodent et al., 2011; Meredith et al., 2013; Radioti et al., 2015]. On average, its brightness strongly varies with Local Time (LT) with a main maximum at dawn [Badman et al., 2006; Lamy et al., 2009; Carbary, 2012], a **peculiarity** of Saturn’s aurorae.

Cusp aurorae have also been **occasionally** identified as emissions radiating a few GW and up to 50 kR, varying on timescales of hours, and confined close to noon either along the main oval or poleward of it depending on the orientation of the interplanetary magnetic field [Gérard et al., 2005; Meredith et al., 2014b; Palmaerts et al., 2016; Kinrade et al., 2017]. Such signatures are sometimes associated with duskside bifurcations of the main emission, similarly attributed to dynamical dayside reconnection [Radioti et al., 2011; Meredith et al., 2014b]. A faint secondary oval,  $\sim 2$  kR bright, has additionally been identified on the southern nightside in HST/STIS and then Cassini/UVIS images equatorward of the main one. **This component** appeared as a **few-degrees-wide** ring near  $-67^\circ$  southern latitude [Grodent et al., 2010; Lamy et al., 2013; Radioti et al., 2017]. Grodent et al. [2010] attributed it to the precipitation of suprathermal electrons from the middle magnetosphere rather than to a field-aligned current system. Finally, a last important auroral feature consists of a spot at the magnetic footprint of the moon Enceladus driven by the planet-satellite interaction. It was identified as a 1 kR bright emission near  $+64.5^\circ$  latitude in only three Cassini/UVIS images [Pryor et al., 2011]. HST **failed to detect this spot** so far [Wannawichian et al., 2008].

In the frame of Cassini’s Grand Finale, HST/STIS regularly observed Saturn’s northern aurorae throughout 2017, during northern summer solstice (reached on 24 May). These conditions offered the best achievable HST viewing of the northern auroral region. They also provided maximal solar illumination (with a sub-solar latitude of  $26.73^\circ$ ), i.e. maximal northern ionospheric conductivity and thus maximized ionosphere-magnetosphere coupling through the current systems driving most of the kronian aurorae. The HST observations were carefully coordinated with *in situ* measurements of the Cassini spacecraft within the auroral region, for which they thus provide a frame of interpretation. In this article, we analyze 24 HST/STIS images concurrently with Cassini SKR observations and propagated solar wind (SW) parameters. The dataset is presented in section 2 and analyzed in section 3. Results are then discussed in section 4. Details on the HST data processing and supplementary Figures are provided in the supplementary material.

## 2 Dataset

### 2.1 HST/STIS observations

During the Cassini Grand Finale, STIS observed Saturn’s FUV auroral emissions during 25 HST orbits distributed throughout 2017. These were scheduled when Cassini was planned to traverse SKR sources, themselves colocated with layers of auroral field-aligned upward currents [Lamy et al., in press]. Each orbit included a single,  $\sim 44$  **min long**, time-tagged exposure. The time-tag mode provides the arrival time of photons recorded on the STIS MAMA (Multi-Anode Microchannel Array) detector at a 125 microsec resolution and thus enables us to track dynamics at timescales shorter than the exposure (**as illustrated in supplementary Figure S1 and Animation S1**). Out of 25 orbits, 24 acquired  $1024 \times 1024$  pix images at  $0.00247$  arcsec.pix $^{-1}$  resolution with the Strontium Fluoride filter F25SrF $_2$  (148 nm central wavelength, 28 nm FWHM) which rejects wavelengths shortward of 128 nm and notably the H Ly- $\alpha$  line. One orbit was also used to slew the northern auroral region with the 0.5 arcsec slit and the G140L grating. In this study, we

focus on the analysis of the images, processed and translated into brightnesses and power radiated over the full H<sub>2</sub> bands (**70-180 nm**) as detailed in the supplementary material.

## 2.2 Cassini/RPWS data and solar wind models

Cassini quasi-continuous observations of the Radio and Plasma Wave Science experiment (RPWS) [Gurnett *et al.*, 2004] were used to monitor the activity of Saturn's Kilometric Radiation measured between a few kHz and occasionally beyond 1000 kHz. We derived both power integrated over 10-1100 kHz and flux densities between 3.5 and 1500 kHz normalized to 1 AU **observing distance** for comparison purposes with previous studies [Lamy *et al.*, 2008]. The normalization assumes a source-observer distance equal to the planet-observer one, an assumption which is less and less valid for closer Cassini-Saturn distances, but fair enough to assess typical intensities. **We also used northern SKR phases, derived as described in [Lamy, 2011] from the most recent northern SKR period (~ 10.8 h throughout 2017) [Lamy, 2017].**

The **solar wind** (SW) parameters used in this study were numerically propagated from the Earth's orbit out to Saturn with two **magneto-hydrodynamic (MHD)** codes. The Tao 1D model was originally developed for the jovian case [Tao *et al.*, 2005] and later extrapolated **to Saturn's orbit** (e.g. [Kimura *et al.*, 2013]). The Multi-scale Fluid-kinetic Simulation Suite (MS-FLUKSS) [Pogorelov *et al.*, 2014] is a 3D model validated in the outer heliosphere thanks to *in situ* plasma measurements of Ulysses, Voyager and New Horizons [Kim *et al.*, 2016]. The input parameters are, for both models, near-Earth SW *in situ* observations provided by either NASA/GSFC's OMNI 1h averaged data obtained from Wind measurements [King and Papitashvili, 2005] and/or Stereo-A measurements instead. The uncertainty depends on the derived parameters and on the angular separation between the Earth and Saturn and gradually increases from opposition. For angular separations less than 90°, which provide a fair coverage of the year through complementary Omni and Stereo-A inputs, the typical uncertainty on the timing of dynamic pressure fronts is estimated to be less than ±35 h, according to previous results from another 1D model [Zieger and Hansen, 2008], whose results are not available for this study.

## 3 Results

### 3.1 A variety of variable components

Figure 1 displays polar projections of all STIS images, labelled a to x, as a function of LT. Images h-i, j-k, l-m, o-p, q-r, t-v and w-x were acquired along successive HST orbits. The observed aurorae reveal a rich variety of emissions, **with highly variable, down to timescales of minutes (see Figure S1 and Animation S1), localized features** dominated in intensity by the main oval. The latter is an inhomogeneous circumpolar ring of emission generally more intense in the dawn and pre-midnight sectors. It is quasi-circular at 72-73° latitude in its quiet state (images n, u-v) with brightnesses ranging from a few tens of kR down to the ~ 8 kR noise level (see supplementary material). Whenever active, it reaches higher latitudes, often with a left-handed spiral shape (the oval develops counterclockwise from the pole). In image a, the spiral even surrounds the magnetic pole up to extreme 87 – 88° latitudes. The brightest events reached peak brightnesses in excess of 150 kR (images a, l, s). **Overall, half of the STIS images were acquired when the Cassini magnetic footprint simultaneously intercepted auroral emissions** (red curves).

Isolated emission regions regularly observed close to noon, located either poleward of the main oval (images c, e, n, q, s and possibly i, w, yellow arrows) or along it (images f-h, j, orange arrows) are then interpreted as cusp aurorae. The identification of cusp emission in the latter case is more ambiguous as hot spots sub-corotating along the main oval can move through noon from dawn to dusk [Meredith *et al.*, 2013]. These emissions are often associated with duskside bifurcations of the main oval toward high latitudes

(images b, e, j-k, n, s, x) accounting for the general left-handed spiral shape of the main emission. **The association between bifurcations**, suggesting dynamical lobe reconnection, and noon spots further supports the interpretation of the latter as cusp emissions. Image s shows the brightest example around 10:30 LT and 84° latitude, **persisting over the 44 min exposure time and variable at timescales of minutes** (see **Animation S1 and Figure S1**) with unusually large brightnesses exceeding 100 kR, the largest ever reported.

A faint dayside secondary oval equatorward of the main one clearly appears at several occasions within 65 – 72° latitude, sometimes in restricted LT sectors (images a, b, l, v, green arrows). While this secondary emission appears distinct from the main one, we cannot exclude that it is actually reminiscent of ancient long-lived structures from the main oval which moved toward low latitudes. Half of these examples correspond to active events when the main oval moved to high latitudes. In image a, this secondary oval appears at 69 – 72° quasi-continuously from 06:00 LT (or 00:00 LT for the emission  $\leq 70^\circ$ ) to 18:00 LT, with brightnesses which can exceed 10 kR (the noise level in Fig. 1a is  $\sim 8$  kR). Interestingly, for this image at least, the Cassini footprint intercepts the secondary oval near 11:00 LT simultaneously with the STIS exposure. Cassini/MAG measurements [Dougherty *et al.*, 2004] of the azimuthal magnetic component simultaneous to image a (see supplementary Figure S2) reveal successive small-scale abrupt gradients consistent with field-aligned current signatures, preceded  $\sim 1$  h earlier by a large positive gradient indicating a strong upward current layer consistent with the poleward main emission (e.g. [Bunce *et al.*, 2008; Talboys *et al.*, 2009, 2011; Hunt *et al.*, 2014; Lamy *et al.*, in press]).

Finally, we also systematically searched for possible emission at the northern Enceladus footprint (white boxes) but could not identify any signal.

### 3.2 Transient enhancements and associated drivers

Figure 2a plots the total auroral power radiated by H<sub>2</sub> (see section 2.1) as a function of time, with the individual power values being listed in Figure 1. The total auroral power radiated in the UV range may be easily obtained by adding a 12% contribution from H-Ly $\alpha$  (e.g. [Lamy *et al.*, 2013]). Overall, the radiated power strongly varies with time, with a factor of  $\sim 10$  between the weakest and the brightest events, weeks apart (s-t), and with a factor of  $\sim 2$  between consecutive orbits (t-v or w-x). Seven events showing active emissions radiated power larger than 65 GW, the brightest of which reach 124, 93 and  $120 \pm 11$  GW for images a, l and s, resp. The latter includes the bright cusp emission, which radiated  $13 \pm 0.5$  GW.

Solar wind and planetary rotation both control SKR activity, in addition to UV aurorae. While SW-induced magnetospheric compressions trigger global SKR enhancement extending toward low frequencies and lasting for more than a planetary rotation [Desch, 1982; Kurth *et al.*, 2005; Lamy *et al.*, 2010; Bunce *et al.*, 2010; Kurth *et al.*, 2016; Reed *et al.*, 2018], short-lasting SKR intensifications occurring close to the phase of regular SKR bursts are **associated** with rotationally-modulated nightside injections [Jackman *et al.*, 2009; Mitchell *et al.*, 2009; Lamy *et al.*, 2013; Reed *et al.*, 2018].

The purpose of Fig. 2 is to assess the origin of the most active aurorae. Fig. 2b-c displays measurements of SKR radiated power and the dynamic spectrum of its flux density, which provide a quasi-continuous proxy of the auroral activity at high temporal resolution. Fig. 2d-e display solar wind propagated velocity and dynamic pressure derived from the models described in section 2.2. Vertical dashed lines mark the timing of HST observations a-x. We can immediately notice that most (if not all) of long-lasting SKR intensifications with extensions toward both low and high frequencies fairly match the arrival of a SW pressure front within error bars. The 5 brightest FUV events a, e, l-m and s (boldface dashed lines), with power  $\geq 75$  GW, peak brightnesses  $\geq 150$  kR and high latitude emissions, all coincide with such SKR enhancements (zoomed in RPWS dynamic

spectra associated with those events are displayed in supplementary Figure S3) and can in turn be identified as SW-driven auroral storms. Precisely, the UV observations were respectively acquired ~23, 19, 28-30 and 20 h after the start of their associated SKR enhancement, itself lasting at least ~52, 22, 47 and 32 h with multiple bursts, respectively, so that the HST images diagnosed a late stage of 4 different storms.

In contrast, the 2 consecutive images j-k, with power of ~ 70 GW and peak brightnesses  $\geq 80$  kR show a main emission confined at usual latitudes with a midnight active region which rotated toward dawn between the 2 images. These were acquired during quiet solar wind conditions at northern SKR phases of 301 and 354°, just before a modest northern SKR burst (see supplementary Figure S3). This SKR burst thus appears roughly consistent with the arrival of the active region to dawn. The auroral episodes j-k therefore suggest a rotationally-driven nightside injection.

### 3.3 Average aurora at solstice

We now turn to the mean spatial distribution and intensity of Saturn's northern UV aurorae. Figures 3a-b displays average polar projections as a function of LT : panel a displays brightnesses at high spatial resolution and panel b displays brightness iso-contours of the smoothed image instead. **Figures 3c-d display average intensity profiles as a function of LT and latitude.** The average main oval is a circumpolar ring of emissions of a few kR confined within 70 – 80° latitudes. Increasing brightnesses then gradually map to a dusk-to-noon partial ring, with the most intense emissions (the red-shaded area in panel b maps brightnesses  $\geq 15$  kR) between pre-midnight and dawn.

The main oval expands poleward beyond ~ 80° between 04:00 and 21:00 LT, encompassing polar arcs and spots produced by dawnside auroral storms, noon cusp and dusk-side bifurcations. The low average brightness of these high latitude emissions illustrates their transient nature. Figure additionally reveals that the average main oval is **shifted** toward the nightside : while the low-latitude boundary (**estimated from the latitudinally-extended blue-shaded 3 kR contour in Figure 3b**) extends down to 70-72° between 18:00 and 06:00 LT **through midnight** (or even below in the pre-midnight sector), it reaches 73-75° instead between 09:00 and 15:00 LT **through noon**, with highest latitudes at 14:00 LT.

This **shift** enables us to distinctly identify an equatorward secondary oval between 67° and 73° **in Figure 3a-b,d**, split from the main oval, with a typical mean brightness of ~2 kR, occasionally exceeding 3 kR (the standard deviations in Fig. 3a-b are  $\leq 1.5$  kR). It is pretty remarkable that this secondary oval is detected quasi-continuously from noon to the dawn and dusk sides with roughly homogeneous intensities, which suggest that it primarily consists of steady weak emissions. These characteristics are fairly consistent with the 1.7 kR secondary oval previously identified at -67° southern nightside latitude [*Grodent et al.*, 2010]. Precisely, when taking into account the 2° northern latitudinal shift due to the northern magnetic field offset, the northern **dayside** oval appears at slightly higher latitudes than the **nightside** southern one, in agreement with the nightside **shift** of the main oval.

Figure 3c quantifies the LT dependence of northern aurorae discussed above by plotting the average brightness profile between 70° and 85° latitude (black line), where the emissions are fully visible **at all LT**. It displays two clear distinct peaks at 05:00 LT and 22:00 LT. When building the same Figure with SW-driven auroral storms removed, these peaks remain but are slightly shifted toward 06:30 and 20:30 LT instead.

Finally, we similarly investigated the role of planetary rotation, previously found to modulate the intensity and position of UV aurorae in both hemispheres [*Nichols et al.*, 2010a,b]. Supplementary Figure S4 displays the auroral brightness integrated over 70–80° latitudes of each image as a function of northern SKR phase and LT. The dashed line displays a guide meridian indicating an active auroral region rotating at the northern SKR

272 period and reaching 06 : 00 LT at a phase of  $0^\circ$  (*i.e.* at the timing of SKR bursts). In  
 273 contrast with previous positive results obtained with a similar representation for the south-  
 274 ern UV aurorae and southern SKR sources [Nichols *et al.*, 2010a; Lamy, 2011; Lamy *et al.*,  
 275 2013], no active region can be continuously tracked along or close to this guide merid-  
 276 ian. **Supplementary Figures S5a-b displays average polar projections of the aurorae**  
 277 **similar to Figures 3a-b but organized as a function of northern SKR phase. The Local**  
 278 **Times were transposed into phases again by assuming that SKR maxima occur at the**  
 279 **pass of a rotating active region through 06 : 00 LT. Figure S5 does not reveal any par-**  
 280 **ticular maximum near  $0^\circ$ , in agreement with Figure S4. The two maxima observed near**  
 281  **$90^\circ$  and  $180^\circ$  instead are mainly due to the auroral storms identified above. Looking**  
 282 **now at the low-latitude boundary of the main emission (yellow contour in Figure S5b),**  
 283 **it clearly reaches higher latitudes on the left-hand side ( $74\text{--}75^\circ$  latitude at  $90^\circ$  phase)**  
 284 **than on the right-hand side ( $72\text{--}73^\circ$  latitude at  $180^\circ$  phase). This latitudinal shift is con-**  
 285 **sistent with that predicted from the tilt of the northern oval when the upward current**  
 286 **layer reaches dawn [Nichols *et al.*, 2010b] and therefore suggests a rotational control of**  
 287 **the oval's position (and not of its intensity, as already observed between 2011 and 2013**  
 288 **[Nichols *et al.*, 2016]), whose detailed study is beyond the scope of this paper.**

#### 289 4 Discussion

290 In the previous section, we described the individual and average properties of the  
 291 kronian northern aurorae at solstice, some of which are further discussed below.

292 The peak of northern average auroral brightness at 05:00 LT matches that previ-  
 293 ously seen with Cassini/UVIS observations [Carbary, 2012], although its displacement  
 294 toward 06:30 when removing auroral storms provides a typical uncertainty linked to the  
 295 statistics of the dataset. This may account for the difference with the southern average  
 296 auroral brightness peak found from HST STIS/ACS observations at 09:00 [Lamy *et al.*,  
 297 2009] and from Cassini/UVIS data at 06:00 LT [Carbary, 2012]. More importantly, the  
 298 HST observations of 2017 additionally reveal a second peak of comparable amplitude at  
 299 20 : 30 – 22 : 00 LT, previously unreported, and strikingly reminiscent of Earth's au-  
 300 rora. This LT sector is also the one where the equatorward latitude of the main oval (iso-  
 301 contours  $\geq 3$  kR in Fig. 3) minimizes. We thus suggest that this secondary peak arises  
 302 **either from a better viewing of the nightside sector or from** more frequent nightside in-  
 303 jections sampled in the analyzed dataset than in past studies [Badman *et al.*, 2006; Lamy  
 304 *et al.*, 2009; Carbary, 2012], possibly favored under solstice conditions.

305 In contrast with a clear LT dependence of the auroral intensity, the rotational dy-  
 306 namics do not seem to play a significant role, if we except the moderate brightening phased  
 307 with the northern SKR seen in the two successive images j-k **and clues of a rotational**  
 308 **control of the oval's position.** Instead, the most obvious variability is that induced by  
 309 large scale auroral storms driven by the SW, for which SKR quasi-continuous observations  
 310 provide total durations estimated between 22 and 48 h. This largely exceeds the 11 – 21 h  
 311 range inferred by [Meredith *et al.*, 2013], which explained a typical duration of  $\sim 1.5$   
 312 planetary rotations for the time needed by hot plasma injected from the nightside with a  
 313 60% subcorotational motion to complete one rotation. Accounting for the observed dura-  
 314 tions would require very low sub-corotational rates (from 20 to 50%). Instead, we propose  
 315 that storms generally do not result from a single magnetospheric compression but from  
 316 a series of them consistent with the multiple SKR bursts observed along one long event.  
 317 The peculiar spiral shape observed in image a with extremely high latitudes surrounding  
 318 the northern magnetic pole finally questions the interpretation of the main emission as a  
 319 tracer of the open-closed field line boundary **located  $1\text{--}2^\circ$  poleward**, in which case the po-  
 320 lar cap **would correspond to a very small region around the pole. Analyzing Cassini *in***  
 321 ***situ* measurements obtained a few hours before image a (namely when the spacecraft**  
 322 **sampled the dawnside region poleward of the main oval) is required to adress this ques-**  
 323 **tion.** The detailed study of another example of UV auroral storm temporally resolved by

324 Cassini/UVIS and of an SKR long-lasting enhancement consistent with a SW origin is the  
 325 subject of a companion paper [Palmaerts *et al.*, 2018].

326 The apparent systematic  $\sim 3^\circ$  nightside **shift in latitude** of the average northern  
 327 auroral oval, previously unreported to our knowledge, is consistent with the modeled in-  
 328 fluence of the solar wind flow on the open-closed field line boundary [Belenkaya *et al.*,  
 329 2008].

330 Cusp emissions and bifurcations were very frequently observed, in  $\sim 50\%$  of the  
 331 images. This unusually high occurrence rate is likely related to the magnetosphere/SW  
 332 configuration reached at solstice. **This scenario** implies enhanced SW-driven mass load-  
 333 ing of the magnetosphere, and therefore supports more frequent nightside plasmoid re-  
 334 leases/injections. The observation of an unusually bright cusp emission in image s, ex-  
 335 tended by a duskside bifurcation connecting it to a spiral-shaped main oval and observed  
 336 during an auroral storm, suggests that it may have been induced by a SW-driven magneto-  
 337 spheric compression as observed at Earth [Farrugia *et al.*, 1995] and similarly proposed at  
 338 Uranus [Lamy *et al.*, 2017].

339 The identification of a dayside low latitude emission with 2 – 3 kR brightnesses  
 340 on average (which compare to that previously identified with comparable brightness and  
 341 latitude on the nightside) imply a steady mechanism able to operate at all longitudes. In  
 342 addition, it is worth noting that the dayside portion of the oval is not active in all indi-  
 343 vidual images and in half of the cases during auroral storms. This suggests an additional  
 344 transient activity possibly linked to dayside compression of magnetic field lines. The **pre-**  
 345 **viously proposed origin of such emission related to a suprathermal population of elec-**  
 346 **trons in the middle magnetosphere Grodent *et al.* [2010] is called into question** by both  
 347 this transient activity and by *in situ* magnetic measurements consistent with small-scale  
 348 field-aligned currents. **These features are alternatively consistent with either ancient**  
 349 **long-lived structures of the main emission associated with strong field-aligned currents**  
 350 **which moved toward lower latitudes and/or auroral precipitations associated with a**  
 351 **secondary current system previously observed within  $68.5 - 72^\circ$  latitudes [Hunt *et al.*,**  
 352 **2015].** The detailed analysis of Cassini plasma measurements during this peculiar event is  
 353 also necessary to address these questions.

## 354 5 Conclusion

355 In this study, we analyzed 24 HST/STIS images of Saturn's northern aurorae ac-  
 356 quired throughout 2017 during northern summer solstice, concurrently with Cassini/RPWS  
 357 SKR observations and numerically propagated SW parameters. The observed northern au-  
 358 rorae display highly variable auroral components, with a total power ranging from 7 to  
 359  $124 \pm 11$  GW. The prominent component is the main oval **observed poleward of  $72^\circ$  and**  
 360 **shifted by  $\sim 3^\circ$  toward the nightside** which bears clear signatures of the solar wind (4  
 361 auroral storms coincident with SKR long-lasting enhancements) and planetary rotation (1  
 362 auroral brightening coincident with a regular SKR burst). Recurrent cusp emissions and  
 363 bifurcations are unexpectedly frequent, in 50% of the images, with an unusually bright  
 364 cusp emission observed during an auroral storm which radiated  $13 \pm 1$  GW, likely triggered  
 365 by the SW. The identification of a dayside secondary oval at  $70^\circ$  latitudes, 2 – 3 kR bright  
 366 on average with some clues of temporal variability brings new constraints to its possible  
 367 origins. On average, the northern solstice aurorae display a strong LT dependence with  
 368 two maxima at dawn and pre-midnight, the latter being attributed to regular nightside in-  
 369 jections, with **clues of a rotational control of the oval's average position, but not of its**  
 370 **intensity.** These results provide a reference **frame** to analyze Cassini *in situ* and/or remote  
 371 measurements, whether simultaneous (the Cassini footprints intercepted an auroral compo-  
 372 nent in half of the images) or not.



## Acknowledgments

The data analyzed in this study are available from the following sources. The UV observations were obtained from the ESA/NASA Hubble Space Telescope (GO program #14811) : the original data can be retrieved from the MAST archive and the processed data from the APIS service hosted by the Paris Astronomical Data Centre at <http://apis.obspm.fr>. The Cassini/RPWS and MAG original data are accessible through the PDS archive at <https://pds.nasa.gov/>. The HFR processed data are available through the LESIA/Kronos database at <http://www.lesia.obspm.fr/kronos>. LL thanks Linda Spilker for her support to the original HST proposal, Fannie Serrano and Pauline Richard, who investigated short-term dynamics of Saturn's aurorae during their internship at LESIA, and Gabby Provan for useful discussions on the inexhaustible topic of kronian magnetospheric periodicities. The French co-authors acknowledge support from CNES and CNRS/INSU programs of Planetology (PNP) and Heliophysics (PNST). SVB was supported by an STFC Ernest Rutherford Fellowship ST/M005534/1. The research at the University of Iowa was supported by NASA through Contract 1415150 with the Jet Propulsion Laboratory.

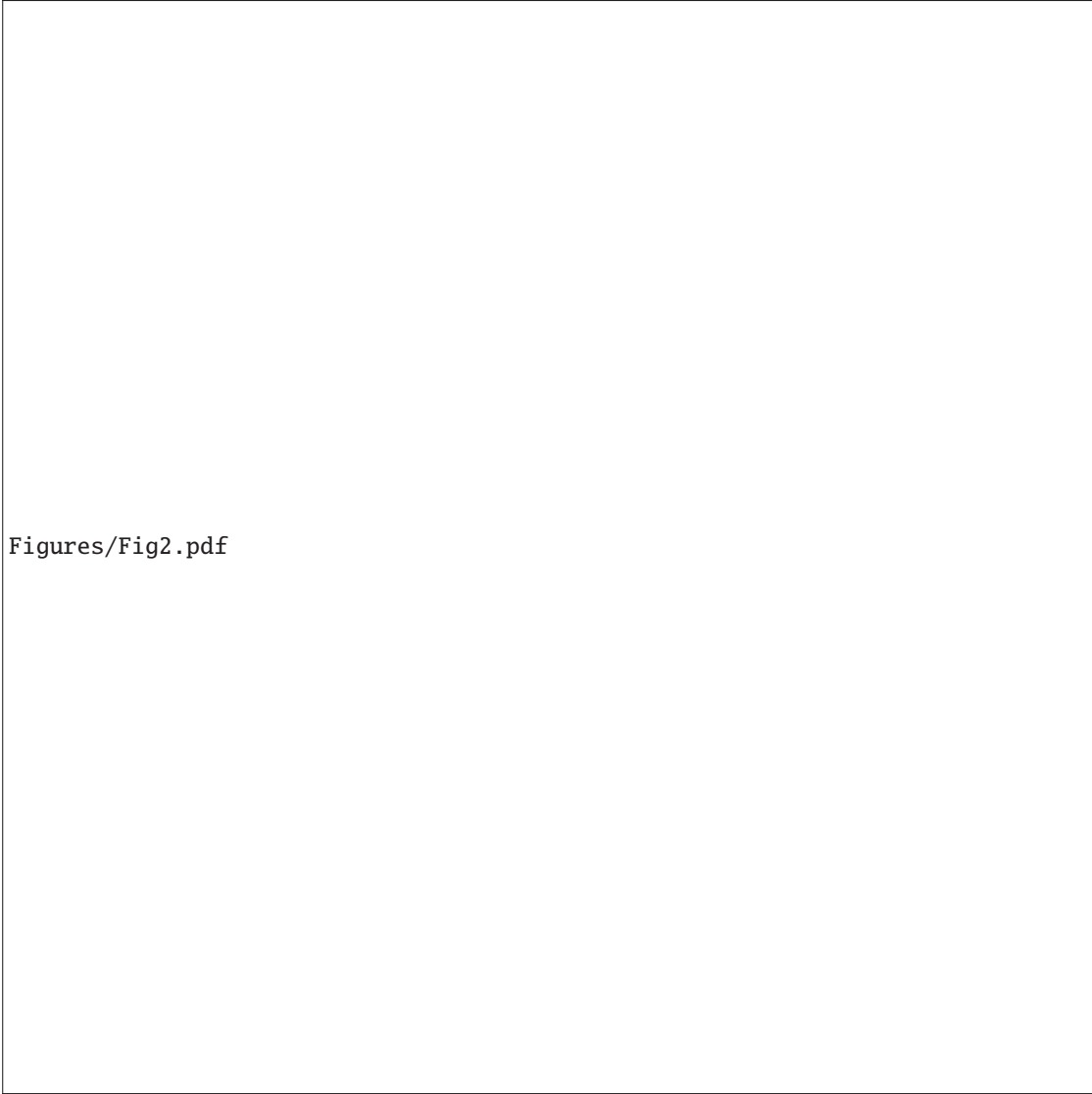
## References

- Badman, S. V., S. W. H. Cowley, J.-C. Gérard, and D. Grodent (2006), A statistical analysis of the location and width of Saturn's southern auroras, *Annales Geophysicae*, *24*, 3533–3545, doi:10.5194/angeo-24-3533-2006.
- Badman, S. V., G. Branduardi-Raymont, M. Galand, S. L. G. Hess, N. Krupp, L. Lamy, H. Melin, and C. Tao (2015), Auroral Processes at the Giant Planets: Energy Deposition, Emission Mechanisms, Morphology and Spectra, *Space Science Reviews*, *187*, 99–179, doi:10.1007/s11214-014-0042-x.
- Badman, S. V., G. Provan, E. J. Bunce, D. G. Mitchell, H. Melin, S. W. H. Cowley, A. Radioti, W. S. Kurth, W. R. Pryor, J. D. Nichols, S. L. Jinks, T. S. Stallard, R. H. Brown, K. H. Baines, and M. K. Dougherty (2016), Saturn's auroral morphology and field-aligned currents during a solar wind compression, *Icarus*, *263*, 83–93, doi:10.1016/j.icarus.2014.11.014.
- Belenkaya, E. S., S. W. H. Cowley, S. V. Badman, M. S. Blokhina, and V. V. Kalegaev (2008), Dependence of the open-closed field line boundary in Saturn's ionosphere on both the IMF and solar wind dynamic pressure: comparison with the UV auroral oval observed by the HST, *Annales Geophysicae*, *26*, 159–166, doi:10.5194/angeo-26-159-2008.
- Bunce, E., S. W. H. Cowley, D. L. Talboys, M. K. Dougherty, L. Lamy, W. S. Kurth, P. Schippers, B. Cecconi, P. Zarka, C. S. Arridge, and A. J. Coates (2010), Extraordinary field-aligned current signatures in Saturn's high-latitude magnetosphere: Analysis of Cassini data during Revolution 89, *J. Geophys. Res.*
- Bunce, E. J., C. S. Arridge, J. T. Clarke, A. J. Coates, S. W. H. Cowley, M. K. Dougherty, J.-C. Gérard, D. Grodent, K. C. Hansen, J. D. Nichols, D. J. Southwood, and D. L. Talboys (2008), Origin of Saturn's aurora: Simultaneous observations by Cassini and the Hubble Space Telescope, *Journal of Geophysical Research (Space Physics)*, *113*, A09209, doi:10.1029/2008JA013257.
- Carbary, J. F. (2012), The morphology of Saturn's ultraviolet aurora, *Journal of Geophysical Research (Space Physics)*, *117*, A06210, doi:10.1029/2012JA017670.
- Clarke, J. T., J.-C. Gérard, D. Grodent, S. Wannawichian, J. Gustin, J. Connerney, F. Crary, M. Dougherty, W. Kurth, S. W. H. Cowley, E. J. Bunce, T. Hill, and J. Kim (2005), Morphological differences between Saturn's ultraviolet aurorae and those of Earth and Jupiter, *Nature*, *433*, 717–719, doi:10.1038/nature03331.
- Clarke, J. T., J. Nichols, J. Gérard, D. Grodent, K. C. Hansen, W. Kurth, G. R. Gladstone, J. Duval, S. Wannawichian, E. Bunce, S. W. H. Cowley, F. Crary, M. Dougherty, L. Lamy, D. Mitchell, W. Pryor, K. Retherford, T. Stallard, B. Zieger, P. Zarka, and

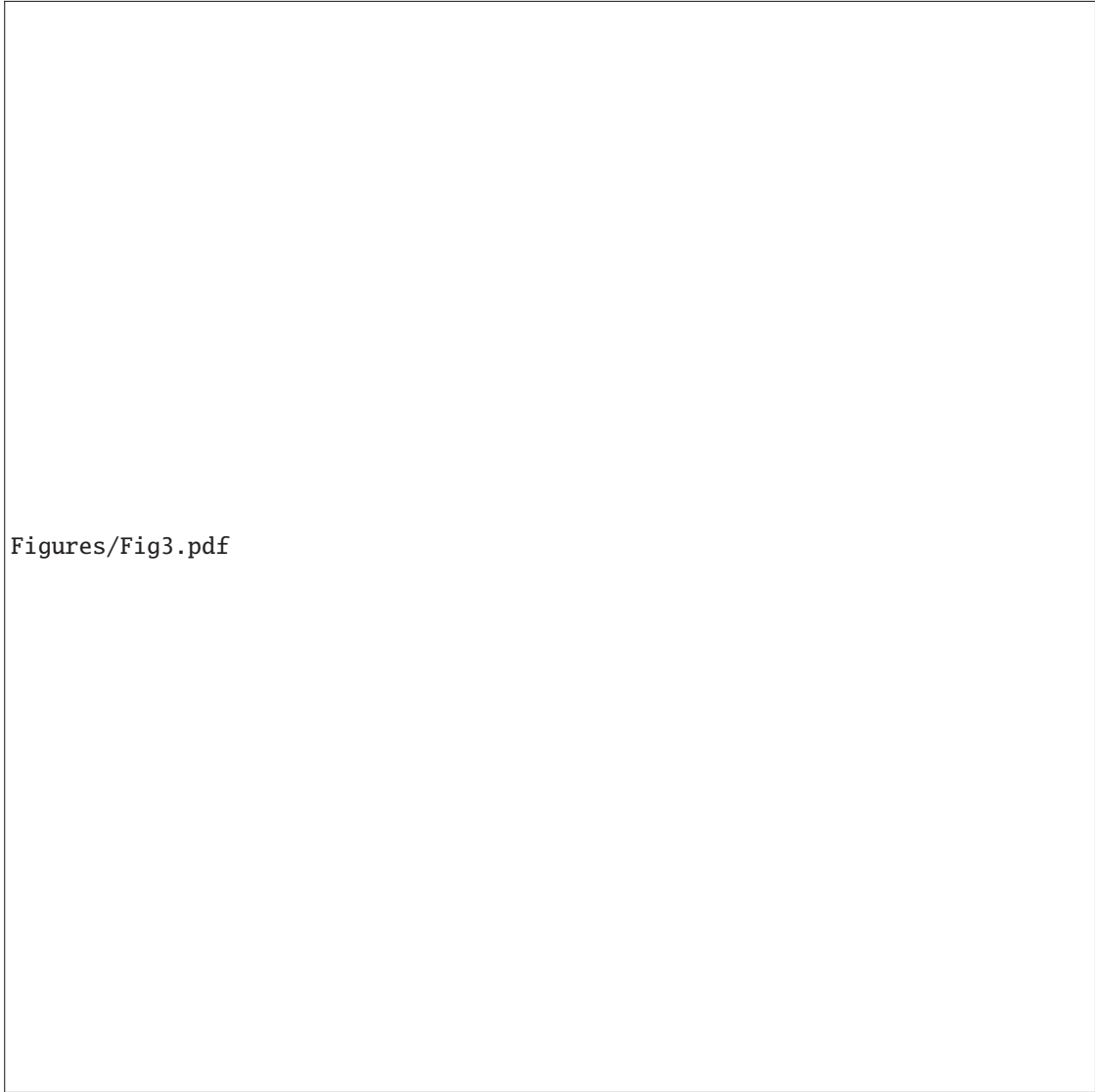
Figures/Fig1.pdf

389 **Figure 1.** Polar projections of HST/STIS images of northern kronian aurorae obtained in 2017, plotted  
 390 as a function of LT (**the red meridian indicate noon**). The 24× ~ 44 min-long exposures (labelled a to x)  
 391 were projected at 1100 km altitude [Gérard *et al.*, 2009]. The light time travel-corrected observing time, the  
 392 northern SKR phase and the total power radiated in the H<sub>2</sub> bands are provided above each image. Yellow  
 393 (orange) arrows indicate plausible cusp emissions poleward of (along) the main oval. Green arrows indicate a  
 394 low-latitude emission. White boxes map to the Enceladus magnetic footprint. The red (gray) curves plot the  
 395 Cassini magnetic footprint during (±2 h aside) each HST exposure.

449 B. Cecconi (2009), Response of Jupiter’s and Saturn’s auroral activity to the solar wind,  
 450 *J. Geophys. Res.*, 114(A13), A05,210, doi:10.1029/2008JA013694.  
 451 Desch, M. D. (1982), Evidence for solar wind control of Saturn radio emission, *J. Geo-*  
 452 *phys. Res.*, 87, 4549–4554, doi:10.1029/JA087iA06p04549.  
 453 Dougherty, M. K., S. Kellock, D. J. Southwood, A. Balogh, E. J. Smith, B. T. Tsurutani,  
 454 B. Gerlach, K. Glassmeier, F. Gleim, C. T. Russell, G. Erdos, F. M. Neubauer, and  
 455 S. W. H. Cowley (2004), The Cassini Magnetic Field Investigation, *Space Science Re-*  
 456 *views*, 114, 331–383, doi:10.1007/s11214-004-1432-2.



396 **Figure 2.** (a) Total auroral power radiated in the H<sub>2</sub> bands. (b) Total SKR power integrated over 10-  
397 1100 kHz with a 90 s resolution [*Lamy et al., 2008*] derived from (c) Cassini/RPWS dynamic spectrum of  
398 flux density between 3.5 and 1500 kHz. (d-e) Velocity and dynamic pressure propagated at Saturn by two  
399 MHD models (described in section 2.2), using either Omni or Stereo-A data inputs. The double black ar-  
400 row plots a  $\pm 35$  h error bar. Boldface portions of colored curves correspond to angular separation between  
401 Wind/Stereo-A and Saturn lower than 90°.



Figures/Fig3.pdf

402 **Figure 3.** (a) Average of the 24 polar projections displayed in Figure 1, **once smoothed over a 3 pix-wide**  
 403 **running box.** (b) Same as (a) **but using a 17 pix-wide running box instead, aimed at maximizing the**  
 404 **signal-to-noise at the expense of spatial resolution.** The color scale indicates iso-contours at 3, 7, 11 and  
 405 15 kR. These two panels display the average locus and brightness of the circumpolar main oval within  $70^{\circ}$ – $85^{\circ}$   
 406 latitude, of noon cusp emissions within or poleward of the main oval and of the equatorward secondary oval,  
 407 visible near  $70^{\circ}$  dayside latitudes. (c) Average intensity profiles integrated in latitude between  $70^{\circ}$  and  $85^{\circ}$   
 408 (black line) encompassing all auroral emissions and between  $55^{\circ}$  and  $65^{\circ}$  (gray line) out of any auroral  
 409 emissions as a function of LT. The average auroral intensity clearly displays two wide maxima at 05:00 and  
 410 22:00 LT. (d) Same as (c) as a function of latitude for successive 02 h-wide LT ranges (colored lines).  
 411 **The main emission is visible at all LT, with distinct high and low latitude emissions mostly visible on the**  
 412 **dayside.**

- 457 Farrugia, C. J., P. E. Sandholt, S. W. H. Cowley, D. J. Southwood, A. Egeland,  
 458 P. Stauning, R. P. Lepping, A. J. Lazarus, T. Hansen, and E. Friis-Christensen (1995),  
 459 Reconnection-associated auroral activity stimulated by two types of upstream dynamic  
 460 pressure variations: Interplanetary magnetic field  $B_z \sim 0$ ,  $B_y \ll 0$  case, *J. Geophys.*  
 461 *Res.*, *100*, 21,753–21,772, doi:10.1029/95JA01082.
- 462 Gérard, J.-C., E. J. Bunce, D. Grodent, S. W. H. Cowley, J. T. Clarke, and S. V. Badman  
 463 (2005), Signature of Saturn’s auroral cusp: Simultaneous Hubble Space Telescope FUV  
 464 observations and upstream solar wind monitoring, *Journal of Geophysical Research*  
 465 (*Space Physics*), *110*(A9), A11201, doi:10.1029/2005JA011094.
- 466 Gérard, J.-C., B. Bonfond, J. Gustin, J. T. Clarke, J. T. Clarke, D. Bisikalo, and V. She-  
 467 matovich (2009), Altitude of Saturn’s aurora and its implications for the character-  
 468 istic energy of precipitated electrons, *Geophys. Res. Lett.*, *36*, L02,202, doi:10.1029/  
 469 2008GL036554.
- 470 Grodent, D. (2015), A Brief Review of Ultraviolet Auroral Emissions on Giant Planets,  
 471 *Space Science Reviews*, *187*, 23–50, doi:10.1007/s11214-014-0052-8.
- 472 Grodent, D., A. Radioti, B. Bonfond, and J.-C. Gérard (2010), On the origin of Saturn’s  
 473 outer auroral emission, *Journal of Geophysical Research (Space Physics)*, *115*(A14),  
 474 A08219, doi:10.1029/2009JA014901.
- 475 Grodent, D., J. Gustin, J.-C. Gérard, A. Radioti, B. Bonfond, and W. R. Pryor (2011),  
 476 Small-scale structures in Saturn’s ultraviolet aurora, *Journal of Geophysical Research*  
 477 (*Space Physics*), *116*(A15), A09225, doi:10.1029/2011JA016818.
- 478 Gurnett, D. A., W. S. Kurth, D. L. Kirchner, G. B. Hospodarsky, T. F. Averkamp,  
 479 P. Zarka, A. Lecacheux, R. Manning, A. Roux, P. Canu, N. Cornilleau-Wehrin, P. Ga-  
 480 llopeau, A. Meyer, R. Boström, G. Gustafsson, J. Wahlund, L. Åhlen, H. O. Rucker,  
 481 H. P. Ladreiter, W. Macher, L. J. C. Woolliscroft, H. Alleyne, M. L. Kaiser, M. D. De-  
 482 sch, W. M. Farrell, C. C. Harvey, P. Louarn, P. J. Kellogg, K. Goetz, and A. Pedersen  
 483 (2004), The Cassini Radio and Plasma Wave Investigation, *Space Science Reviews*, *114*,  
 484 395–463.
- 485 Gustin, J., D. Grodent, A. Radioti, W. Pryor, L. Lamy, and J. Ajello (2017), Statistical  
 486 study of Saturn’s auroral electron properties with Cassini/UVIS FUV spectral images,  
 487 *Icarus*, *284*, 264–283, doi:10.1016/j.icarus.2016.11.017.
- 488 Hunt, G. J., S. W. H. Cowley, G. Provan, E. J. Bunce, I. I. Alexeev, E. S. Belenkaya, V. V.  
 489 Kalegaev, M. K. Dougherty, and A. J. Coates (2014), Field-aligned currents in Sat-  
 490 urn’s southern nightside magnetosphere: Subcorotation and planetary period oscillation  
 491 components, *Journal of Geophysical Research (Space Physics)*, *119*, 9847–9899, doi:  
 492 10.1002/2014JA020506.
- 493 Hunt, G. J., S. W. H. Cowley, G. Provan, E. J. Bunce, I. I. Alexeev, E. S. Belenkaya, V. V.  
 494 Kalegaev, M. K. Dougherty, and A. J. Coates (2015), Field-aligned currents in Sat-  
 495 urn’s northern nightside magnetosphere: Evidence for interhemispheric current flow  
 496 associated with planetary period oscillations, *Journal of Geophysical Research (Space*  
 497 *Physics)*, *120*, 7552–7584, doi:10.1002/2015JA021454.
- 498 Jackman, C. M., L. Lamy, M. P. Freeman, P. Zarka, B. Cecconi, W. S. Kurth, S. W. H.  
 499 Cowley, and M. K. Dougherty (2009), On the character and distribution of lower-  
 500 frequency radio emissions at Saturn and their relationship to substorm-like events,  
 501 *Journal of Geophysical Research (Space Physics)*, *114*(A13), A08211, doi:10.1029/  
 502 2008JA013997.
- 503 Kim, T. K., N. K. Pogorelov, H. A. Zank, G. P. abd Elliott, and D. J. McComas (2016),  
 504 Modeling the Solar Wind at the Ulysses, Voyager, and New Horizons Spacecraft, *Astro-*  
 505 *physical Journal*, *32*(1), 72, doi:10.3847/0004-637X/832/1/72.
- 506 Kimura, T., L. Lamy, C. Tao, S. V. Badman, S. Kasahara, B. Cecconi, P. Zarka,  
 507 A. Morioka, Y. Miyoshi, D. Maruno, Y. Kasaba, and M. Fujimoto (2013), Long-term  
 508 modulations of Saturn’s auroral radio emissions by the solar wind and seasonal vari-  
 509 ations controlled by the solar ultraviolet flux, *Journal of Geophysical Research (Space*  
 510 *Physics)*, *118*, 7019–7035, doi:10.1002/2013JA018833.

- 511 King, J. H., and N. E. Papitashvili (2005), Solar wind spatial scales in and comparisons of  
512 hourly Wind and ACE plasma and magnetic field data, *Journal of Geophysical Research*  
513 (*Space Physics*), *110*, A02104, doi:10.1029/2004JA010649.
- 514 Kinrade, J., S. V. Badman, E. J. Bunce, C. Tao, G. Provan, S. W. H. Cowley, A. Gro-  
515 cott, R. L. Gray, D. Grodent, T. Kimura, J. D. Nichols, C. S. Arridge, A. Radioti, J. T.  
516 Clarke, F. J. Crary, W. R. Pryor, H. Melin, K. H. Baines, and M. K. Dougherty (2017),  
517 An isolated, bright cusp aurora at Saturn, *Journal of Geophysical Research (Space*  
518 *Physics*), *122*, 6121–6138, doi:10.1002/2016JA023792.
- 519 Kurth, W. S., D. A. Gurnett, J. T. Clarke, P. Zarka, M. D. Desch, M. L. Kaiser, B. Cec-  
520 conni, A. Lecacheux, W. M. Farrell, P. Galopeau, J. Gérard, D. Grodent, R. Prangé,  
521 M. K. Dougherty, and F. J. Crary (2005), An Earth-like correspondence between  
522 Saturn’s auroral features and radio emission, *Nature*, *433*, 722–725, doi:10.1038/  
523 nature03334.
- 524 Kurth, W. S., E. J. Bunce, J. T. Clarke, F. J. Crary, D. C. Grodent, A. P. Ingersoll, U. A.  
525 Dyudina, L. Lamy, D. G. Mitchell, A. M. Persoon, W. R. Pryor, J. Saur, and T. Stallard  
526 (2009), Auroral processes, in *Saturn from Cassini-Huygens*, pp. 333–374, Springer, New  
527 York.
- 528 Kurth, W. S., G. B. Hospodarsky, D. A. Gurnett, L. Lamy, M. K. Dougherty, J. Nichols,  
529 E. J. Bunce, W. Pryor, K. Baines, T. Stallard, H. Melin, and F. J. Crary (2016), Saturn  
530 kilometric radiation intensities during the Saturn auroral campaign of 2013, *Icarus*, *263*,  
531 2–9, doi:10.1016/j.icarus.2015.01.003.
- 532 Lamy, L. (2011), Variability of southern and northern SKR periodicities, in *Planetary Ra-*  
533 *dio Emissions VII*, edited by H. O. Rucker, W. S. Kurth, P. Louarn, & G. Fischer, pp.  
534 39–50, Austrian Academy of Sciences Press, Vienna.
- 535 Lamy, L. (2017), The Saturnian Kilometric Radiation before the Cassini Grand Finale,  
536 in *Planetary Radio Emissions VIII*, edited by G. Fischer, G. Mann, M. Panchenko, &  
537 P. Zarka, p. 171–190, Austrian Academy of Sciences Press, Vienna.
- 538 Lamy, L., P. Zarka, B. Cecconi, R. Prangé, W. S. Kurth, and D. A. Gurnett (2008), Sat-  
539 urn kilometric radiation: Average and statistical properties, *J. Geophys. Res.*, *113*(A12),  
540 7201–+, doi:10.1029/2007JA012900.
- 541 Lamy, L., B. Prangé, R., P. Zarka, B. Cecconi, J. Nichols, and J. Clarke (2009), An au-  
542 roral oval at the footprint of Saturn’s kilometric radio sources, colocated with the UV  
543 aurorae, *J. Geophys. Res.*, *114*, A10,212, doi:10.1029/2009JA014401.
- 544 Lamy, L., P. Schippers, P. Zarka, B. Cecconi, C. S. Arridge, M. K. Dougherty, P. Louarn,  
545 N. André, W. S. Kurth, R. L. Mutel, D. A. Gurnett, and A. J. Coates (2010), Properties  
546 of Saturn kilometric radiation measured within its source region, *Geophys. Res. Lett.*,  
547 *37*, 12,104–+, doi:10.1029/2010GL043415.
- 548 Lamy, L., R. Prangé, W. Pryor, J. Gustin, S. V. Badman, H. Melin, T. Stallard, D.-G.  
549 Mitchell, and P. C. Brandt (2013), Multispectral simultaneous diagnosis of Saturn’s au-  
550 rorae throughout a planetary rotation, *Journal of Geophysical Research (Space Physics)*,  
551 *118*, 4817–4843, doi:10.1002/jgra.50404.
- 552 Lamy, L., R. Prangé, K. C. Hansen, C. Tao, S. W. H. Cowley, T. S. Stallard, H. Melin,  
553 N. Achilleos, P. Guio, S. V. Badman, T. Kim, and N. Pogorelov (2017), The aurorae of  
554 Uranus past equinox, *Journal of Geophysical Research (Space Physics)*, *122*, 3997–4008,  
555 doi:10.1002/2017JA023918.
- 556 Lamy, L., P. Zarka, B. Cecconi, R. Prangé, W. S. Kurth, G. Hospodarsky, A. Persoon,  
557 M. Morooka, J.-E. Wahlund, and G. Hunt (in press), The low frequency source of Sat-  
558 urn’s Kilometric Radiation, *Science*.
- 559 Meredith, C. J., S. W. H. Cowley, K. C. Hansen, J. D. Nichols, and T. K. Yeoman (2013),  
560 Simultaneous conjugate observations of small-scale structures in Saturn’s dayside ultra-  
561 violet auroras: Implications for physical origins, *Journal of Geophysical Research (Space*  
562 *Physics)*, *118*, 2244–2266, doi:10.1002/jgra.50270.
- 563 Meredith, C. J., I. I. Alexeev, S. V. Badman, E. S. Belenkaya, S. W. H. Cowley, M. K.  
564 Dougherty, V. V. Kalegaev, G. R. Lewis, and J. D. Nichols (2014a), Saturn’s dayside

- 565 ultraviolet auroras: Evidence for morphological dependence on the direction of the up-  
566 stream interplanetary magnetic field, *Journal of Geophysical Research (Space Physics)*,  
567 *119*, 1994–2008, doi:10.1002/2013JA019598.
- 568 Meredith, C. J., S. W. H. Cowley, and J. D. Nichols (2014b), Survey of Saturn auro-  
569 ral storms observed by the Hubble Space Telescope: Implications for storm time  
570 scales, *Journal of Geophysical Research (Space Physics)*, *119*, 9624–9642, doi:10.1002/  
571 2014JA020601.
- 572 Mitchell, D. G., S. M. Krimigis, C. Paranicas, P. C. Brandt, J. F. Carbary, E. C. Roelof,  
573 W. S. Kurth, D. A. Gurnett, J. T. Clarke, J. D. Nichols, J.-C. Gérard, D. C. Grodent,  
574 M. K. Dougherty, and W. R. Pryor (2009), Recurrent energization of plasma in the  
575 midnight-to-dawn quadrant of Saturn’s magnetosphere, and its relationship to auroral  
576 UV and radio emissions, *Planet. Sp. Sci.*, *57*, 1732–1742, doi:10.1016/j.pss.2009.04.002.
- 577 Nichols, J. D., B. Cecconi, J. T. Clarke, S. W. H. Cowley, J.-C. Gérard, A. Grocott,  
578 D. Grodent, L. Lamy, and P. Zarka (2010a), Variation of Saturn’s UV aurora with SKR  
579 phase, *Geophys. Res. Lett.*, *371*, L15102, doi:10.1029/2010GL044057.
- 580 Nichols, J. D., S. W. H. Cowley, and L. Lamy (2010b), Dawn-dusk oscillation of Saturn’s  
581 conjugate auroral ovals, *Geophys. Res. Lett.*, *372*, L24102, doi:10.1029/2010GL045818.
- 582 Nichols, J. D., S. V. Badman, E. J. Bunce, J. T. Clarke, S. W. H. Cowley, G. J. Hunt, and  
583 G. Provan (2016), Saturn’s northern auroras as observed using the Hubble Space Tele-  
584 scope, *Icarus*, *263*, 17–31, doi:10.1016/j.icarus.2015.09.008.
- 585 Palmaerts, B., A. Radioti, E. Roussos, D. Grodent, J.-C. Gérard, N. Krupp, and D. G.  
586 Mitchell (2016), Pulsations of the polar cusp aurora at Saturn, *Journal of Geophysical*  
587 *Research (Space Physics)*, *121*(A10), 11, doi:10.1002/2016JA023497.
- 588 Palmaerts, B., A. Radioti, Z. H. Yao, T. J. Bradley, E. Roussos, L. Lamy, E. J. Bunce,  
589 S. W. H. Cowley, N. Krupp, W. S. Kurth, E. J. Bunce, J.-C. Gérard, and W. Pryor  
590 (2018), Auroral storm and polar arcs at Saturn - Final Cassini/UVIS auroral observa-  
591 tions, *Geophysical Research Letters*, p. in press.
- 592 Pogorelov, N. V., S. N. Borovikov, J. Heerikhuisen, K. K. Tae, I. A. Kryukov, and G. P.  
593 Zank (2014), MS-FLUKSS and Its Application to Modeling Flows of Partially Ionized  
594 Plasma in the Heliosphere, in *2014 Annual Conference on Extreme Science and Engi-  
595 neering Discovery Environment*, ACM Digital Library (New York), doi:doi:10.1145/  
596 2616498.2616499.
- 597 Prangé, R., L. Pallier, K. C. Hansen, R. Howard, A. Vourlidas, R. Courtin, and C. Parkin-  
598 son (2004), An interplanetary shock traced by planetary auroral storms from the Sun to  
599 Saturn, *Nature*, *432*, 78–81, doi:10.1038/nature02986.
- 600 Pryor, W. R., A. M. Rymer, D. G. Mitchell, T. W. Hill, D. T. Young, J. Saur, G. H. Jones,  
601 S. Jacobsen, S. W. H. Cowley, B. H. Mauk, A. J. Coates, J. Gustin, D. Grodent, J.-C.  
602 Gérard, L. Lamy, J. D. Nichols, S. M. Krimigis, L. W. Esposito, M. K. Dougherty,  
603 A. J. Jouchoux, A. I. F. Stewart, W. E. McClintock, G. M. Holsclaw, J. M. Ajello, J. E.  
604 Colwell, A. R. Hendrix, F. J. Crary, J. T. Clarke, and X. Zhou (2011), The auroral foot-  
605 print of Enceladus on Saturn, *Nature*, *472*, 331–333, doi:10.1038/nature09928.
- 606 Radioti, A., D. Grodent, J.-C. Gérard, E. Roussos, C. Paranicas, B. Bonfond, D. G.  
607 Mitchell, N. Krupp, S. Krimigis, and J. T. Clarke (2009), Transient auroral features at  
608 Saturn: Signatures of energetic particle injections in the magnetosphere, *Journal of Geo-  
609 physical Research (Space Physics)*, *114*, A03210, doi:10.1029/2008JA013632.
- 610 Radioti, A., D. Grodent, J.-C. Gérard, S. E. Milan, B. Bonfond, J. Gustin, and W. Pryor  
611 (2011), Bifurcations of the main auroral ring at Saturn: ionospheric signatures of con-  
612 secutive reconnection events at the magnetopause, *Journal of Geophysical Research*  
613 *(Space Physics)*, *116*(A15), A11209, doi:10.1029/2011JA016661.
- 614 Radioti, A., D. Grodent, J.-C. Gérard, E. Roussos, D. Mitchell, B. Bonfond, and W. Pryor  
615 (2015), Auroral spirals at Saturn, *Journal of Geophysical Research (Space Physics)*, *120*,  
616 8633–8643, doi:10.1002/2015JA021442.
- 617 Radioti, A., D. Grodent, Z. H. Yao, J.-C. Gérard, S. V. Badman, W. Pryor, and B. Bon-  
618 fond (2017), Dawn Auroral Breakup at Saturn Initiated by Auroral Arcs: UVIS/Cassini

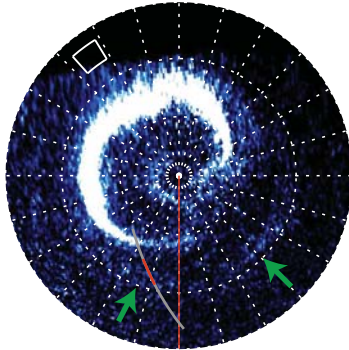
- 619 Beginning of Grand Finale Phase, *Journal of Geophysical Research (Space Physics)*,  
 620 122(A11), 12, doi:10.1002/2017JA024653.
- 621 Reed, J. J., C. M. Jackman, L. Lamy, W. S. Kurth, and D. K. Whiter (2018), Low-  
 622 Frequency Extensions of the Saturn Kilometric Radiation as a Proxy for Magneto-  
 623 spheric Dynamics, *Journal of Geophysical Research (Space Physics)*, 123, 443–463, doi:  
 624 10.1002/2017JA024499.
- 625 Stallard, T., S. V. Badman, U. Dyudina, D. Grodent, and L. Lamy (in press), Saturn’s  
 626 aurora, in *Saturn in the 21st Century*, pp. 333–374, Cambridge University Press, Cam-  
 627 bridge.
- 628 Talboys, D. L., C. S. Arridge, E. J. Bunce, A. J. Coates, S. W. H. Cowley, and M. K.  
 629 Dougherty (2009), Characterization of auroral current systems in Saturn’s magneto-  
 630 sphere: High-latitude Cassini observations, *Journal of Geophysical Research (Space*  
 631 *Physics)*, 114, A06220, doi:10.1029/2008JA013846.
- 632 Talboys, D. L., E. J. Bunce, S. W. H. Cowley, C. S. Arridge, A. J. Coates, and M. K.  
 633 Dougherty (2011), Statistical characteristics of field-aligned currents in Saturn’s night-  
 634 side magnetosphere, *Journal of Geophysical Research (Space Physics)*, 116, A04213,  
 635 doi:10.1029/2010JA016102.
- 636 Tao, C., R. Kataoka, H. Fukunishi, Y. Takahashi, and T. Yokoyama (2005), Magnetic  
 637 field variations in the Jovian magnetotail induced by solar wind dynamic pressure en-  
 638 hancements, *Journal of Geophysical Research (Space Physics)*, 110(A9), A11208, doi:  
 639 10.1029/2004JA010959.
- 640 Wannawichian, S., J. T. Clarke, and D. H. Pontius (2008), Interaction evidence between  
 641 Enceladus’ atmosphere and Saturn’s magnetosphere, *Journal of Geophysical Research*  
 642 *(Space Physics)*, 113, A07217, doi:10.1029/2007JA012899.
- 643 Zieger, B., and K. C. Hansen (2008), Statistical validation of a solar wind propagation  
 644 model from 1 to 10 AU, *Journal of Geophysical Research (Space Physics)*, 113(A12),  
 645 A08107, doi:10.1029/2008JA013046.



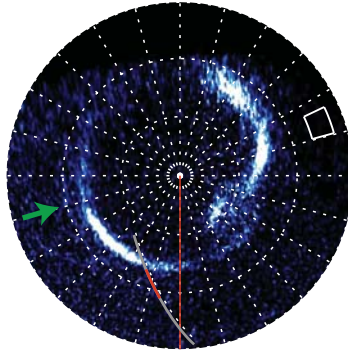
Figure 1.

24:00

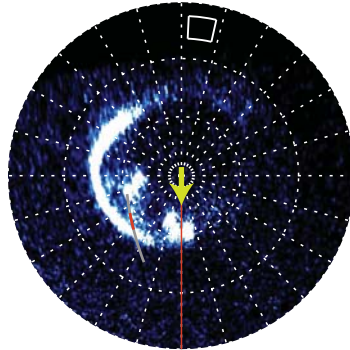
a - 2017-02-14 (DOY 45) 02:51:10  
P = 124±11 GW,  $\phi_{N_{SKR}} = 271^\circ$



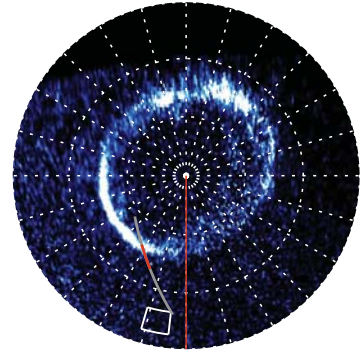
b - 2017-03-07 (DOY 66) 15:27:26  
P = 46±11 GW,  $\phi_{N_{SKR}} = 225^\circ$



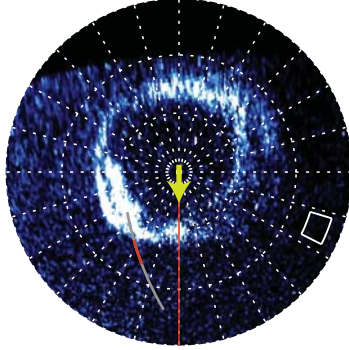
c - 2017-03-14 (DOY 73) 17:31:21  
P = 54±10 GW,  $\phi_{N_{SKR}} = 138^\circ$



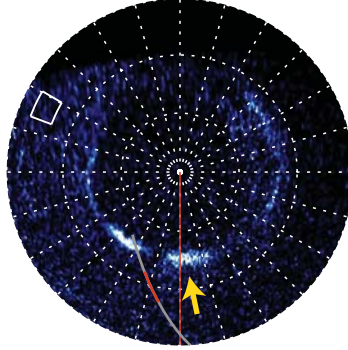
d - 2017-03-29 (DOY 88) 02:29:453  
P = 63±12 GW,  $\phi_{N_{SKR}} = 128^\circ$



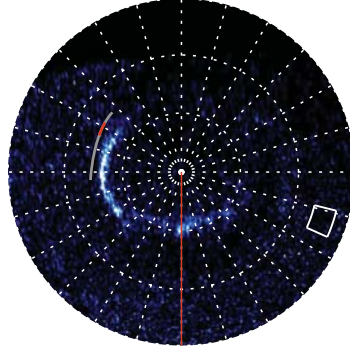
e - 2017-04-05 (DOY 95) 06:15:57  
P = 79±14 GW,  $\phi_{N_{SKR}} = 99^\circ$



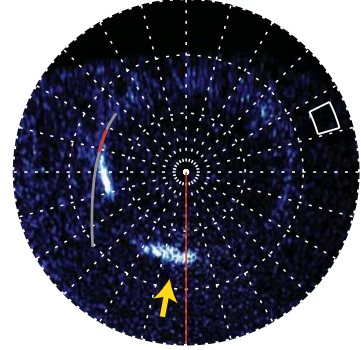
f - 2017-04-19 (DOY 109) 15:11:48  
P = 30±11 GW,  $\phi_{N_{SKR}} = 87^\circ$



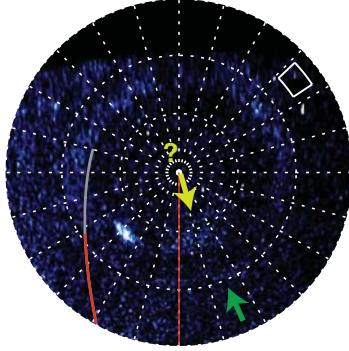
g - 2017-05-02 (DOY 122) 16:19:03  
P = 7±11 GW,  $\phi_{N_{SKR}} = 93^\circ$



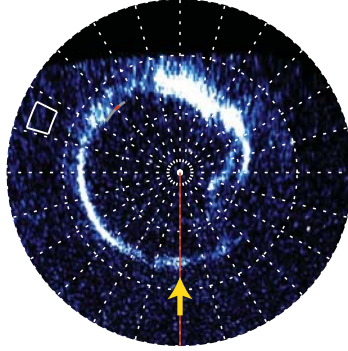
h - 2017-05-22 (DOY 142) 00:26:14  
P = 24±12 GW,  $\phi_{N_{SKR}} = 93^\circ$



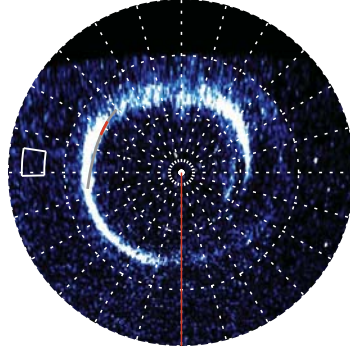
i - 2017-05-22 (DOY 142) 02:01:39  
P = 18±13 GW,  $\phi_{N_{SKR}} = 147^\circ$



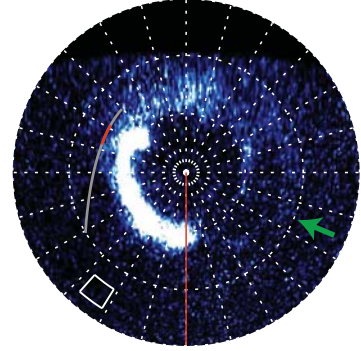
j - 2017-06-03 (DOY 154) 20:55:54  
P = 71±13 GW,  $\phi_{N_{SKR}} = 301^\circ$



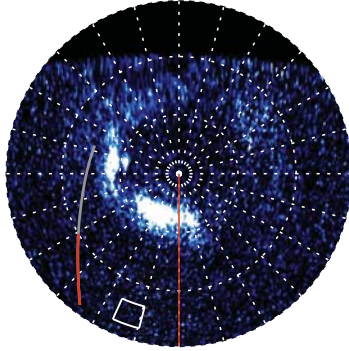
k - 2017-06-03 (DOY 154) 22:31:16  
P = 73±14 GW,  $\phi_{N_{SKR}} = 354^\circ$



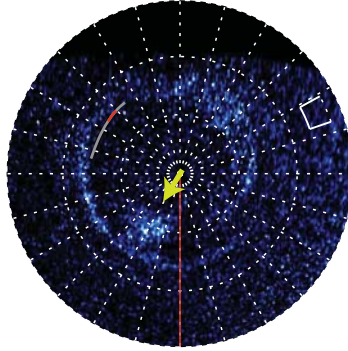
l - 2017-06-23 (DOY 174) 08:10:50  
P = 93±11 GW,  $\phi_{N_{SKR}} = 45^\circ$



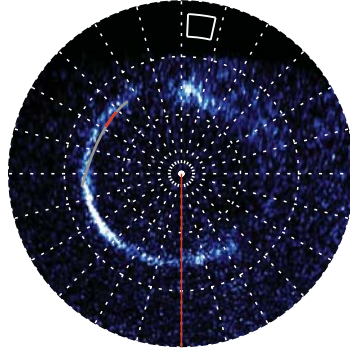
m - 2017-06-23 (DOY 174) 09:46:12  
P = 77±13 GW,  $\phi_{N_{SKR}} = 98^\circ$



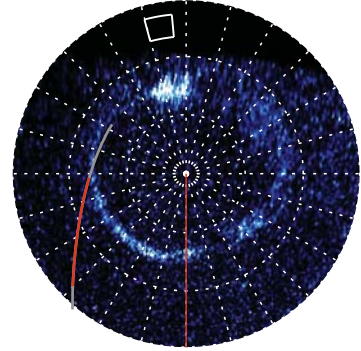
n - 2017-07-06 (DOY 187) 06:03:25  
P = 41±14 GW,  $\phi_{N_{SKR}} = 302^\circ$



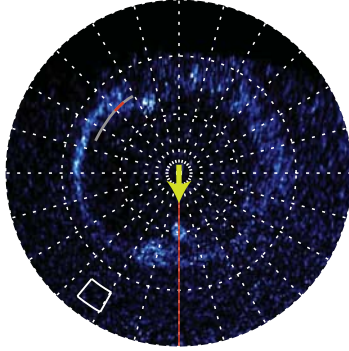
o - 2017-07-25 (DOY 206) 15:51:27  
P = 38±11 GW,  $\phi_{N_{SKR}} = 352^\circ$



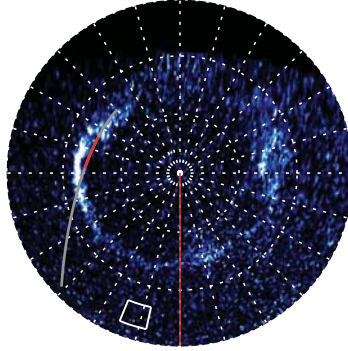
p - 2017-07-25 (DOY 206) 17:26:49  
P = 43±13 GW,  $\phi_{N_{SKR}} = 45^\circ$



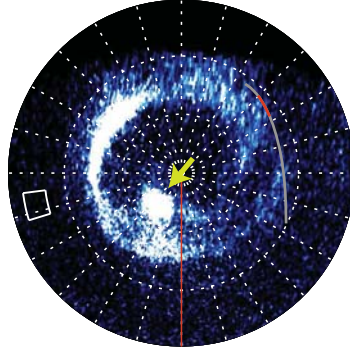
q - 2017-08-07 (DOY 219) 13:44:11  
P = 24±10 GW,  $\phi_{N_{SKR}} = 242^\circ$



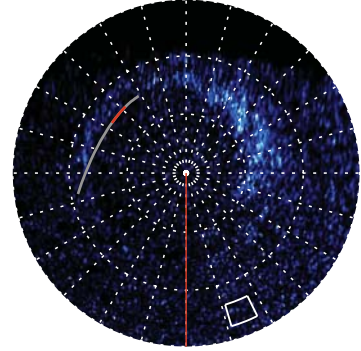
r - 2017-08-07 (DOY 219) 15:19:32  
P = 37±12 GW,  $\phi_{N_{SKR}} = 287^\circ$



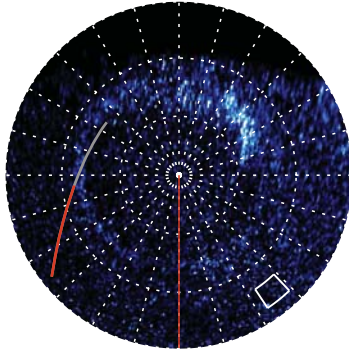
s - 2017-08-14 (DOY 226) 06:14:26  
P = 120±11 GW,  $\phi_{N_{SKR}} = 190^\circ$



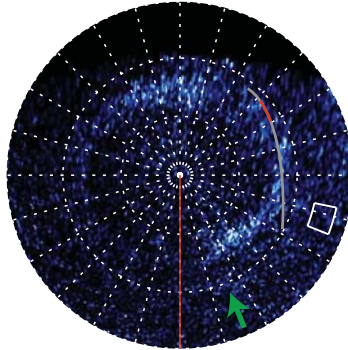
t - 2017-08-26 (DOY 238) 23:20:06  
P = 21±12 GW,  $\phi_{N_{SKR}} = 277^\circ$



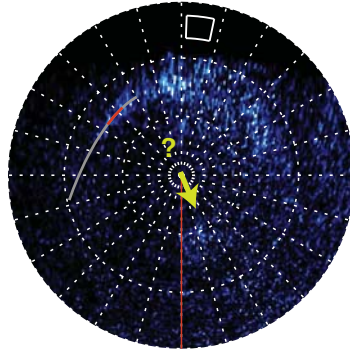
u - 2017-08-27 (DOY 239) 00:55:26  
P = 34±13 GW,  $\phi_{N_{SKR}} = 330^\circ$



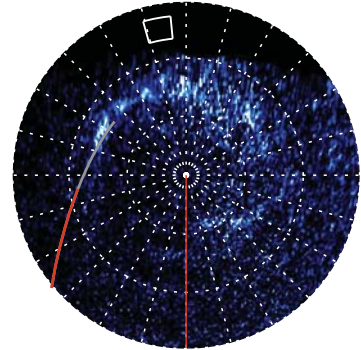
v - 2017-08-27 (DOY 239) 04:06:42  
P = 42±14 GW,  $\phi_{N_{SKR}} = 76^\circ$



w - 2017-09-08 (DOY 251) 21:15:51  
P = 23±11 GW,  $\phi_{N_{SKR}} = 162^\circ$



x - 2017-09-08 (DOY 251) 22:51:16  
P = 41±12 GW,  $\phi_{N_{SKR}} = 214^\circ$



06:00

18:00

12:00

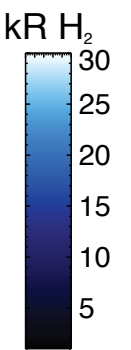


Figure 2.

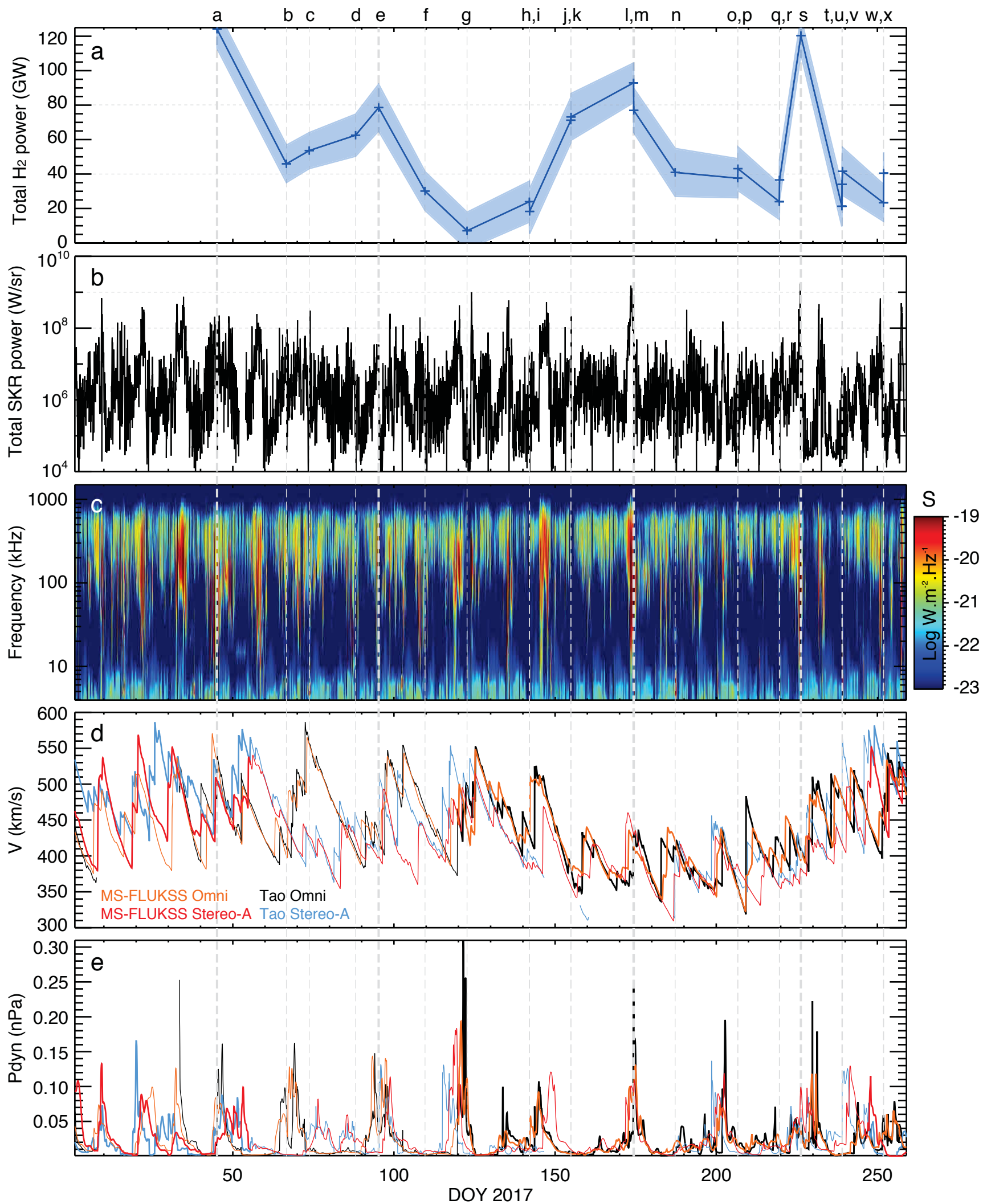
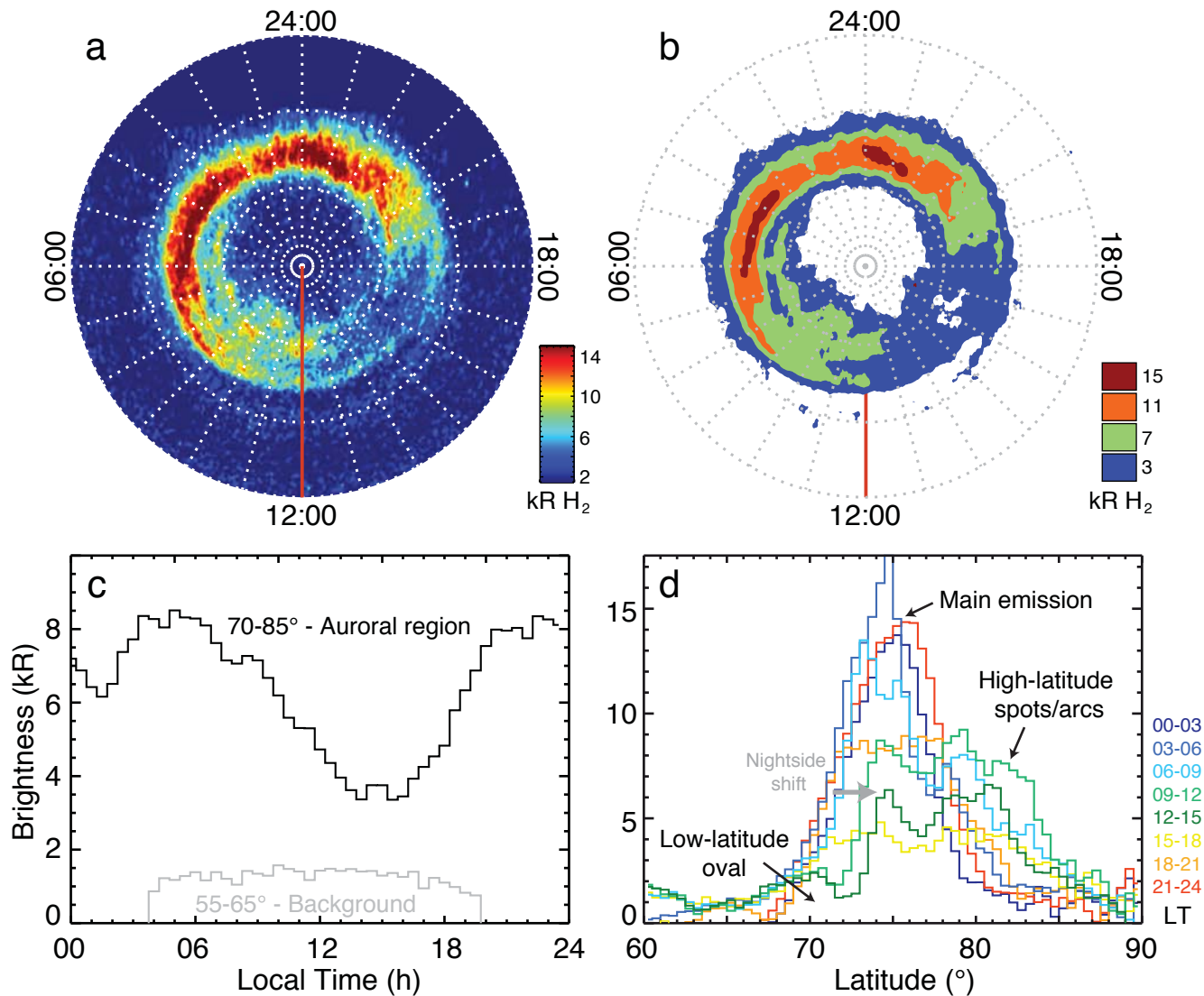


Figure 3.



**Supplemental Figure S2.**

