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## Auroral beads at Saturn and the driving mechanism: Cassini proximal orbits

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## ABSTRACT

During the Grand Finale Phase of Cassini, the Ultraviolet Imaging Spectrograph onboard the spacecraft detected repeated detached small scale auroral structures. We describe these structures as auroral beads, a term introduced in the terrestrial aurora. Those on DOY 232 2017 are observed to extend over a large range of local times, i.e., from 20 LT to 11 LT through the midnight. We suggest that the auroral beads are related to plasma instabilities in the magnetosphere, which are often known to generate wavy auroral precipitations. In particular, we propose that shear flow - ballooning (plasma pressure gradient) instabilities generate the observed auroral beads. Energetic neutral atom enhancements are observed simultaneously with the auroral observations, which are indicative of heated high pressure plasma region. During the same interval we observe conjugate periodic enhancements of energetic electrons, which are consistent with the hypothesis that a drifting interchange structure passed the spacecraft. Our study indicates that auroral beads structures are common phenomena at Earth and giant planets, which probably demonstrates the existence of similar fundamental magnetospheric processes at the two planets.

37 *Keywords:* Saturn, aurora, Cassini, plasma instability

## 38 1. INTRODUCTION

39 The aurora at Saturn often exhibits a particularly dynamical morphology, the study of which has  
40 largely contributed to better understanding of Saturn’s magnetosphere. Extensive auroral studies  
41 have shown that the magnetosphere of Saturn is influenced by both the solar wind and internally  
42 driven processes (e.g. [Grodent \(2015\)](#); [Bunce et al. \(2008\)](#); [Badman et al. \(2014\)](#); [Radioti et al.  
43 \(2017\)](#); [Yao et al. \(2017a\)](#)). The shear in the rotational flow which is present near the boundary  
44 between open and closed field lines ([Bunce et al. 2008](#); [Talboys et al. 2011](#); [Jinks et al. 2014](#)) is the  
45 suggested driver of Saturn’s main auroral emission. Additionally, hot tenuous plasma carried inward  
46 in fast-moving flux tubes, which returns from a tail reconnection site to dayside have been shown  
47 to generate auroral brightening enhancement in the dawn region ([Badman et al. 2016](#); [Clarke et al.  
48 2005](#); [Mitchell et al. 2009](#); [Nichols et al. 2014](#); [Radioti et al. 2015](#); [Radioti et al. 2016](#)).

49 Close auroral views from the Ultraviolet Imaging Spectrograph (UVIS) on board Cassini allowed  
50 the detection and study of Saturn’s small scale structures within the main auroral emission over the  
51 last years. Small scale auroral structures have been previously reported on the noon and dusk sectors  
52 ([Grodent et al. 2011](#)). Isolated patches observed simultaneously in both hemispheres are suggested  
53 to be consistent with field-aligned currents and related to ultra low frequency waves ([Meredith et al.  
54 2013](#)). Detached auroral features, of diameter of 6000 km in the ionosphere, propagating from dawn  
55 to early afternoon are also reported in the aurora of Saturn ([Radioti et al. 2015](#)) and were linked  
56 to large dynamic hot plasma populations which create regions with strong velocity gradients. The  
57 small scale structures revealed by the high resolution auroral images are crucial for identifying the  
58 driving mechanisms, for example to determine which plasma processes are involved by the shear  
59 flow. Localised enhancements and small-scale structures are suggested to be part of a large scale  
60 auroral enhancement in the dawn sector related to tail reconnection ([Radioti et al. 2016](#)) and re-  
61 connection outflow. Transient auroral intensifications are found to systematically exist in Saturn’s

62 near-noon local times and is attributed to field aligned currents pulsating due to travelling slow mode  
63 compressional waves (Yao et al. 2017c).

64 In this study, we take advantage of the very close view of Saturn’s aurorae collected at the end of  
65 Cassini mission and during the proximal orbits, when the spacecraft approached Saturn very closely.  
66 The unprecedented auroral images reveal a particular auroral morphology consisting of repetitive  
67 detached small scale structures forming the bead structures. Auroral beads have been observed in  
68 the terrestrial aurora and are believed to have very important implications in the understanding  
69 of the substorm mechanism. They are suggested to be related to plasma pressure gradient driven  
70 instabilities, known as ballooning instabilities (e.g. Pu et al. (1997); Liang et al. (2008); Kalmoni et al.  
71 (2015)). Auroral beads at Earth are associated with drift ballooning mode waves in the near-Earth  
72 plasma sheet (e.g. at  $\sim 10 R_E$  in the nightside magnetotail), which create upward and downward field  
73 aligned currents reaching the ionosphere and short periodic ultra-low frequency (ULF) pulsations,  
74 which often develop into substorm onsets (Keiling 2012). Bead auroral structures are very often  
75 observed a few minutes prior to substorm expansion onset and thus the development of auroral beads  
76 has been used as a diagnostic tool of plasma instabilities in the Earth’s magnetotail (Liang et al.  
77 2008; Kalmoni et al. 2015). In the present letter, we report the existence of auroral beads at Saturn  
78 using the unprecedented auroral images at the end of Cassini mission during the proximal orbits, and  
79 propose a hypothesis of its driving mechanisms by analysing the observations from magnetic field,  
80 energetic particles and Energetic Neutral Atoms (ENA) emissions.

## 81 2. AURORAL BEADS AND ELECTRON MAGNETOSPHERIC WAVES OBSERVED BY 82 CASSINI ON 20 AUGUST, 2017

83 A few days before the end of its mission, Cassini spacecraft approached very close to Saturn and  
84 captured unprecedented detailed views of its aurora. Here, we present Cassini Ultraviolet Imaging  
85 Spectrograph (UVIS) (Esposito et al. 2004) auroral observations taken on 20 August, 2017 close to  
86 the end of the mission, together with simultaneous energetic electron observations obtained with the  
87 Cassini Low Energy Magnetospheric Measurement System (LEMMS) and Ion and Neutral Camera  
88 (INCA) measurements (Krimigis et al. 2004).

Figure 1 shows a sequence of polar projections of Saturn’s southern aurora observed with the FUV channel of the UVIS instrument on 20 August, 2017 DOY 232. During this sequence the spacecraft closely approached the planet. Its altitude changed from 7.2 to 5.3  $R_S$  and its sub-spacecraft latitude increased from 34.9° to 40.8° between the start of the first image and the end of the last one. For the construction of the projections we consider that the auroral emission peaks at 1100 km above the surface (Gérard et al. 2009). The projections display FUV emissions restricted to the 120-163 nm range in order to minimise contamination from solar reflection. The projected distance subtended by a pixel, changes proportionally with the range to the planet along the line of sight. More details on the method may be found in Grodent et al. (2011). In this study the images consist of three subimages and each subimage is taken over  $\sim 30$  min. The starting time of each image is indicated on the top left of the panels of Figure 1. The right side of the figure shows one of the three subimages (used to construct the complete image) which corresponds to the selected region indicated on the complete projection on the left side.

The polar projections displayed on the left side of Figure 1 illustrate the whole auroral region, while the right hand side of the figure focuses on the nightside auroral region, where multiple detached and consecutive auroral spots are observed. One can easily discern 10-12 of them in the first image which are observed to enhance in the second image. Because of their shape, they are described here after as ‘auroral beads’. This term has been used at Earth to describe auroral features with similar morphological characteristics (Liang et al. 2008; Henderson 2009; Rae et al. 2009). The brightness of the beads ranges from 30 to 80 kR, while they move to higher latitudes. **The longitudinal separation between beads is 0.5 local hour. The auroral beads are spanning over a large local time sector (15h wide), from  $\sim 20$  LT to  $\sim 11$  LT via midnight at approximately 73° latitude. The rotating velocity is analysed in details in the Appendix to the paper.** They can last for at least 3 hours, which is the whole duration sequence. The yellow stars show the magnetically mapped location of Cassini spacecraft at the time of the observation, indicating that Cassini’s location was close to the auroral beads. **The mapping results were obtained using the internal field model of Dougherty et al. (2005) combined with the ring current model of**

116 **Bunce et al. (2007)**. Given the location of Cassini close to the planet, the uncertainty  
 117 in the mapping introduced by the magnetopause distance inaccuracy is very limited,  
 118 less than  $0.2^\circ$  of latitude for a magnetopause distance change from  $22$  to  $27R_S$ . . The  
 119 auroral beads reported here have a much smaller scale than the features reported by Radioti et al.  
 120 (2015), while it is unclear if the two structures correspond to similar drivers to those reported here.  
 121 Auroral beads similar to those reported here are quite a common feature. They have been observed  
 122 at various high resolution datasets and mostly during the Grand Finale Cassini phase.

123 A similar pattern of repetitive spots is observed at lower latitudes, near  $\sim 70^\circ$  along the 'outer  
 124 emission' of the auroral region, shown with the red arrows in the middle right panel of Figure 1. The  
 125 beads structures at lower latitudes are fainter ( $\sim 10$  kR) than those observed at  $70^\circ$  and do not seem  
 126 to be radially aligned with those at higher latitudes. The magnetospheric source region of the outer  
 127 emission is located closer to the planet in the inner magnetosphere (e.g.: Grodent et al. (2010)). The  
 128 similarity of the auroral structures on the main and the outer emission, may suggest similar plasma  
 129 processes (i.e., interchange instabilities), although the energy sources (e.g., pressure gradient force,  
 130 shear flow etc.) are likely different.

131 Simultaneously with the UV auroral observations, the INCA instrument onboard Cassini observed  
 132 enhancements of the Energetic Neutral Atoms (ENA) emissions, which are shown in Figure 2. The  
 133 images are 30 min integrations centered at the indicated time, and the x axis towards noon. In the  
 134 past, similar ENA enhancements were associated with dynamical events and were closely correlated  
 135 with UV transient features (Mitchell et al. 2009; Radioti et al. 2013). In this study we use ENA  
 136 observations in order to derive information about the spatial extent and the velocity of the heated  
 137 plasma region related to the simultaneous UV emissions. The ENA enhancement covers a wide range  
 138 of local times. At the beginning of the sequence the emission extends from  $\sim$  noon to midnight  
 139 with a peak at 18LT and at the end of the sequence it reaches 06LT. It should be noted that part  
 140 of the nightside emission between 7:20 UT and 9:16 UT is out of the field of view, because of the  
 141 changes of Cassini trajectory (Cassini was at  $11 R_S$  and at  $29^\circ$  latitude at the beginning of the  
 142 sequence, while at 7:12 UT it was located at  $7 R_S$  and at  $37^\circ$  latitude). The image taken at 7:12 UT

143 shows that there is enhancement before and after 00 LT while a portion of the nightside region is  
144 missing, suggesting that there is continuous emission rotating from pre-midnight to post-midnight,  
145 as documented numerous times in the literature (Krimigis et al. 2007; Mitchell et al. 2009; Carbary  
146 et al. 2008; Dialynas et al. 2013). During the time of the auroral observations from  $\sim$ 05:15 to 08:30  
147 UT the ENA enhancement is located in the nightside region at the same local time sector as the  
148 spotty auroral emissions. As mentioned in the introduction, the ENA emissions are indicative of a  
149 rotating heated plasma region moving between the orbits of Rhea ( $9 R_S$ ) and Titan ( $20.9 R_S$ ). It  
150 should be noted that this information is derived from equatorial projections of the ENA emission,  
151 which are not shown here. The heated plasma region is estimated to rotate with an angular velocity  
152 of  $\sim 70\%$  of rigid corotation.

153 The LEMMS instrument on board Cassini, measured the differential intensities of energetic magne-  
154 tospheric electrons simultaneously with UVIS. Figure 3 shows the differential intensities of energetic  
155 electrons from LEMMS channels C1 to C6, covering energies from 27 to 550 keV. The time interval  
156 covered by the UVIS observations is shown by the grey shaded region on Figure 3. The electron  
157 intensities measured by the four lower channels C1, C2, C3 and C4 are observed to fluctuate and  
158 peak at approximately 05:00, 06:00, 07:00 and 08:00 UT, as indicated by the dashed lines. The  
159 green arrows show the intervals between two peaks, which are approximately 1 hour. Contrary to  
160 the electron flux enhancements observed in Figure 3, the 1-hour quasi-periodic pulsations (some-  
161 times referred to as QP60) described by Roussos et al. (2016) and Palmaerts et al. (2016) are mostly  
162 detected at higher energies (from channel C5 at 175 keV up to several MeV) but could be mixed  
163 with other electron populations at the lower energies considered in the present study. However, it is  
164 clear in Figure 3 that the enhancements discussed here are not present at energies above 175 keV.  
165 Additionally, they have a different morphology with a duration of about 10 min, except for the first  
166 peak, while each individual QP60 generally lasts for about 60 min with a rapid flux increase followed  
167 by a slow decay. We therefore consider that the events do not correspond to the same process that  
168 generates the QP60 reported by Roussos et al. (2016) and Palmaerts et al. (2016). We need to point  
169 out that the energetic electrons were measured at relatively high latitude (30 to 40 degrees), where

170 only the relatively field-aligned population on the equator could arrive. We could roughly estimate  
171 the pitch angles for these electrons travelling to the magnetic equator. Since Cassini's footpoint is  
172 on the main emission, indicating that the magnetic field is traced to the outer magnetosphere (close  
173 to the open-closed field lines). The in situ measured magnetic field strength is about 50 to 200 nT  
174 (not shown in this letter), and the equator magnetic strength in the outer magnetosphere is usually  
175 a few nT (<5 nT) (Yao et al. 2017b), so that the maximum equatorial pitch angle for the measured  
176 electrons is 18°. Usually this is almost at a space-borne instrument's angular resolution, and thus  
177 could be described as a good field-aligned population.

### 178 3. AURORAL BEADS AT SATURN AND THEIR RELATION TO MAGNETOSPHERIC 179 INSTABILITIES

180 We suggest that the auroral beads observed in the midnight to dawn region (20LT to 11LT) re-  
181 ported here are related to plasma instabilities in the magnetosphere, which in turn generate wave  
182 perturbations. At Earth, the auroral beads are often suggested to be driven by plasma ballooning  
183 instability, or balloon instability in mixture with shear flow named as shear flow-ballooning instability  
184 (i.e. Vinas & Madden (1986)). It is intriguing why Saturn has the similar auroral beads on its main  
185 aurora as at Earth.

186 The ENA enhancements observed in this study (Figure 2) are indicative of plasma pressure gradient  
187 forces, which create diamagnetic currents. The diamagnetic currents stretch the magnetic field.  
188 Pressure gradient in stretched magnetic field is indeed a favourable condition for driving ballooning  
189 instabilities. **Previous literature have revealed that flow shear exist on the dawn sector  
190 outer magnetopause between the solar wind plasma flow and rotating magnetospheric  
191 plasma (Masters et al. 2010; Delamere et al. 2013; Desroche et al. 2013).** Therefore, shear  
192 flow and pressure gradient co-exist in driving the main aurora. Regarding the similar morphology to  
193 the Earth auroral beads and the favourable conditions in driving plasma instability, we propose that  
194 the observed auroral beads at Saturn are driven by shear flow-ballooning instability, although we  
195 could not evaluate the relative importances between the shear flow and the plasma pressure gradient  
196 force.

197 The quasi periodic  $\sim 1$  hour fluctuations observed in the electron intensities measured by the three  
198 lower channels C1, C2 and C3 of LEMMS are consistent with drifting interchange structures in the  
199 inner plasma sheet similar to those reported by [Motoba et al. \(2015\)](#) and [Yao et al. \(2017a\)](#). These  
200 drifting structures can lead to excess of electrons on one side of the wave structure crest and result  
201 in the creation of field aligned currents ([Roux et al. 1991](#)). In that case, the electrons stream toward  
202 the ionosphere as upward field aligned currents, which are carried by downward moving electrons and  
203 result in auroral intensifications such as the auroral beads observed here. The proposed mechanism  
204 is illustrated in Figure 5. Following the similar timing and perturbed nature of energetic electrons  
205 and auroral beads, we suggest that they are counterparts of the same process. **As explained in**  
206 **the Appendix to this letter, it is difficult to know exactly how fast the beads structure**  
207 **rotated, but we could resolve all possible velocities, which are at angular velocity of**  
208 **11%, 25%, 39% and 53%. The corresponding periods of electron pulsating are 189 min,**  
209 **63 min, 38 min and 27 min. Since the electrons are found to pulsate at  $\sim 1$  hour, which is**  
210 **very consistent with the solution of 25%. Therefore, we suggest that the auroral beads**  
211 **structure rotated at angular velocity of 25% rigid corotation, which corresponds to the**  
212  **$\sim 1$  hour electron pulsation .** As illustrated in Figure 5, the interchange plasma instability in the  
213 magnetosphere drives an interchange downward/upward field-aligned currents, and thus pulsating  
214 electron precipitations, causing auroral beads in the ionosphere.

215 The low latitude auroral emission (outer emission) shown in Figure 1 presents also auroral beads  
216 features morphological similar to those reported on the main emission. We do not have enough  
217 evidence to argue about the origin of these low latitude auroral beads. Ballooning instability is not  
218 expected to be involved in the triggering process because of the low curvature drift in that region.  
219 They could be related to shear flow instabilities like the giant undulations in the terrestrial aurora  
220 which are explained in terms of shear flow instabilities in the inner magnetospheric boundary driven  
221 by large shear flows between the inner plasmasheet and plasmasphere ([Lui et al. 1982](#)).

222 Our study indicates that auroral beads structures are caused by fundamental plasma processes that  
223 commonly exist at Earth and Saturn and possibly at other planets in our solar system.

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## APPENDIX

**The calculation of auroral beads rotating velocity**

It is challenging to trace each auroral beads between the two auroral images, therefore we could not obtain an unambiguous calculation of auroral beads structure's rotating velocity. However, a generalised solution could be obtained, and the comparison with other dataset, i.e., electron pulsations, could help us to determine the most likely solution. Our methodology is described below step by step.

1. We integrate auroral intensity for the latitudes between 71 degrees to 76 degrees. As illustrated in the Figure in Appendix, the integral area well covers the beads structure, so that we obtain distributions of local time VS intensity for the beads auroral oval in the two images separated by 96 min.
2. It is clear that the beads structure has a wavelength of  $\sim 0.5$  local hour, and there is a clear time shift between the two distributions, so that we can tell there was a propagation although it is challenging to tell how many wavelengths are involved in the rotation.
3. If the rotation between the two beads structures is less than one wavelength (0-level connection as shown in the figure), the auroral structure shall have rotated  $\sim 0.4$  local hour in 96 min, corresponding to 11% rigid corotation velocity. If the rotation between the two beads structures is more than one wavelength but less than two wavelengths (1-level connection), then the auroral structure shall have rotated 0.9 local hour, corresponding to 25% of rigid corotation velocity. More generally, for n-level

242 connection, the rotating velocity is  $(11+14*n)\%$  of rigid corotation. Since the main auroral oval is  
 243 known to rotate at 50-60% of rigid corotation (Grodent et al. 2005; Yao et al. 2018), the poleward  
 244 auroral structure, corresponding to more distant magnetosphere, shall rotate at a lower angular ve-  
 245 locity. Therefore we reasonably suggest that  $n$  shall be not greater than 3. Note that the calculation  
 246 does not involve the motion of spacecraft's footpoint, which would induce a small correction due  
 247 to Doppler shift. The spacecraft's footpoint moves along the planetary rotating direction (i.e., the  
 248 same direction of auroral rotation) at an angular velocity of 0.1 local hour per hour, i.e.,  $\sim 4\%$  of  
 249 rigid corotation. Since the spacecraft's footpoint and auroral beads rotate in the same direction, the  
 250 relative speed of auroral beads in spacecraft's frame is  $(7+14*n)\%$  of planetary rigid corotation.

251 4. Since the wavelength is  $\sim 0.5$  local hour, the time difference between Cassini's two successive  
 252 auroral beads would be  $13.2/(0.07+0.14*n)$  min, where  $n$  indicates the  $n$ -level connection. For  $n =$   
 253  $(0, 1, 2, 3)$ , the time difference between two auroral peaks would be (189 min, 63 min, 38 min, 27  
 254 min).

255 5. The electron pulsation peaks have a time separation of  $\sim 1$  hour, which is consistent with the  
 256 solution for  $n=1$ , i.e., 1-level connection. Therefore, we suggest the 1-level connection picture for the  
 257 beads velocity, i.e., subcorotation with a velocity of 25% rigid corotation.

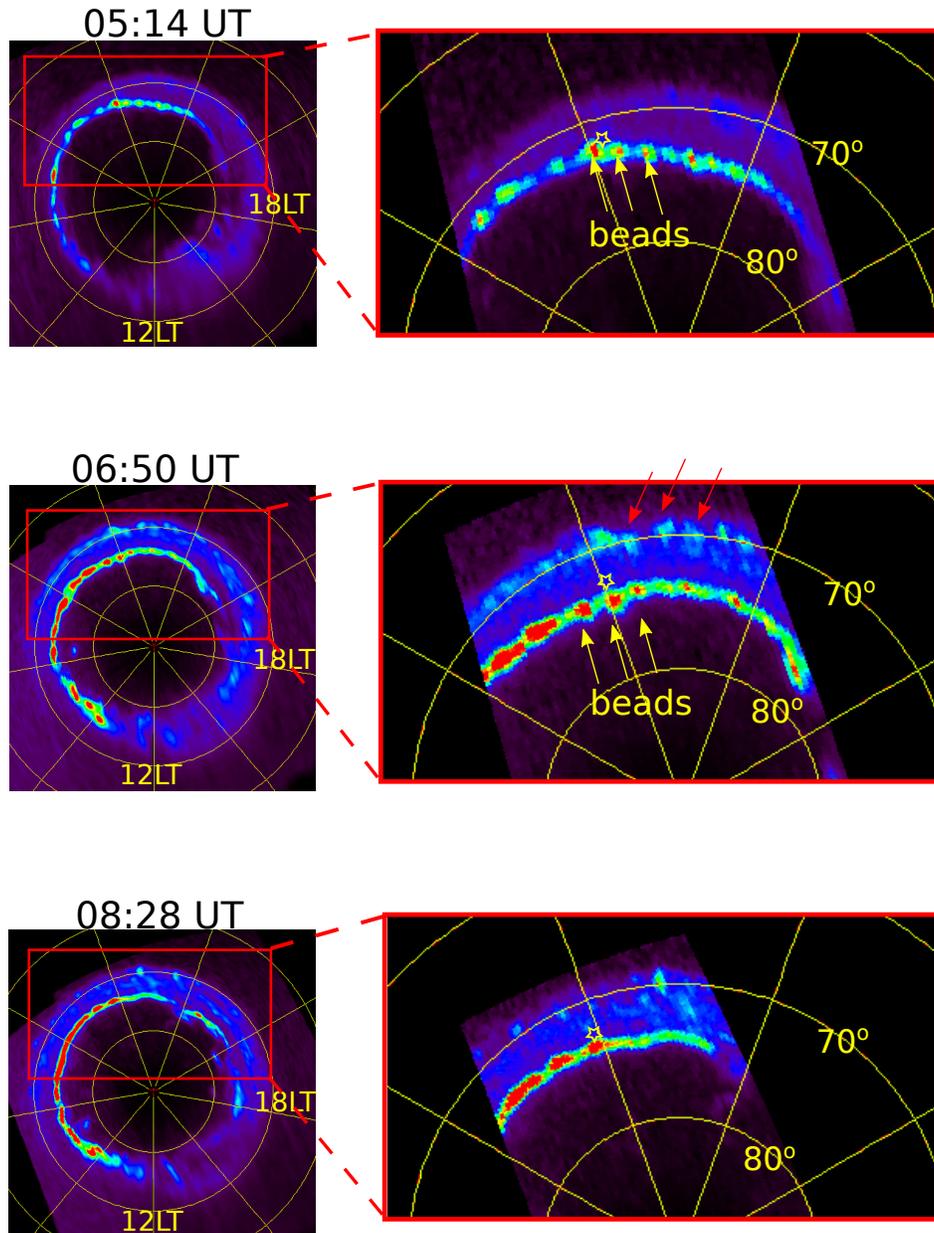
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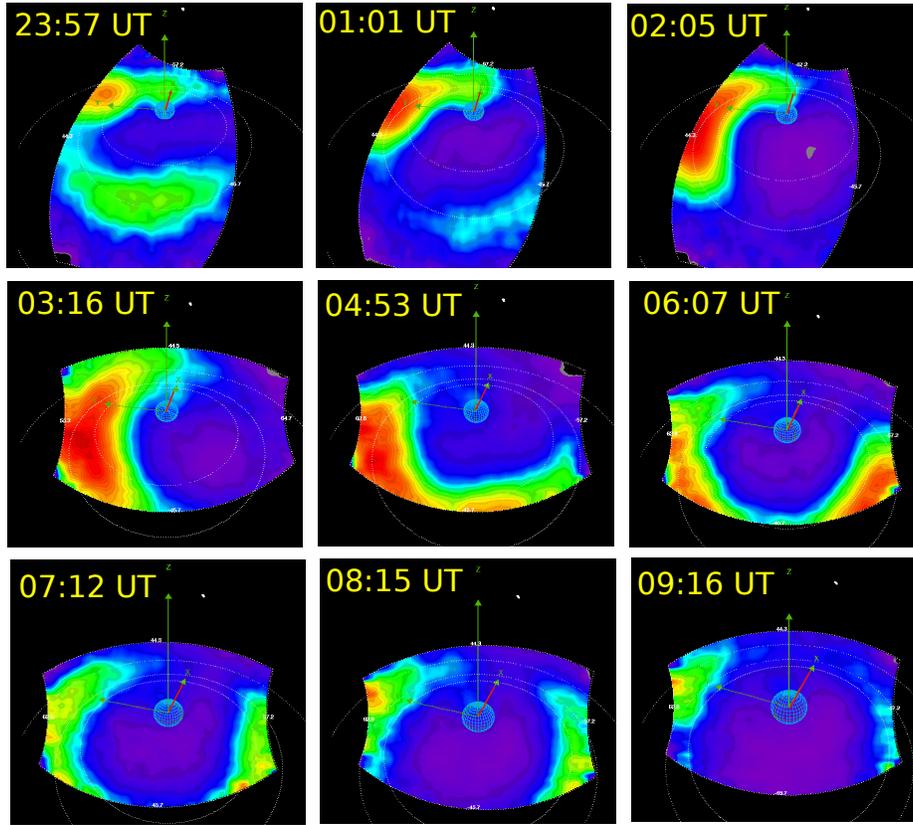
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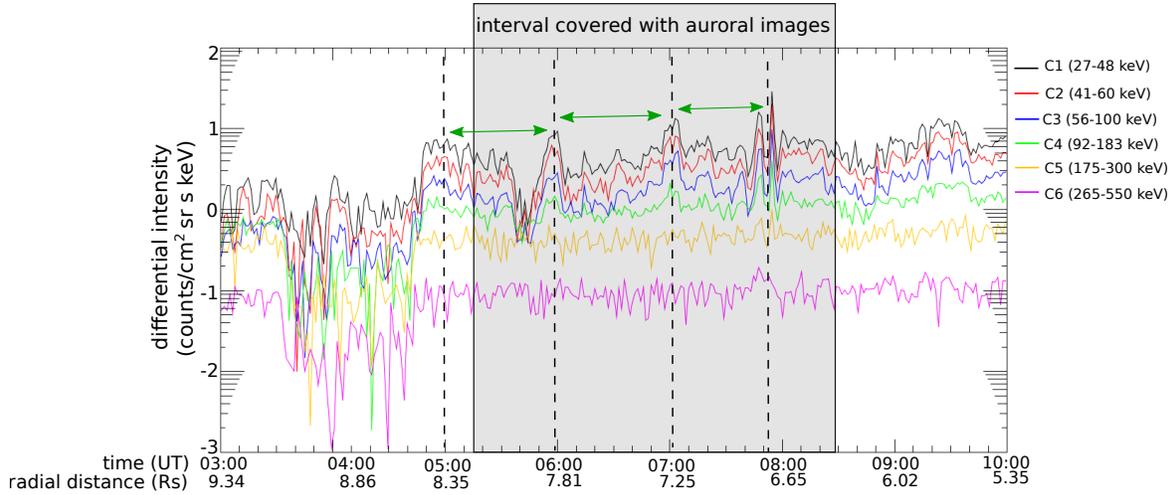
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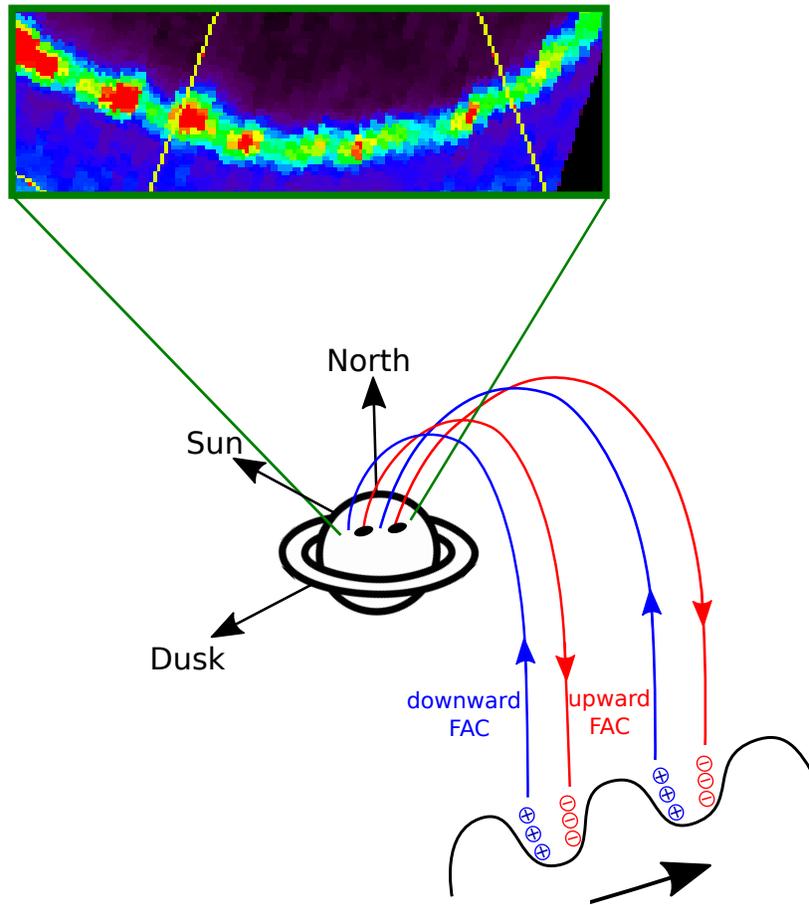
**Figure 1.** A sequence of polar projections of Saturn's southern aurora obtained with the FUV channel of UVIS onboard Cassini during the Cassini proximal orbits. The first image starts at 0514 UT and the last one at 0828 UT on DOY 232, 2017. Noon is to the bottom and dusk to the right. The grid shows latitudes at intervals of  $10^\circ$  and meridians every  $30^\circ$ . Each panel of the right column displays one of the 3 subimages used to reconstruct the corresponding complete image on the left. The yellow arrows indicate some of the auroral beads on the main emission and the red ones those on the low latitude emission. The yellow star points out to the magnetically mapped location of Cassini spacecraft the time of the observation.



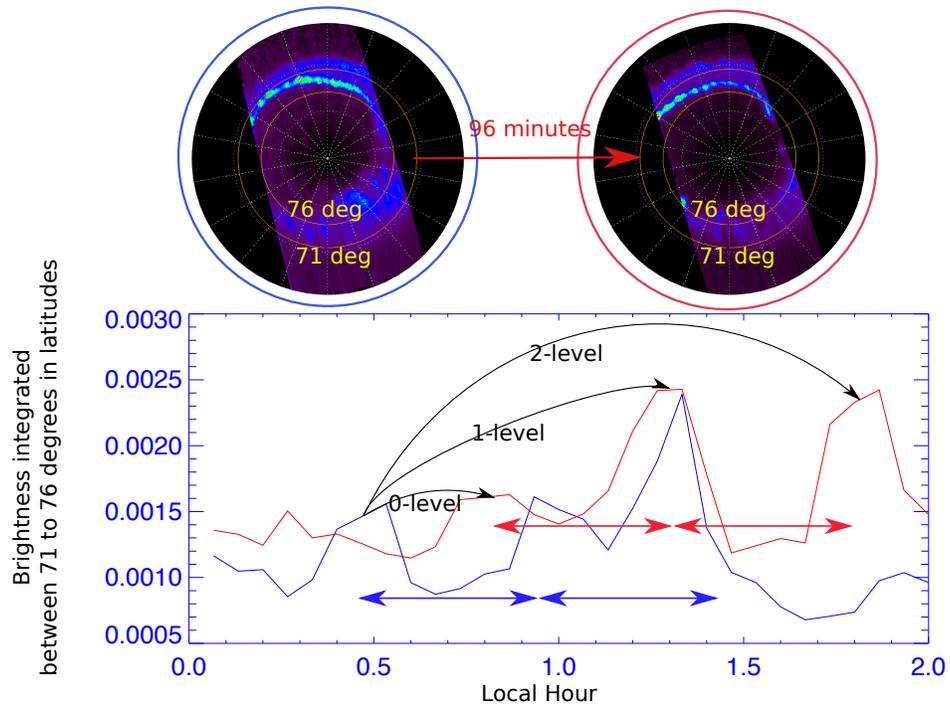
**Figure 2.** ENA emissions from Saturn's magnetosphere starting on DOY 231 2017 at 23:57 and ending on 232 2017 at 09:16 UT. The images were integrated over 30 minutes and centered on the indicated time. The circles represent the orbits of Saturn's innermost moons, namely Dione ( $\sim 6.2 R_S$ ) and Rhea ( $\sim 8.7 R_S$ ), together with the orbit of Titan ( $\sim 20 R_S$ ). The Z axis is aligned with Saturn's spin axis, the X axis (highlighted in red) indicates the direction toward the sun, and the Y axis points to dusk.



**Figure 3.** Differential intensities of energetic electrons from channels C1 to C6 covering the energies from 27 to 550 keV of the Low Energy Magnetospheric Measurement System (LEMMS) instrument onboard Cassini. The grey shaded region shows the interval during which UVIS captured the auroral emission shown in Figure 1. The dashed lines mark the peaks of the electron intensities mainly seen in the low energy channels. The green arrows indicate the approximately every hour intervals between two peaks.



**Figure 4.** Schematic illustration of the build-up of field-aligned currents by magnetospheric plasma instabilities, which generate drifting interchange structures. These perturbations can lead to excess of electrons on one side of the wave crest structure and result in creation of field aligned currents. Upward field aligned currents carried by downward moving electrons result in localised auroral intensifications in the form of 'beads'.



**Figure 5. Appendix to the letter.** Top panel: the two auroral images shown in Figure 1. Bottom panel: the distributions of local time VS auroral intensity integrated between 71 to 76 degrees in latitude for the two auroral images on the top panel.