

## Small-scale structures in Saturn's ultraviolet aurora

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[1] On 26 August 2008, the Ultraviolet Imaging Spectrograph Subsystem (UVIS) instrument onboard the Cassini spacecraft recorded a series of spatially resolved spectra of the northern auroral region of Saturn. Near periapsis, the spacecraft was only five Saturn radii ( $R_S$ ) from the surface and spatially resolved auroral structures as small as 500 km across ( $0.5^\circ$  of latitude). We report the observation of two types of UV auroral substructures at the location of the main ring of emission, bunches of spots and narrow arcs. They are found in the noon and dusk sectors, respectively, at latitudes ranging from  $73$  to  $80^\circ$  corresponding to equatorial regions located beyond  $16 R_S$ . Their brightness ranges from 1 to 30 kR and their characteristic size varies from 500 km to several thousands of km. These small-scale substructures are likely associated with patterns of upward field aligned currents resulting from nonuniform plasma flow in the equatorial plane. It is suggested that magnetopause Kelvin-Helmholtz waves trigger localized perturbations in the flow, like vortices, able to give rise to the observed UV auroral substructures.

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### 1. Introduction

[2] So far, there has been no attempt to measure the smallest characteristic size of Saturn's ultraviolet auroral emission. Most previous studies [Gérard *et al.*, 2004, 2006; Grodent *et al.*, 2005, 2010; Clarke *et al.*, 2005; Nichols *et al.*, 2009, 2010] were concerned with the overall or large-scale auroral morphology and its response to the solar wind forcing. They were based on ultraviolet observations with the Space Telescope Imaging Spectrograph (STIS) and Advanced Camera for Surveys (ACS) instruments on board the Hubble Space Telescope (HST) which provide a nominal spatial resolution of about 150 km at Saturn. However, the  $\sim 1$  kR detection threshold, requiring exposure times as long as 15 min., and the presence of reflected sunlight leaking in the images, combined with the  $\sim 2$  pixel point spread function lead, in practice, to a resolution in excess of 500 km. The necessity to combine pixels in order to raise the signal-to-noise ratio and the effect of corotation of the main auroral components during the exposure time further degrade the sharpness of the images.

[3] The current view of Saturn's overall auroral morphology comprises several components: first, a main ring of emission which is usually narrower and brighter on the dawn side than on the dusk side. Its brightness is varying with time and longitude from 1 to several tens of kR with peaks larger than 100 kR. It is roughly located near  $75^\circ$  of latitude. Nichols *et al.* [2009] showed that the radius of the northern

ring is  $\sim 1.5^\circ$  smaller than the southern ring, presumably as a result of the lower magnetic field in the south. The ring occasionally forms a spiral shape or an arc of circle whose center is shifted from Saturn's spin axis [Nichols *et al.*, 2008]. The size and overall brightness of the main ring were shown to respond rapidly to the solar wind dynamic pressure with smaller, brighter main auroral ring during periods of strong activity [Clarke *et al.*, 2009]. The main ring itself appears to consist of several substructures usually forming  $\sim 60^\circ$  long arcs, of variable widths ranging from  $1^\circ$  to  $10^\circ$  of latitude (or 1000 to 10,000 km), spreading along different parallels. It is generally thought that, among different proposed models, the main auroral ring is formed at the boundary between open and closed magnetic field lines, on the closed field lines side, and results from the interaction between the upper atmospheric neutrals and strong field aligned currents carried by planetward moving electrons [Cowley *et al.*, 2004]. The latter currents originate from the velocity shear between open field lines at high latitudes, embedded in the nonrotating solar wind, and the closed field lines which are carried along by the ionospheric plasma flow entailed in the fast rotating planet [Bunce *et al.*, 2008a]. As a result, the general shape of the main ring is likely related to the imbalance between the rate of reconnection of the planetary magnetic field at the dayside magnetopause and the rate of reconnection in the nightside magnetotail [Cowley *et al.*, 2004]. Contrary to the Earth, the main auroral ring is found to corotate with the planet at approximately 70% of rigid rotation [Grodent *et al.*, 2005]. At the same time, isolated substructures of the main aurora, usually located near LT noon, can be as slow as 20% of rigid rotation. This feature is thought to be a signature of dayside reconnection and is referred to as the cusp aurora [Gérard *et al.*, 2005]. Similar substructures which have the form of

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bifurcations of the main auroral ring close to noon and afternoon sectors are suggested to represent the amount of newly open flux and thus associated with reconnection at the magnetopause [Radioti *et al.*, 2011]. A second type of auroral emission takes the form of transient isolated elongated spots lasting several minutes and appearing distinct from the rest of the emission [Radioti *et al.*, 2009]. Their brightness is measured to be up to  $\sim 20$  kR and their power is of the order of 0.1–0.2 GW. They are suggested to be related to dynamical processes taking place in the magnetosphere.

[4] Reanalysis of HST/STIS observations of Saturn's southern auroral emission obtained in 2004 [Grodent *et al.*, 2005] confirmed the presence of a distinct secondary ring of emission equatorward of the main auroral ring. This faint partial ring could only be observed in the nightside sector where it is put forward by the limb brightening effect. Its position magnetically maps to 4–11  $R_S$  (1 Saturn radius = 1  $R_S$  = 60,268 km) in the equatorial plane where Cassini observed a population of hot electrons whose energy is sufficient to maintain a permanent outer ring of auroral emission [Grodent *et al.*, 2010]. This secondary ring particularly differs from the main ring by the fact that it does not seem to be affected by abrupt changes of the solar wind dynamic pressure. The presence of a permanent source of energy and the lack of response to solar wind conditions thus favor a scenario in which the main and secondary rings are produced by different mechanisms. Recently, the Ultraviolet Imaging Spectrograph Subsystem (UVIS) instrument onboard the Cassini spacecraft unveiled the presence of the northern UV auroral footprint resulting from the electromagnetic interaction of Enceladus and its cryovolcanic plume with Saturn's magnetospheric plasma [Pryor *et al.*, 2011]. The auroral spot smallest dimension fits in 2 UVIS spatial pixels (2 mrad), corresponding to  $\sim 840$  km on Saturn. Four hours later, Cassini flew even closer to Saturn, at a distance of  $\sim 5$   $R_S$  from the surface, where the UVIS instrument recorded three pseudoimages (this term will be described below) with a surface spatial resolution close to 200 km. As shown in the following sections, these reconstructed views reveal auroral structures as small as 500 km across, even smaller than the smallest spatial scale of the footprint of Enceladus. They also suggest that the main ring of auroral emission is not uniform but appears to be made of numerous small-scale substructures.

## 2. Observations and Technical Issues

[5] On 26 August 2008 (DOY 239), Cassini reached the periapsis of its highly inclined 82nd orbit around Saturn. During this period the subspacecraft latitude was higher than  $70^\circ$  and offered a remarkable vantage point to observe the dayside and nightside sectors of Saturn's northern polar region. The Ultraviolet Imaging Spectrograph (UVIS) instrument obtained three sequences of observations of the ultraviolet auroral emissions. The first two sequences, at 02:15 UT and 03:37 UT, were described by Pryor *et al.* [2011] and revealed the northern auroral footprint of Enceladus. In the present study we focus on the third sequence which was obtained from 07:36 to 08:53 UT and consists of three swaths of the northern polar region. During this 77 min period, the subspacecraft latitude rapidly decreased from  $\sim 62^\circ$  to  $55^\circ$  and the spacecraft altitude changed from  $\sim 5$   $R_S$  to 4.5  $R_S$  which,

so far, is the closest approach of Saturn's surface at such high subspacecraft latitude. In the following, we take advantage of this unique observing geometry to unravel the small-scale structures of the main ring of emission.

[6] The FUV channel (111–191 nm) of the UVIS spectrometer was used with the low-resolution slit which provides 64 spatial pixels of 1 mrad (along the slit) by 1.5 mrad (across the slit) [Esposito *et al.*, 2004]. The auroral region was scanned three times by performing continuous slews of the spacecraft in the direction perpendicular to the long axis of the slit. The integration time of each record was 8 s and the region of interest, displayed in each panel of Figure 1a, was covered in 22 min. This results in three pseudoimages of  $64 \times 165$  pixels. The term “pseudo” refers to the fact that in a true image the  $64 \times 165$  pixels would have been illuminated simultaneously while with UVIS, a reconstructed image shows different parts of the auroral region at different times. As an example, the last row (slit) of the image was recorded almost 22 min after the first row. This delay introduces artifacts which must be taken into account in the data analysis. They primarily stem from the quickly changing viewing geometry during the exposure: subspacecraft latitude, longitude and altitude, and from the proper auroral dynamics, including corotation of auroral features.

[7] Figure 1a displays the region of interest of the three pseudoimages of the third sequence recorded on 26 August 2008 between 07:36 and 08:53 UT. Time increases from bottom to top, the beginning of each image is separated by  $\sim 26$  min. The vertical axis is rescaled by a factor of 1.5 in order to display square pixels of 1 by 1 mrad. The color bar at the bottom of the panel provides a correspondence between the color table and the emission brightness in kiloRayleighs (kR), where 1 kR =  $10^9$  photons  $\text{cm}^{-2} \text{s}^{-1}$  emitted in  $4\pi$  sr by  $\text{H}_2$  molecules in the EUV + FUV range (excluding Ly- $\alpha$ ) and assuming no absorption by methane [Gustin *et al.*, 2009]. So far, the kiloRayleigh unit which has been considered in most studies using HST STIS and ACS images excluded the EUV range (below 120 nm) because they are not sensitive to this wavelength band. Since synthetic spectra of  $\text{H}_2$  [Gustin *et al.*, 2009] suggest that the contributions of both bands are equivalent then one needs to consider a factor of  $\sim$ two between HST/STIS/ACS kR and Cassini/UVIS kR such that 2 kR (UVIS) is equivalent to 1 kR (STIS/ACS), and the same for the emitted power. The color table was saturated at 37 kR in order to reveal the fainter emissions.

[8] The displayed images (Figures 1, 2, and 4) are only showing the FUV emission from 120 to 163 nm in order to increase the auroral signal to planetary background ratio. As a result of the relative motion of the spacecraft and the auroral features, and since the reconstructed field of view (FOV) is smaller than the auroral region, each image shows different portions of the aurora, from dawn to dusk. However, there is a slight overlap between the images which, despite the time gap, allows one to connect the left side of the first image (bottom) with the right side of the second image (middle), and the left side of the second image with the right side of the third image (top).

[9] Figure 1b shows the polar projections of the three images. The polar projection procedure does not preserve photometry; therefore, the color table of Figure 1a may only be used as a proxy for the emission brightness. All the pixels

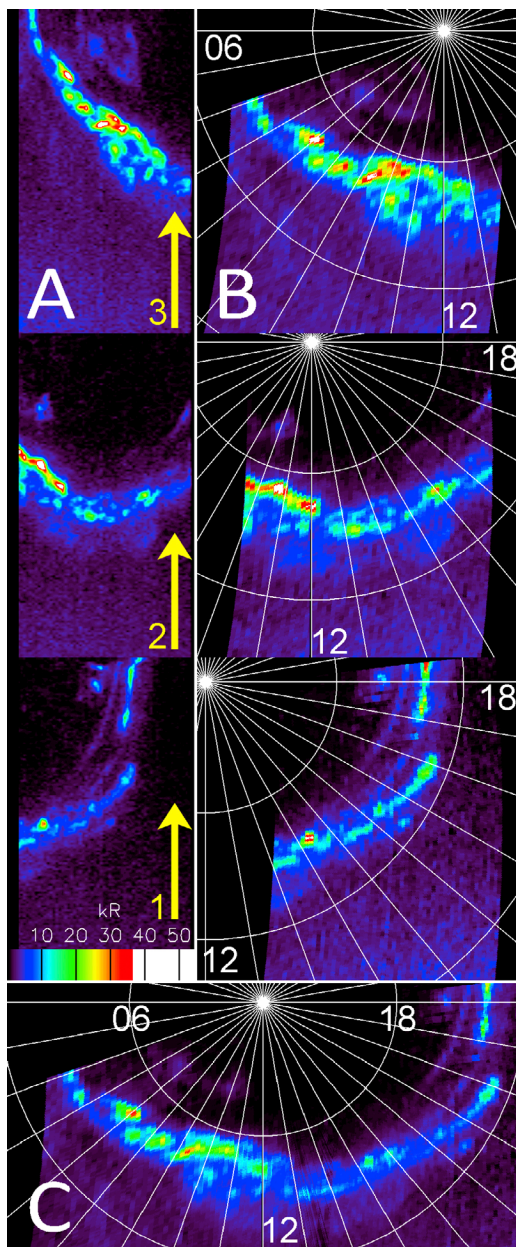
of the images were considered individually. They were all assigned a specific longitude, latitude, and local time assuming that the auroral emission peaks at 1100 km above the ellipsoidal surface of Saturn [Gérard *et al.*, 2009]. This allows correcting the views for the rapidly changing viewing geometry during the exposure. The general morphology of the aurora is quite similar in the raw images (Figure 1a) and in their projection (Figure 1b). This is because UVIS observed from high latitude and because the FOV did not intercept the emission close to the planetary limb which is usually considerably stretched in the polar projections. The bottom panel of Figure 1b (the first in time) illustrates the limited contamination of the signal by reflected sunlight. A large portion of the aurora appears in the nightside so that it was not necessary to remove the local background ( $<1$  kR near the aurora). Finally, Figure 1c is the sum of the three polar views of Figure 1b. The overlapping bands were averaged with a

mask which locally gives rise to fine meridional artifacts stemming from the different projected pixel sizes from image to image.

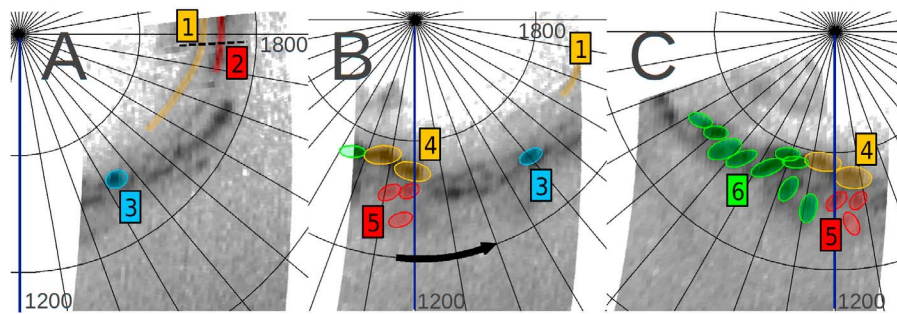
[10] In any case, Figure 1c provides a global view of the auroral emission with a spatial resolution close to 200 km. It is important to note that Figure 1c is a reconstructed view based on observations acquired during 77 min. Therefore, it is not an instantaneous snapshot of the aurora but is such that the auroral features appearing near 18:00 LT (dusk, right ansa) were captured about an hour before the features near 08:00 LT (left ansa) came into view. It is likely that when the UVIS slit recorded the 08:00 LT portion of the aurora, the dusk ansa features evolved and rotated at  $\sim 70\%$  of the planetary spin period ( $\sim 10.8$  h) to reach 19:30 LT.

### 3. Auroral Observations

[11] All the panels of Figure 1 demonstrate that the portion of main ring of emission observed at high spatial resolution with the UVIS instrument is actually made of distinct small-scale substructures. These substructures are indicated with color shapes in Figure 2 which reproduces the three polar views of Figure 1b. We consider six groups



**Figure 1.** Pseudoimages obtained with the FUV channel of the Cassini-UVIS spectro-imager on DOY 239 (26 August) of 2008. The three reconstructed images correspond to three swaths of the northern polar region of Saturn which were performed between 07:36 and 08:53 UT. During this 77 min period, the subspacecraft latitude decreased from  $\sim 62^\circ$  to  $55^\circ$  and the spacecraft altitude changed from  $\sim 5 R_S$  to  $4.5 R_S$ . (a) The region of interest of the three pseudoimages. Time increases from bottom to top, and the beginning of each image is separated by  $\sim 26$  min. The vertical axis is rescaled by a factor of 1.5 in order to display square pixels of 1 by 1 mrad. The color bar at the bottom of the panel gives a correspondence between the color table and the emission brightness in kiloRayleighs (kR) of  $H_2$ . The color table was saturated at 37 kR in order to reveal the fainter emissions. The yellow arrows mark the scan direction. Image 1 (yellow number) was obtained first. (b) The polar projections of the three images. The polar projection procedure does not preserve photometry; therefore, the color table of Figure 1a may only be used as a proxy for the projected emission brightness. The general morphology of the aurora is almost similar in Figures 1a and 1b because Cassini observed them from high latitude and because the field of view did not intercept the emission close to the planetary limb which is usually considerably stretched in the polar projections. The grid shows  $10^\circ$  spaced meridians and parallels. It is fixed in local time with 12:00 LT (noon) toward the bottom and 18:00 LT (dusk) toward the right. (c) The sum of the three polar views of Figure 1b. It provides one with a global view of the northern auroral emission with a spatial resolution close to 200 km. Note that Figure 1c is a reconstructed view based on observations acquired during 77 min. Therefore, it is not an instantaneous snapshot of the aurora but is such that the auroral features appearing near 18:00 LT (dusk, right ansa) were captured about an hour before the features near 08:00 LT (left ansa) came into view.



**Figure 2.** (a–c) Gray scale versions of the three polar views displayed in Figure 1b (images 1 to 3). Individual auroral substructures are highlighted with color shapes. We consider six groups of individual features, marked 1 to 6. Within each group, the features are close enough that we can consider them as almost simultaneous. These auroral features are roughly taking the shape of elongated spots (groups 3 to 6) or narrow arcs (groups 1 and 2). The vertical dark blue line marks the noon meridian and the black arrow in Figure 2b indicates the sense of rotation of the different features. In Figure 2c, the spots contained in groups 4, 5, and 6 display a “bunch of grapes” configuration. The dashed line appearing in the upper right corner of Figure 2a corresponds to the slice presented in Figure 3. Like Figure 1, the grid shows  $10^\circ$  spaced meridians and parallels. It is fixed in local time with 12:00 LT (noon) toward the bottom and 18:00 LT (dusk) toward the right.

of individual features, marked 1 to 6 in Figure 2. These auroral features are roughly taking the shape of elongated spots (groups 3 to 6) or narrow arcs (groups 1 and 2). Within each group, the features are close enough that we can consider them as almost simultaneous. For example, in group 6 the observation time delay between the first and last auroral spots is slightly less than 7 min and the delay between contiguous spots is about 30 s. These numbers are sufficiently small compared to the features life time ( $>1$  h) that, as a first approximation, these auroral spots may be considered as concomitant. Spectral analysis of each individual features shows that the FUV emission is not absorbed by hydrocarbons, implying that they are produced at an altitude near or above 1100 km [Gustin *et al.*, 2009; Gérard *et al.*, 2009].

### 3.1. Spots

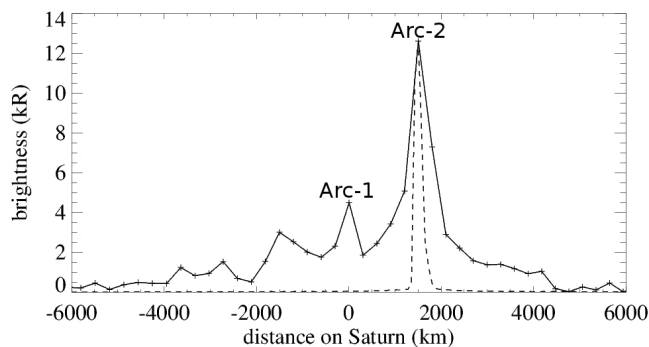
[12] Groups 4, 5 and 6 display 14 isolated spots arranged in a “bunch of grapes” configuration. Each spot is approximately shaped like an ellipse with full major axis of  $\sim 2600$  km and minor axis of  $\sim 1300$  km, at an assumed altitude of 1100 km. Their brightness is relatively large (on the order of 10–30 kR) which translates to an emitted UV power of roughly 3–10 GW per spot. Each one can be easily discriminated from its direct neighbors, although some of them appear to overlap. In group 6 (Figure 2c), the orientation of the major axis continuously changes from almost aligned with a parallel (first spot on the left) to almost aligned with a meridian (last spot on the right). However, the changing orientation of the lower spot of group 5 (Figure 2b and 2c) indicates that this orientation is probably less straightforward than group 6 suggests. The spots are located in the prenoon sector and their latitude ranges from 75 to 80 degrees. According to the magnetic field model of Saturn’s magnetosphere described by Bunce *et al.* [2008b], these northern latitudes map to the equatorial plane at distances between  $\sim 16 R_S$  and the dayside magnetopause. Their typical length scale (2000 km) roughly

corresponds to  $\sim 4 R_S$  in the equatorial plane, close to the dayside magnetopause.

[13] The fact that spots groups 3, 4 and 5 are observed in two different views makes it possible to estimate their corotation rate, provided their centroid does not change with time. Groups 4 and 5 appear to have rotated  $\sim 10^\circ$  in 26 min which corresponds to  $\sim 70\%$  of rigid rotation, as expected [Grodent *et al.*, 2005]. Group 3 consists of one single bright spot which rotated  $\sim 7^\circ$  in the same time, or  $\sim 50\%$  of full corotation. This discrepancy was already observed in previous HST/STIS images [Grodent *et al.*, 2005], where isolated auroral structures were shown to slow down from 65% to 20% of rigid rotation as they rotated from prenoon to postnoon. To date, the origin of this behavior remains unidentified although bifurcations of the main auroral ring in the noon and afternoon sectors have been associated with reconnection at Saturn’s magnetopause [Radioti *et al.*, 2011]. The mean and maximum brightness of the two spots of group 4 decreased by a factor of two from Figure 2b to Figure 2c, which is consistent with the trend observed in previous HST/STIS images, while the brightness of spot 3 remained quasi-unchanged from Figures 2a to 2b.

### 3.2. Arcs

[14] Groups 1 and 2 both consist of a single arc visible in Figure 2a near 73 and 76 degrees of latitude in the LT dusk sector approximately corresponding to 11 and 17  $R_S$  in the equatorial plane, respectively. They emerge in the nightside region and thus are mostly free of solar light contamination. The two arcs are perpendicular to the long axis of the slit. Accordingly, we can take advantage of the best spatial resolution offered by the UVIS instrument without being affected either by the slewing motion of the slit or by the possible rotation of the arcs with the planet (which could not be estimated). The dashed line in the upper right corner of Figure 2a indicates the direction of the slice which is extracted from the corresponding raw image and plotted in Figure 3. The x axis of Figure 3 provides the distance at an



**Figure 3.** Brightness of arcs 1 and 2 in the direction perpendicular to the arcs, as a function of distance. This slice is extracted from the bottom image displayed in Figure 1a and corresponds to the dashed line in the upper right corner of Figure 2a. The  $x$  axis provides the distance at an altitude of 1100 km, with a reference  $x$  value (0 km) arbitrarily set to the peak of arc 1. The  $y$  axis gives the absolute brightness (kR) and indicates that with  $\sim 13$  kR, arc 2 is about three times brighter than arc 1. The plot suggests that the full width at half maximum (FWHM) of both arcs is about 600 km (corresponding to a latitudinal width of  $0.6^\circ$ , this is three times larger than the  $\sim 200$  km FWHM of the projected instrument point spread function which is represented with a dashed line for comparison).

altitude of 1000 km, with a reference  $x$  value (0 km) arbitrarily set to the peak of arc 1. The  $y$  axis indicates that with  $\sim 13$  kR, arc 2 is about three times brighter than arc 1. Figure 3 also suggests that the full width at half maximum (FWHM) of both arcs is  $\sim 600$  km, corresponding to a latitudinal width of  $0.6^\circ$  and a spatial scale of 1 to 2  $R_S$  in the equatorial plane, this is three times larger than the  $\sim 200$  km FWHM of the projected point spread function (PSF) (G. Holsclaw and the Cassini/UVIS Team, private communication, 2011) which is shown in Figure 3 for comparison (dashed line). Taking into account the broadening effect of the PSF leads to a deconvolved width of 500 km ( $0.5^\circ$  of latitude). To date, this represents the smallest UV auroral spatial scale ever observed on Saturn.

## 4. Discussion

### 4.1. Other Images

[15] The Cassini/UVIS data set counts hundreds of reconstructed images of the UV auroral emissions appearing at both poles of Saturn. However, the majority were obtained when Cassini flew at an altitude ranging from  $\sim 10$  to  $20 R_S$ , providing a limited spatial resolution of order of 400 to 1000 km which does not permit to discriminate the small-scale structures reported in the present study. Among the few sufficiently spatially resolved images, two sequences bracket the set of observations displayed in Figure 1. They were obtained approximately 4 h before, in the same hemisphere (26 August 2008, 03:37) (Figure 4a) and 22 h after, in the opposite hemisphere (27 August 2008, 05:46) (Figure 4b), at an altitude of  $6.5 R_S$  and  $6 R_S$ , respectively. Their local time polar projections are presented in Figures 4a and 4b. Figure 4a consists of the sum of two pseudoinages of the north polar region acquired approximately half an hour apart,

and covering the dusk (right) side half of the map then the dawn half portion. The broken arc feature near midnight results from the delay between the two images during which this auroral emission, spanning several degrees of latitude, is rotated by 10 to  $15^\circ$ . Figure 4b is likewise made of the sum of two images of the south polar region. In this case, the dawn half portion (left) was recorded before the dusk half portion of the LT map.

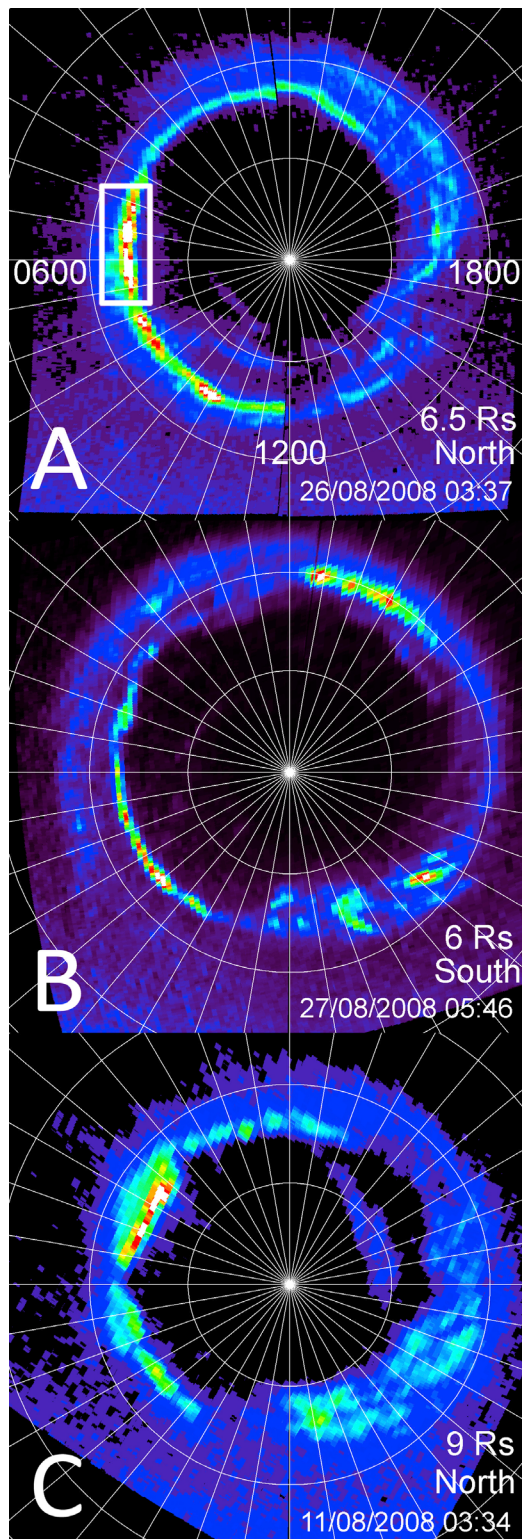
[16] Both maps reveal auroral arc features similar to those observed in Figure 1, they appear at the same local time near 15:00 LT suggesting that, contrary to the spots, they are probably almost fixed in LT. Even though Figures 2c and 4a are showing the same hemisphere relatively close in time ( $\sim 4$  h), there is no clear evidence of a group of isolated spots in Figure 4a. However, assuming that the groups of spots appearing in the prenoon sector of Figure 2c are continuously revolving at 70% of rigid rotation allows one to trace back their location to near the 06:00 LT region in Figure 4a. A bright and narrow auroral arc structure appears in this sector (highlighted with a white rectangle in Figure 4a). As expected, this arc is not uniform but made of distinct substructures which may have evolved in the bunch of grapes configuration observed 4 h later in Figure 1c. The auroral emission displayed in Figure 4b was obtained in the other hemisphere almost two Kronian rotations after the emission shown in Figures 1 and 2. Therefore, it would be untrustworthy to correlate these auroral structures. Nevertheless, it is interesting to note that both hemispheres show similar auroral substructures near the same local times. This is further confirmed by the auroral map shown in Figure 4c, which is the combination of two pseudoinages of the northern auroral region obtained on 11 August 2008 at 03:34. Cassini was at an altitude of  $9 R_S$  and observed again the same types of auroral substructures. The poorer spatial resolution makes it difficult to discriminate between narrow arc and isolated spot substructures. Figures 1 and 4 suggest that the main ring of emission is commonly fragmented into small substructures at all local times in both hemispheres. It is usually broader and patchy in the afternoon (12:00–24:00 LT) sector.

### 4.2. Origin of the Auroral Substructures

[17] The fragmentation of the main ring of emission into small-scale spots and narrow arcs is likely the result of a complex spatial dispersion of field-aligned currents (FAC) reaching the upper atmosphere of Saturn. Talboys *et al.* [2009a, 2009b, 2011] reported structuring of FAC system, based on magnetic field perturbations observed with Cassini/MAG at high latitude near periapsis. They showed that the FAC pattern is regularly arranged in a set of upward current region, giving rise to auroral UV emission, flanked by downward current layers unable to produce auroral emissions. Bunce *et al.* [2010] showed similar structures organized in reverse order, with a downward current layer bracketed by two upward FAC regions. In both cases, the size of the upward FAC region mapped to the ionosphere corresponds to latitudinal width which can be as small as  $1^\circ$  to  $2^\circ$  comparable to the latitudinal extent of the spots and arcs observed in Figure 2. The upward FAC regions map to northern ionospheric latitudes ranging from  $73$  to  $80^\circ$  of latitude, in agreement with the location of these substructures. Talboys *et al.* and Bunce *et al.* also show that the net current

carried by the upward FAC structures is typically  $\leq 5$  MA per radian of azimuth. This current is sufficient to produce the several kiloRayleighs of auroral UV emissions that we observe in the small-scale spots and arcs. If the structure of the auroral emission is indeed related to the spatial structure of the FAC system, then it is also likely that they share a similar origin which is related to the nonuniform azimuthal flow of

plasma in the equatorial plane. The abrupt changes from upward to downward current layers might be explained by velocity shears marking the rapid transitions from subcorotational to supercorotational plasma flows. It is reasonable to suggest that, considering the spatial scale of the magnetosphere, these transitions are not necessarily uniformly distributed in distance from the planet or in azimuth. Therefore, it is expected that the main ring of emission may not be uniform but more likely consists of substructures such as the spots and arcs that we describe. One possible explanation for the auroral spots forming “bunch of grapes” like features (groups 4, 5 and 6 in Figure 2c) could then be related to local fluctuations of the plasma flow, or vortices, induced by Kelvin-Helmholtz (K-H) waves at the magnetopause and the inner edge of the boundary layer [e.g., *Pu and Kivelson*, 1983; *Galopeau et al.*, 1995; *Masters et al.*, 2009; *Walker et al.*, 2011; *Delamere et al.*, 2011]. MHD simulations of Saturn’s magnetosphere performed by *Walker et al.* [2011] and *Fukazawa et al.* [2007] suggest well formed vortices with a characteristic length of several  $R_S$ , in agreement with the size determined from the UV spots ( $\sim 4 R_S$ ). The signature of a somewhat smaller plasma vortex was recorded by Cassini in the dayside outer magnetosphere of Saturn [*Masters et al.*, 2010]. Its inferred size is larger than  $0.55 R_S$ . According to *Masters et al.* [2010], the twisted magnetic field topology produced by the formation of the vortex implies the presence of system of field aligned currents reaching the northern and southern ionosphere of Saturn. The authors suggest that acceleration of electrons into the ionosphere associated with the upward FACs should produce a UV auroral footprint which they estimate to be at most between  $\sim 0.2$  and  $\sim 0.9$  kR. These numbers are one to two orders of magnitude below the measured brightness of the spots ( $\sim 30$  kR). Possible reasons for this discrepancy might be that (1) our observed spots are not related to K-H vortices, (2) they correspond to K-H vortices producing larger precipitating energy fluxes than that estimated from the December



**Figure 4.** Local time polar views of three sets of images. (a and b) The two sequences which were obtained approximately 4 h before (26 August 2008, 03:37) and 22 h after (27 August 2008, 05:46) the set of images displayed in Figures 1 and 2, at an altitude of  $6.5 R_S$  and  $6 R_S$ , respectively. Figure 4a consists of the sum of two pseudoimages of the north polar region acquired approximately half an hour apart, and covering the dusk (right) side half of the map then the dawn half portion. The white rectangle highlights a narrow auroral arc structure made of distinct substructures which may have evolved in the bunch of grapes configuration observed 4 h later in the top panel of Figure 1b. Figure 4b is made of the sum of two images of the south polar region. The dawn half portion (left) was recorded before the dusk half portion of the LT map. (c) The combination of two pseudoimages of the northern auroral region obtained on 11 August 2008 at 03:34. Cassini was at an altitude of  $9 R_S$ . Like Figure 4a, the right side half of the map was obtained before the left half. Figure 4c also illustrates the degradation of the spatial resolution as Cassini observes the auroral region from a larger altitude. The grids display  $10^\circ$  spaced meridians and parallels. They are fixed in local time with 12:00 LT (noon) toward the bottom and 18:00 LT (dusk) toward the right.

2004 Cassini-vortex unique encounter, (3) the typical UV spots size consistently corresponds to a surface area in the equatorial plane one to two orders of magnitude larger than the estimated minimum size of the small vortex reported by Masters *et al.* [2010], or (4) other auroral processes may be at play like the generation of an Alfvén current system which can be very efficient at accelerating electrons at Saturn and give rise to significant auroral emissions [e.g., Hess *et al.*, 2011]. If a spot is indeed a signature of K-H induced vortex, then one should conclude that the bunch of UV spots appearing in Figures 1 and 2 is actually revealing a collection of successive vortices, similar to the case of the Earth dayside aurora where several bright spots associated with individual vortices are commonly observed [e.g., Vo and Murphree, 1995]. The multiple UV spots at Saturn would then be compatible with the MHD simulations of Fukazawa *et al.* [2007] and Walker *et al.* [2011] showing successive vortices forming along the magnetopause. The elongated shape and orientation of the observed spots would then be related to the spatial distribution of the associated FAC system which itself depends on the spatial extent of the vortices.

## 5. Conclusion

[18] On 26 August 2008, the UVIS instrument onboard the Cassini spacecraft recorded spatially resolved spectra of the northern auroral region of Saturn which reveal a series of auroral structures characterized by horizontal extent as small as 500 km.

[19] Instead of the usual quasi-uniform main ring of UV auroral emission associated with the field aligned currents resulting from the velocity shear between open and closed magnetic field lines, we observe substructures taking the form of short narrow arcs near dusk and 14 small spots arranged in a bunch of grapes configuration near the noon sector. The brightness of the arcs is on the order of 10 kR and the individual spots reach 30 kR, totaling 3–10 GW of UV emission per spot.

[20] The smallest observed horizontal spatial scale is the width of one of these arcs; it is  $0.5^\circ$  of latitude or 500 km which is associated with the width of a source region of 1 to  $2 R_S$  in the equatorial plane. The arcs are located between 73 and 76 degrees of latitude, mapping to a region of the equatorial plane between 11 and  $17 R_S$ .

[21] The occurrence of spots in repeated sequences of observation makes it possible to estimate their corotation level. Most of them move around the north pole at 70% of rigid rotation. The spots are found at somewhat higher latitudes than arcs, between 75 and 80 degrees, consistent with equatorial plane distances from  $\sim 16 R_S$  to the dayside magnetopause. Their typical length scale (2000 km) relates to an equatorial source region of approximately  $4 R_S$ .

[22] These small-scale substructures are likely associated with patterns of upward field aligned currents resulting from nonuniform distribution of the plasma flow in the equatorial plane. Such FAC patterns are commonly inferred from Cassini high-latitude magnetic observations [e.g., Talboys *et al.*, 2009a, 2009b; Bunce *et al.*, 2010]. Walker *et al.* [2011] and Masters *et al.* [2009, 2010] suggest that magnetopause Kelvin-Helmholtz waves trigger localized perturbations in the flow, like vortices. The latter suggest that FAC patterns associated with these vortices are able to pro-

duce measurable UV auroral emissions. Accordingly, we suggest that the bunch of auroral UV spots that we observe in the northern ionosphere of Saturn are signatures of successive K-H vortices traveling tailward along the day-side magnetopause.

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