

A brief review of ultraviolet auroral emissions on giant planets

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Abstract

The morphologies of the ultraviolet auroral emissions on the giant gas planets, Jupiter and Saturn, have conveniently been described with combinations of a restricted number of basic components. Although this simplified view is very handy for a gross depiction of the giant planets' aurorae, it fails to scrutinize the diversity and the dynamics of the actual features that are regularly observed with the available ultraviolet imagers and spectrographs. In the present review, the typical morphologies of Jupiter and Saturn's aurorae are represented with an updated and more accurate set of components. The use of sketches, rather than images, makes it possible to compile all these components in a single view and to put aside ultraviolet imaging technical issues that are blurring the emission sources, thus preventing one from disentangling the different auroral signatures. The ionospheric and magnetospheric processes to which these auroral features allude can then be more easily accounted. In addition, the use of components of the same kind for both planets may help to put forward similarities and differences between Jupiter and Saturn. The case of the ice giants Uranus and Neptune is much less compelling since their weak auroral emissions are very poorly documented and one can

25 only speculate about their origin. This review presents a current perspective that will
26 inevitably evolve in the future, especially with upcoming observing campaigns and
27 forthcoming missions like Juno.

28

29 1. Introduction

30

31 1.1. General characteristics of the giant gas planets aurorae

32

33 The giant gas planets, Jupiter and Saturn, are sharing several remarkable characteristics
34 (Table 1). They are big, fast rotators and produce large internal magnetic fields. They are
35 much farther from the Sun than the Earth and thus receive relatively little energy from
36 it. Their magnetosphere is tapped with internal plasma sources, and, an issue that is of
37 direct concern to the present review, their hydrogen rich atmospheres display auroral
38 emissions. This latter statement is particularly true for the gas giants Jupiter and Saturn,
39 which emit auroral powers of 10^{12} W and 10^{11} W, respectively, compared to 10^{10} W for
40 the Earth. The cases of icy giants Uranus and Neptune are less compelling because their
41 much weaker auroral emissions (10^9 W and 10^8 W, respectively) have not been
42 sufficiently observed. As a result, they will be concisely addressed in section 4.

43

| | Mean solar irradiance (Wm^{-2}) | Equatorial radius (km) | Rotation period (h) | Surface magnetic field (nT) | Emitted UV auroral power (TW) |
|---------|--|------------------------|---------------------|-----------------------------|-------------------------------|
| Earth | 1366.1 | 6,378 | 23.9345 | 30,600 | 0.01 |
| Jupiter | 50.5 | 71,492 | 9.9248 | 430,000 | 1 |
| Saturn | 15.04 | 60,268 | 10.6567 | 21,400 | 0.1 |
| Uranus | 3.7 | 25,559 | 17.24 | 22,800 | 0.001 |
| Neptune | 1.5 | 24,764 | 16.11 | 14,200 | 0.0001 |

44 Table 1 : Principal characteristics of the giant planets relevant to the auroral emissions
45 compared to the Earth. Rotation periods of the gas giants correspond to the deep
46 interior.

47

48

49 Another outstanding characteristic of Jupiter and Saturn comes from the fact that
50 plasma flowing inside their magnetospheres is largely controlled by the corotation
51 electric field. Contrary to the Earth, the contribution from the solar wind convection
52 field may be disregarded, as it is much less important for Jupiter and for Saturn.

53

54 One immediate corollary to this domination by the corotation field is the rotating or sub-
55 corotating nature of the auroral features around the poles. Contrary to the Earth, where
56 the bulk aurora is fixed with respect to the Sun, the aurora on Jupiter and Saturn is
57 corotating at a significant fraction of planetary rigid rotation. It is said to corotate with
58 the planetary magnetic field. Deviation from corotation may then be interpreted as the
59 signature of an “unusual” magnetospheric process, where “unusual” means a process
60 capable of disrupting the plasma’s rotation around the planet with the magnetic field
61 and/or generate beams of electrons at energies sufficiently large to excite atmospheric
62 H₂ molecules or H atoms through collisions. As will be seen in the following sections,
63 numerous such processes exist in Jupiter and Saturn’s magnetospheres and may account
64 for the majority of ultraviolet (UV) auroral emissions.

65

66 1.2. First detections of aurora on giant gas planets

67

68 The UV aurorae on giant planets were first spotted more than three decades ago by the
69 UVS spectrograph on board the two Voyager spacecraft. During the two flybys of Jupiter
70 in 1979, auroral emissions from H₂ and H were unambiguously revealed [Broadfoot et
71 al., 1979]. A couple of years later, Voyager 2 flew by Saturn and obtained similar
72 evidences of auroral activity [Broadfoot et al., 1981]. The very limited spatial resolution
73 of the UVS spectrograph did not make it possible to determine the precise spatial
74 distributions of these aurorae. It is only thanks to the advent of the UV cameras on board
75 the Hubble Space Telescope (FOC, WFPC1, WFPC2, STIS, ACS) that the accurate
76 determination of the auroral morphology of Jupiter and Saturn became possible (see
77 reviews of Clarke et al. [2004] for Jupiter and Kurth et al. [2009] for Saturn).

78

79 1.3. Atmospheric origins of the giant planets UV aurora

80

81 Comparisons between observed auroral spectra and models suggest that, on giant
82 planets, auroral emissions observed in the UV range are principally the result of inelastic
83 collisions between atmospheric H₂ molecules and energetic magnetospheric electrons
84 precipitating in the atmosphere along magnetic field lines. These primary electrons
85 gradually lose their energy to the ionosphere through ionization, dissociation and
86 excitation of H₂ molecules. Ionization, the most efficient process, produces numerous
87 secondary electrons that in turn impact H₂ molecules. The primary and secondary
88 electrons interactions with H₂ mainly depend on their energy. They are governed by
89 various cross-sections (ionizations, electronic excitations, vibrational and rotational
90 excitations). In theory, any electron with energy above the excitation threshold of the B
91 state of the H₂ molecule (~10 eV) has a chance to produce a UV photon of interest. The
92 excitation cross section of the various excited states of H₂ maximize in the 20-160 eV

93 range, meaning that primary electrons and mostly secondary electrons colliding with H₂
94 contribute to the production of auroral UV photons. Above ~50 eV, ionization and
95 electronic excitation cross-sections follow similar electron energy dependences,
96 however, ionization is one to two orders of magnitude more probable than excitation
97 [Gustin et al., 2013].

98 The bulk of the UV auroral emission in the far ultraviolet (FUV) 70-180 nm range mainly
99 results from electron impact excitation of H₂ to various excited rotational-vibrational-
100 electronic states (see Gustin et al. [2009, 2012, 2013] for a thorough discussion on the
101 origins of the auroral H₂ UV emissions). This process initiates de-excitation of excited H₂
102 through the emission of UV photons forming the Lyman and Werner bands, Lyman-
103 alpha and continuum emissions. The energy degradation of the primary and secondary
104 electrons in their course towards deeper atmospheric levels continues until they are
105 thermalized in the ambient atmosphere. Direct excitation of atomic H produces Lyman-
106 α emission. However, in the giant planets where H dominates H₂ at very high altitudes,
107 the dominant source of H-Lyman- α emission is related to dissociative excitation of H₂
108 giving rise to fast-excited H fragments losing their excess energy through emission of
109 Ly- α as well as Lyman and Balmer series photons. In any case, dissociative excitation
110 dominates the production of the auroral Lyman line and contributes ~99 % of the
111 auroral UV spectrum of Jupiter [Grodent et al., 2001; Gustin et al., 2012] and Saturn.

112

113 1.4. Other wavelength ranges

114

115 In the following, we focus on ultraviolet emissions that are directly accessible to
116 instruments like the UV cameras onboard the Hubble Space Telescope (the Advanced
117 Camera for Surveys, ACS; the Space Telescope Imaging Spectrograph, STIS) for Jupiter

118 and Saturn, or the Cassini Spacecraft (UltraViolet Imaging Spectrograph, UVIS) for
119 Saturn. Nevertheless, it should be noted that aurorae on the giant planets are also
120 glowing in other wavelengths including the radio [e.g. Lamy et al., 2009], infrared [e.g.
121 Radioti et al., 2013a], visible [e.g. Vasavada et al., 1999] and X-Ray [e.g. Branduardi et al.,
122 2008] ranges. These radiations are more or less directly related to the UV emissions but
123 they deserve specific treatments, beyond the scope of the present review paper, and
124 provide complementary information. The interested reader will find useful information
125 about auroral emissions in other wavelengths in the review paper by Badman et al. (this
126 issue).

127 2. Jupiter

128

129 2.1. Current understanding

130

131 It is commonly admitted that the Jovian ultraviolet aurora consists of three main
132 components; the main oval, the polar emissions (poleward of the main emission), and
133 the satellites footprints (equatorward of the main emission).

134 The simplicity of this first order picture makes it very handy. However, it presents a
135 skewed view of reality and does not reflect the variety of auroral structures appearing at
136 Jupiter's poles. Furthermore, it leaves no room to the important dynamics of these
137 features. Each auroral feature relates to one or more processes occurring in the
138 magnetosphere. By oversimplifying the description of these auroral signatures, one
139 might miss an important mechanism in the Jovian magnetosphere, or worse, improperly
140 interpret it. The growing performances of the ultraviolet cameras successively installed
141 on board the Hubble Space Telescope made it possible to go into the details of Jupiter's
142 aurora. The STIS camera, for example, is able to reach a spatial resolution on the order of
143 100 km at the distance of Jupiter, roughly corresponding to a fraction of a percent of the
144 characteristic size of the auroral region. STIS is also sensitive enough to the Jovian UV
145 auroral emissions to permit temporal resolution of a few seconds, giving insight to the
146 fastest processes taking place inside the magnetosphere and close to its boundary, or in
147 the ionosphere. Its unprecedented spectral resolution of a fraction of an Angstrom (0.1
148 nm) makes it possible to probe the temperature and composition of the polar
149 atmosphere. It also provides information on the precipitating particles giving rise to the
150 aurora.

151

152 The present bottleneck for the interpretation of the auroral emissions resides in the
153 remaining uncertainties on the magnetic field models. Although the magnetic field in the
154 inner magnetosphere (the internal field) is relatively well constrained up to the orbit of
155 Io, beyond this limit, the external field mainly originating from the current sheet and
156 magnetopause currents becomes gradually dominant and unpredictable. Beyond the
157 orbit of Ganymede, the last Galilean moon providing auroral constrains on the field,
158 magnetic mapping of the auroral emissions becomes increasingly uncertain. At larger
159 distances, near the magnetopause, magnetic models become rather speculative and
160 complicate the deciphering of the poleward most auroral emissions. In the following
161 sections, we give an overall description of the typical components of the Jovian UV
162 aurora and try to relate them to most likely magnetospheric processes. It is probable
163 that this overall picture will progress in the future, especially with the expected great
164 harvest of the Juno and JUICE missions.

165

166 2.2. Main components of Jupiter's aurora

167

168 2.2.1. Northern and southern polar regions

169

170 Gérard et al. [2013] analysed quasi-simultaneous HST images of both hemispheres of
171 Jupiter and found that most morphological auroral features identified in one hemisphere
172 have a conjugate counterpart in the other hemisphere, with some significant differences
173 in the power associated with conjugate regions. Nevertheless, in the following we focus
174 on the northern hemisphere of Jupiter. The main reason for this approach stems from
175 the large hemispheric asymmetries in the internal magnetic field of Jupiter. The
176 northern aurora is more tilted towards the equator than the south and, from Earth orbit,

177 it appears with a better viewing geometry when the field is inclined towards the Earth.
178 Another reason may be linked with the presence of a possible magnetic anomaly in the
179 northern hemisphere [Grodent et al., 2008]. The presence of this anomaly locally
180 perturbs the surface magnetic field and has the effect of a “magnifying glass” on the
181 auroral emissions. In this ionospheric region, magnetic field lines are threading a
182 smaller area in the magnetosphere and the auroral features appear more detached from
183 each other, allowing easier disentangling. Figure 1 shows typical polar projections of
184 ACS FUV images of Jupiter aurora obtained quasi-simultaneously (~ 3 min apart) in both
185 hemispheres since the field of view (FOV) of ACS and STIS are too small to accommodate
186 both hemispheres in the same image. The southern hemisphere is displayed for an
187 observer looking through the planet from above the north pole. The images were
188 obtained on 22 March 2007 during orbit J8-K8 (visit I8) of program GO-10862. Blue
189 arrows point to the auroral footprints of Ganymede and Europa (Europa’s footprint is
190 barely visible). The blue circle points to a systematic discontinuity in the main emission.
191 The green ellipse encircles a possible auroral signature of plasma injection. A small
192 portion of the main emission (main emission) appears near 180° , leftward of the
193 injection. Polar emissions appear in the northern hemisphere near 70° latitude (purple
194 ellipse), no conjugate emission is visible in the south. The influence zone of a likely local
195 magnetic anomaly appears as a white-transparent disc (B_{anomaly}). Yellow circles indicate
196 the direction of magnetic noon at $15 R_J$ (1 Jovian radius = $1 R_J = 71,492$ km), which
197 corresponds to the longitude of the footprint of Ganymede when the moon is at 12LT. All
198 longitudes are in System III (S3). Planetocentric parallels and meridians are drawn
199 every 10° . The black line is the region occulted by the repelling wire. In this set of
200 images, the Central Meridian Longitude (CML) is optimized for viewing both
201 hemispheres quasi simultaneously.

202

203 The next figure (Figure 2) sketches the typical FUV auroral components of the northern
204 hemisphere of Jupiter that are commonly observed from Earth orbit. The various
205 features are conveniently projected onto an orthographic polar map.

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207

208 2.2.2. The main emission (oval)

209 2.2.2.1. Overall shape and origin

210

211 The main auroral oval, more correctly named main emission since it does not form an
212 oval, is structured into a relative stable strip of emission around the magnetic poles.
213 Grodent et al. [2003a] performed a long-term comparison of HST images and showed
214 that the bulk of the auroral morphology is fixed in system-III longitude (SIII), meaning
215 that follows Jupiter's fast rotation. It forms a complex structure mixing multiple narrow
216 arc-like structures, discontinuities, and diffuse patches of emission (orange structures
217 marked "1" in Figure 2). The global statistical shape of the northern aurora has been
218 shown to be influenced by a magnetic anomaly, giving rise to a kink in the main emission
219 (region marked "2" in Figure 2). Such an anomaly has not been reported for the
220 southern hemisphere. In general, the main auroral emissions vary in width between
221 ~100-500 km, though it is even broader at dusk. Its global emission is estimated to
222 contribute almost 75% of the Jovian auroral brightness integrated over the poles. The
223 typical brightness exceeds ~100 kR at UV wavelengths, peaking at up to several MR
224 intensities [Gustin et al., 2006]. In general, the dawnside portion (left side of Figure 2)
225 forms a relatively narrow arc, appearing almost continuous in UV images, the post-noon

226 portion (upper left part of Figure 2) consists of auroral patches and the dusk portion
227 (right side of Figure 2) appears to broaden and break from the main emission. The
228 nightside sector of Jupiter's polar regions is not accessible to Earth orbit observatories
229 like HST. Therefore, current knowledge of the nightside auroral morphology mainly
230 relies on speculations.

231 Theoretical modelling suggests that the main Jovian auroral emission results from the
232 magnetosphere-ionosphere coupling current system associated with the breakdown of
233 rigid corotation in the middle magnetosphere and maps to the equatorial plane between
234 $15 R_J$ (the orbit of Ganymede) and $40 R_J$ [Cowley and Bunce, 2001; Hill, 2001;
235 Southwood and Kivelson, 2001; Nichols and Cowley, 2004]. As the plasma diffuses out-
236 wards in the equatorial plane its angular velocity decreases due to conservation of the
237 angular momentum. At a certain distance, breakdown of corotation occurs and a strong
238 current system develops. When the plasma angular velocity becomes lower than that of
239 the neutral atmosphere, ion-neutral collisions occur in the Pedersen layer of the
240 ionosphere and produce a frictional torque that strives to spin up the plasma back to
241 corotation. The current circuit is closed by a system of field-aligned currents which flow
242 from the ionosphere to the equator (upward) in the inner part of the system, and return
243 (downward) in the outer part. The upward field aligned currents are mainly carried by
244 downward moving electrons. When these electrons fill in the loss cone, their velocity
245 component parallel to the magnetic field is sufficient for the downward electrons to
246 reach the jovian atmosphere where they lose their energy through collisions with the
247 neutrals. Part of this precipitated energy is radiated away in the UV domain and
248 produces the main auroral emission.

249 Recent work has also shown that the main auroral oval and the Ganymede auroral

250 footprint move in latitude over periods of a few months [Bonfond et al., 2012a]. This
251 intriguing motion is not yet explained and could be a subtle combination of moon
252 activity, mass loading rates, magnetodisc configuration, solar wind interaction and
253 ionospheric conductivity.

254

255 2.2.2.2. Discontinuity

256 Radioti et al. [2008] reported the presence of a discontinuity in Jupiter's main emission,
257 where the emission almost systematically drops abruptly to less than 10% of the
258 maximum value. HST UV images taken at different central meridian longitudes in both
259 hemispheres show that the discontinuity (empty region marked "3" in Figure 2) appears
260 fixed in magnetic local time and map to a region of the equatorial plane between 08:00
261 and 13:00 LT. According to Galileo data, this sector threads downward field-aligned
262 currents [Khurana, 2001] presumably resulting from solar wind driven magnetospheric
263 convection. Additionally, plasma flow measurements in the Jovian magnetosphere,
264 inferred from Galileo [Krupp et al., 2001] show evidence of nearly corotating plasma in
265 the dawn-to-dusk sector. According to corotation enforcement process described above,
266 this would require weaker field-aligned currents (or reversed) and consequently fainter
267 aurora emissions in the prenoon magnetic local time. The discontinuity may then
268 originate from the reduced or/and downward field-aligned currents in that region.

269

270 2.2.3. The secondary emissions

271 2.2.3.1. Overall shape and origin

272

273 Secondary auroral emissions are appearing equatorward of the main emission and
274 poleward of the Io footprint [Radioti et al., 2009a]. They consist of emissions extending
275 from the main emission towards lower latitudes, occasionally forming discrete belt of
276 emissions parallel to the main emission and/or patchy irregular structures (light blue
277 diffuse arcs marked “4” in Figure 2). They may also form isolated features that have
278 been attributed to hot plasma injections in the middle magnetosphere. Together, they
279 form the equatorward diffuse emissions (EDE).

280 Grodent et al. [2003a] suggested that these emissions might account for the same
281 corotation breakdown mechanism as for the main emission. The secondary emission
282 may then represent a first step, at lower latitudes and lower intensities, of the process of
283 corotation enforcement. It should be pointed out that the stepwise departure from rigid
284 corotation is purely empirical, while the existing theoretical calculations, based on
285 uniform magnetospheric plasma distribution, predict a smooth monotonic decline in
286 plasma angular velocity with increasing latitude in the auroral ionosphere [e.g. Cowley
287 et al., 2008a].

288 At Jupiter, Bhattacharya et al. [2001] suggested that wave particle interactions in a
289 broad region in the magnetosphere (10 to 25 R_J) could lead to electron scattering and
290 precipitation into the ionosphere contributing to the EDE. Tomás et al. [2004] related
291 the transition of the electron pitch angle distribution (PAD) from pancake to
292 bidirectional (observed within 10 to 17 R_J) to a discrete auroral emission equatorward
293 of the main oval, under the assumption of electron scattering in the loss cone due to
294 whistler mode waves. The brightness of the EDE usually ranges from 40 to 100 kR in the
295 north and from 10 to 50 kR in the south. Based on the analysis of a large HST 1997 –
296 2007 dataset, it appeared that the EDE are almost always present, especially in the dusk
297 side. The persistence of the EDE suggests that its origin is associated with a permanent

298 magnetospheric feature such as the PAD boundary. Radioti et al. [2009a] showed that
299 the PAD boundary magnetically maps to the diffuse auroral emission region in the
300 northern and southern hemisphere. Comparison of the derived precipitation energy flux
301 with the observed brightness of the EDE further showed that the energy contained in
302 the PAD boundary could account for the measured auroral emissions in both
303 hemispheres.

304

305 2.2.3.2. Signatures of injections

306

307 As stated above, not all components of the EDE may be associated with a transition of
308 the electron pitch angle distribution. Transient isolated auroral patches appearing
309 equatorward of the main emission (purple patches marked “5” in Figure 2) could be
310 related to other mechanisms, such as electron scattering by whistler mode waves
311 associated with anisotropic injection events [Xiao et al., 2003; Mauk et al., 2002] or with
312 field aligned currents flowing along the boundary of a hot injected plasma cloud. These
313 auroral signatures of injections may take the form of quasi-corotating shapeless features
314 detaching from the main emission near the footpaths of Europa and Ganymede. At times,
315 they overlap these satellites footprints, making their detection ambiguous. In the Jovian
316 magnetosphere, the processes of plasma injection and interchange motion are thought
317 to be associated with the radial inward transport of hot tenuous magnetotail plasma,
318 compensating for the continuous opposite outward flow of cold iogenic plasma in such a
319 manner as to conserve magnetic flux. To date, only one HST observation of an auroral
320 injection signature could be unambiguously associated with an in situ Galileo detection
321 of a cloud of injected energetic particles [Mauk et al., 2002]. The fact that this case is
322 unique does not stem from the rarity of the phenomenon; it is actually very frequent

323 both in the HST and Galileo datasets, but from the lack of simultaneous Galileo – HST
324 observations. Bonfond et al. [2012a] reported what appears to be an exceptional event.
325 While the auroral injection signatures are usually confined between the main emission
326 and the Io footprint, in June 2007 a large patch of UV emission was observed with HST in
327 the northern hemisphere as far down as the expected location of the Io footprint. This
328 feature appears to be the remnant of a large injection blob seen in the same sector in the
329 southern hemisphere 34 hours before. Instead of simply overlapping the Io footprint
330 (see below), this feature appears to have triggered a momentary substantial decrease of
331 the Io footprint brightness. This behaviour was suggested to result from the depleted
332 nature of the flux tubes containing the sparse injected hot plasma that may have
333 disrupted the Io-Jupiter interaction.

334

335 2.2.4. The satellites footprints

336

337 A comprehensive review of the different satellites footprints may be found in Bonfond
338 [2012b]

339 The satellite's Ultraviolet auroral footprint appear in Jupiter's ionosphere close to the
340 feet of the field lines passing through the satellites Io, Europa and Ganymede [Clarke et
341 al., 2002] (yellow spots marked "6", "7" and "8" in Figure 2, respectively). The observed
342 morphology consists of either one, for Europa, or several distinct spots for Io and
343 Ganymede [Bonfond et al., 2009, 2013] eventually followed by a trailing tail as is the
344 case for Io and Europa [Clarke et al., 2002; Grodent et al., 2006] (yellow diffuse arc
345 downstream of spots "6" and "7" in Figure 2). It is actually anticipated that with a
346 sufficiently sensitive instrument (which is not yet the case), one should observe the

347 same features for all satellites footprints. Indeed, these small auroral features most
348 probably stem from a common (universal) process in which the slow moving satellites
349 pose obstacles to the fast corotating magnetospheric plasma flow. The magnetic
350 perturbation associated with the continuous collisions of the plasma with the satellites'
351 interaction regions propagates along the magnetic field lines as Alfvén waves. The locus
352 of the perturbed points forms Alfvén wings directed towards both poles. On their way to
353 the planet, the waves probably undergo filamentation (Chust et al., 2005; Hess et al.,
354 2010a) and are partially reflected on plasma density gradients, especially at the plasma
355 torus or the plasma sheet boundaries. The fraction of the waves escaping the torus or
356 the sheet causes electron acceleration in both directions. These electrons ultimately
357 precipitate into Jupiter's atmosphere where they produce the observed auroral
358 signatures. Io's footprint brightness may reach up to 20 MR in the UV, representing a
359 large local input of power to the upper atmosphere [Bonfond et al. 2013]. The emissions
360 from the Ganymede and Europa footprints are generally on the order of a few hundreds
361 of kR in the UV. Bonfond et al. [2008, 2013], Jacobsen et al. [2007] and Hess et al.
362 [2010a] proposed that the combination of Alfvén waves reflection and bidirectional
363 electron acceleration may explain the relative motion of the different spots of the Io and
364 Ganymede footprints, respectively, as well as the presence of electron beams affecting
365 the ionization processes near Io [Dols et al., 2012; Saur et al., 2003].

366 The brightness of the Io and Ganymede footprint spots varies with the System III
367 longitude of the satellite, i.e. with the location of the moon relative to the plasma
368 torus/sheet center, with a ~ 10 hr periodicity [Grodent et al. 2009, Bonfond et al. 2013].
369 At Ganymede, a second time scale for brightness variations ranges from 10 to 40 min
370 and was tentatively associated with interactions between Ganymede's mini-

371 magnetosphere and local magnetospheric inhomogeneities, such as those produced by
372 localized plasma injections. A similar process has been suggested to explain an
373 exceptional drop of the Io footprint brightness [Bonfond et al. 2012a, Hess et al. 2013].
374 The shortest time scale observed so far is on the order of 1 to 2 min. At Ganymede, these
375 variations were suggested to be triggered by bursty reconnections at the satellite's
376 magnetopause [Jia et al., 2010]. Alternatively, they may be related to double layer
377 regeneration as suggested for the Io footprint [Hess et al., 2010b; Bonfond et al., 2013].

378 The size of the ionospheric footprints appears to map to a region much wider than the
379 moons. This implies that the satellite-magnetosphere interactions are not restricted to
380 the satellites themselves, but more likely include either parts of the neutral cloud that
381 surrounds and follows them in the case of Io and Europa or its mini-magnetosphere as is
382 the case for Ganymede [Grodent et al., 2006, 2009; Bonfond 2010].

383 Several authors [Hill and Vasyliūnas, 2002; Delamere et al., 2003; Ergun et al., 2009]
384 proposed that, contrary to the spots, Io's tail emission results from a steady state
385 process owing to the progressive reacceleration of the plasma downstream of Io. On the
386 other hand, MHD simulations indicate that it might actually be the result of multiple
387 reflections of the Alfvén waves [Jacobsen et al., 2007]. Grodent et al. [2006] observed a
388 faint ~7500 km long tail following the spot when Europa is close to the centre of the
389 plasma sheet, suggesting that this auroral feature is the signature of an extended plasma
390 plume downstream of Europa [Kivelson et al., 1999].

391 Although it is very much likely that there is an electrodynamic interaction between
392 Callisto and Jupiter's magnetospheric environment that is similar to those at Io, Europa,
393 and Ganymede (Menietti et al., 2001), so far, there is no strong evidence for a permanent
394 Callisto footprint (Clarke et al., 2011). One possible reason for this lack of observation

395 stems from Callisto orbiting at the distance mapping to the main auroral emission. As a
396 result, the footprint cannot be disentangled from the much brighter main emission.

397

398 2.2.5. The polar emissions

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400 Jupiter's polar auroral emissions, which include all auroral emission lying poleward of
401 the main auroral emission, are directly linked to outer magnetosphere dynamics. Their
402 origin continues to be debated. The polar emissions vary independently of the satellite
403 and main auroral emission, and they appear to be ordered by magnetic local time
404 [Grodent et al., 2003b], indicating potential external control by the solar wind. They are
405 suggested to be magnetically connected to the outer magnetosphere and possibly
406 related to a sector of the Dungey and/or Vasyliūnas cycle flows [Cowley et al., 2003;
407 Grodent et al., 2003b; Stallard et al., 2003].

408

409 Based on their average brightness and temporal variability, the northern hemisphere UV
410 polar emissions can be organized into three regions: the active, dark, and swirl regions
411 [Grodent et al., 2003b] (regions marked "9", "10" and "11" in Figure 2, respectively).
412 Their shapes and locations vary with time and as Jupiter rotates.

413

414 2.2.5.1. Active region

415

416 The active region is very dynamic and is characterized by the presence of flares, bright
417 spots, and arc-like features. It is located just poleward of the main emission and maps
418 roughly to the noon local time sector (green patch marked "9" in Figure 2). There have

419 been several interpretations of this region. Pallier and Prangé [2001] suggested that the
420 bright spots of the active region are the signature of Jupiter’s polar cusp, or possibly
421 dayside aurora driven by an increase of the solar wind ram pressure. Waite et al. [2001]
422 used the MHD model of Ogino et al. [1998] to map an observed polar flare to near the
423 cushion region, $\sim 40\text{-}60 R_J$ in the morning sector, and postulated that the flare could be
424 produced by a magnetospheric disturbance due to a sharp increase in the solar wind
425 dynamic pressure. Alternately, Grodent et al. [2003b] interpreted the polar flares as the
426 signature of “explosive” magnetopause reconnection on the day side, based on their
427 \sim minutes-long characteristic time scale. They also suggest that the arc-like structures
428 could be the signature of a Dungey cycle dayside x-line, following the arguments of
429 Cowley et al. [2003]. Recent observations showed that the flares could re-occur quasi-
430 periodically every 3-2 minutes and this behaviour has been tentatively associated with
431 pulsed reconnections on the dayside magnetopause [Bonfond et al., 2011].

432

433 2.2.5.2. Dark region

434

435 The dark region is located just poleward of the main oval in the dawn to pre-noon local
436 time sector. As its name suggests, the dark region is an area that appears dark in the UV,
437 displaying only a slight amount of emission (0-10 kiloRayleighs) above the background
438 level. The dark region displays a crescent shape that contracts and expands as Jupiter
439 rotates, but appears fixed in local time (empty region marked “10” in Figure 2).

440 Grodent et al. [2003b] associated the UV dark region with the Stallard et al. [2003]
441 rotating Dark Polar Region (r-DPR), an area of subcorotating ionospheric flows, as
442 measured by the Doppler shifts of infrared emission spectra. The dawn side r-DPR, and
443 thus the dark region, is thought to be linked to the Vasyliūnas-cycle [Vasyliūnas, 1983]

444 sunward return flow of depleted flux tubes [Cowley et al., 2003]. In the Vasyliūnas-cycle,
445 mass-loaded flux tubes are stretched as they rotated into the night side; they eventually
446 pinch off, and reconnection occurs in the midnight-predawn local time sector, releasing
447 a plasmoid that can escape down the tail, while empty flux tubes rotate back around to
448 the day side at a velocity close to that of corotation. Similarly, Southwood and Kivelson
449 [2001] argued that the main oval emissions map to the plasma disk, which would mean
450 that the dark region, just poleward of the main oval, maps to the cushion region. The
451 cushion region is an area of southward-oriented and strongly fluctuating field in the
452 outer magnetosphere in the post-dawn to noon local time sector where the field
453 becomes more dipole-like than in the inner magnetosphere. It has been associated with
454 empty flux tubes that were emptied by Vasyliūnas-type reconnection as they rotated
455 through the night side [Kivelson and Southwood, 2005].

456

457 2.2.5.3. Swirl region

458

459 The swirl region is an area of patchy, transient emissions that exhibit turbulent, swirling
460 motions. The swirl region is located poleward of the active and dark regions, and is
461 roughly the center of the polar auroral emissions (red features marked “11” in Figure 2).
462 It is generally interpreted as mapping to open field lines. In comparing the UV and IR
463 observations, Grodent et al. [2003b] associated the UV swirl region with the fixed Dark
464 Polar region (f-DPR), an area in which the ionospheric flows are nearly stagnant in the
465 magnetic pole reference frame [Stallard et al., 2003]. The stagnant flows in the f-DPR
466 (swirl region) then suggest that the area maps to open field lines associated with
467 Dungey cycle return flows [Cowley et al., 2003], which are expected to flow across the
468 ionosphere slowly because the Jovian magnetotail is ~hundreds or thousands of R_J in

469 length. A long-lived quasi –Sun-aligned polar auroral filament (PAF) was observed on
470 several occasions in the swirl region in images sequences obtained with HST [Nichols et
471 al., 2009a] (white arc marked “12” in Figure 2). This feature consists of two components:
472 a sunward portion remaining approximately Sun-aligned and an anti-Sunward portion
473 sub-rotating at a few tens of percent. This ~100 kR auroral feature appears to be
474 independent of the local solar wind conditions. It was postulated that PAFs might be
475 associated with large plasmoids slowly drifting down the magnetotail.

476

477 The magnetospheric mapping of these polar auroral regions was initially inferred from
478 model magnetic fields (principally VIP4) that are known to be increasingly inaccurate
479 beyond the orbit of Io. Instead of following these model magnetic field lines, Vogt et al.
480 [2011] mapped equatorial regions to the ionosphere by requiring that the magnetic flux
481 in some specified region at the equator equals the magnetic flux in the area to which it
482 maps in the ionosphere. This mapping method directly takes into account the
483 complexity of Jupiter’s surface magnetic field, including the perturbation caused by a
484 magnetic anomaly in the north and provides a more accurate mapping to the distant
485 magnetosphere. Vogt et al. [2011] found that the polar auroral active region maps to
486 field lines beyond the dayside magnetopause that can be interpreted as Jupiter’s polar
487 cusp; the swirl region maps to lobe field lines on the night side and can be interpreted as
488 Jupiter’s polar cap; the dark region spans both open and closed field lines and must be
489 explained by multiple processes. Additionally, they concluded that the flux through most
490 of the area inside the main oval matches the magnetic flux contained in the magnetotail
491 lobes and is probably open to the solar wind.

492

493 2.2.5.4. Nightside and polar dawn spots

494

495 Several detailed studies based on ultraviolet images taken with HST revealed transient
496 auroral spots appearing in the dawn and midnight sectors along the poleward edge of
497 the main emission [Grodent et al., 2004; Radioti et al., 2011]. These polar auroral
498 emissions take the form of multiple dawn arcs, polar dawn spots, or midnight spots
499 (blue features marked “13” and “14” in Figure 2, respectively). They were found to
500 corotate with the planet, and their sizes, durations, locations, and 2 to 3 days
501 reoccurrence period are consistent with auroral emissions triggered by internally
502 driven tail reconnection. More specifically, based on a recent reanalysis of near
503 simultaneous HST UV images and Galileo magnetic field observations, Radioti et al.
504 [2011] proposed that the nightside spots, like the polar dawn spots, are triggered by the
505 inward moving plasma flow released during magnetic reconnection at Jupiter’s tail.
506 These aurorae may then be related to the precipitation of plasma heated in the
507 reconnection region and to the field-aligned currents that couple the changing angular
508 momentum of the flux tubes between the magnetosphere and ionosphere. Radioti et al.
509 [2011] and Kasahara et al. [2013] showed that the energy released by this process is
510 sufficient to account for the observed spots emitted power (a fraction to several GW).
511 Results from Ge et al. [2010], assuming an updated magnetosphere model, provide
512 further direct evidence of a link between Jovian tail reconnection and polar auroral
513 emissions. More precisely, they confirm that the ionospheric footpoints of tail
514 dipolarization events are close to the polar dawn auroras. Vogt et al. (2014) performed
515 an analysis of the magnetic signature of 43 tailward moving plasmoids and showed that
516 their properties are consistent with a typical mass loss rate of $\sim 0.7\text{--}120$ kg/s, much
517 lower than the mass input rate from Io (suggesting that additional mass loss

518 mechanisms may be significant), and a flux closure rate of $\sim 7\text{--}70$ GWb/day, confirming
519 that tail reconnection and plasmoids play an important role in flux transport at Jupiter.

520

521 3. Saturn

522

523 3.1. Current understanding

524

525 Given the similarities between Jupiter and Saturn (Table 1), it is not surprising that the
526 overall morphology of Saturn's UV auroral emissions resembles that of Jupiter. Saturn's
527 aurora forms a variable ring of emission quasi-rotating around both magnetic poles and
528 displays isolated intermittent structures, spots and arcs, on both sides of this principal
529 component. However, closer inspection of these auroral features reveals significant
530 differences with Jupiter, which will be discussed below. Following the marked response
531 of Saturn's aurora to the changing solar wind conditions, it is often assumed that
532 Saturn's auroral morphology is halfway between that of Jupiter and the Earth's,
533 combining the usual Earth auroral components with Jupiter's corotating nature. This
534 simplified view is certainly a useful starting point, but it can also be very misleading.
535 Therefore, it is preferable to assume that Saturn's UV aurora is not an intermediate case
536 but a case on its own, sharing some similarities with the Earth and Jupiter.

537

538 Like Jupiter, Saturn's UV aurora has been studied with the STIS and ACS cameras on
539 board HST. Since, at opposition, the distance from Earth orbit to Saturn is about twice
540 the distance to Jupiter, the spatial resolution is degraded by a factor of ~ 2 , roughly
541 corresponding to 300 km per pixel. The auroral brightness on Saturn is usually one
542 order of magnitude smaller than on Jupiter, with typical values ranging from 10 to 100
543 kR. The combination of fainter emissions and lower spatial resolution gives rise to
544 images of lesser quality than for Jupiter. However, they are still detailed enough to
545 reveal the complex and changing morphology of the aurora [e.g. Clarke et al., 2005]. One

546 of the most important lessons that we have learned from the HST – Cassini campaign
547 that took place preceding the Saturn orbit insertion of Cassini in Jan. 2004 is the clear
548 influence of the solar wind, most specifically its ram pressure directly measured by
549 Cassini, on the global auroral morphology. During this campaign, the brightness of the
550 aurora significantly increased in response to the arrival of large solar wind pressure
551 pulses (e.g. Cray et al., 2005). On one occasion, the global morphology itself
552 dramatically changed during the compression event. Within a few hours, the main
553 emission ring, that was initially surrounding the pole, collapsed to a bright feature filling
554 in a small region on the dawn side of the polar cap [e.g. Grodent et al., 2005; Badman et
555 al., 2005].

556

557 The orbital insertion of Cassini marked the beginning of a new era in the exploration of
558 Saturn. In particular, the UV aurora revealed itself to the ultraviolet imaging
559 spectrograph (UVIS; Esposito et al., 2004). The high latitude orbits provided stunning
560 views of the auroral emissions from almost above the poles. The data captured near
561 Cassini's periapsis showed unexpected fine details of both poles, inaccessible to HST, of
562 the auroral emissions that are greatly helping their interpretation. The UVIS instrument
563 is observing the auroral emissions more frequently than the HST cameras do. Therefore,
564 it is able to sample the auroral dynamics at various timescales. The most important
565 advantage of UVIS stems from the combined use of the different instruments onboard
566 the spacecraft. For example, it makes it possible to observe the auroral emissions from a
567 vantage point threading the same magnetic flux tube [Bunce et al., 2014]. As a result, it is
568 now possible to simultaneously measure the characteristics of the energetic particles
569 giving rise to the aurora and the aurora itself. UVIS is primarily a spectrograph. Its FUV
570 and EUV channels are designed to obtain high-resolution spectra in the 56-191nm range

571 from which one may derive, for example, color ratios indicating the penetration depth of
572 the impinging particles and thus estimate their energy [e.g. Gustin et al., 2012]. Since the
573 FUV and EUV channels both consist of a spectral slit, UVIS is not providing true images
574 of the auroral region. The second spatial dimension is obtained by slewing the
575 spacecraft in the direction perpendicular to the slit length. This motion allows one to
576 spatially scan the auroral regions from which pseudo-2D images may be reconstructed
577 [Grodent et al., 2011]. Figure 3 displays a typical pseudo image of Saturn's FUV aurora
578 obtained with the UVIS camera onboard the Cassini spacecraft. This composite image
579 was reconstructed from a ~1 hr observing sequence during which the UVIS spectral
580 long-slit was scanned twice across the auroral region (the aurora was uninterruptedly
581 accumulated in the spectral slit during 8 sec bins). It was obtained on 6 Jan 2013 from
582 08:38 (SCT). The sub-spacecraft latitude was close to 48° and the altitude was $\sim 8.6 R_s$,
583 which offered an optimum view point of Saturn's north pole.

584

585 The increasing number of observations with HST and Cassini UVIS is at the basis of the
586 growing complexity of possible auroral morphologies. These various auroral emission
587 distributions may be ordered according to their spatial and dynamical characteristics.
588 These in turn may be related to specific processes in the magnetosphere. Contrary to
589 Jupiter, Saturn's UV aurora has been imaged at all local times, primarily thanks to the
590 occasional high latitude vantage point of the Cassini spacecraft providing an optimum
591 view of Saturn's poles. It should be mentioned that during April and May, 2013, a new
592 campaign took place during which coordinated observations of Saturn's aurora were
593 made by the Cassini spacecraft and several Earth-based telescopes. The results of this
594 campaign will be published in a journal special issue (2014 Icarus Special Issue: Saturn
595 Auroral Campaign).

596

597

598 3.2. Main components of Saturn's aurora

599

600 Figure 4 shows the typical UV auroral components observed at Saturn's poles. They are
601 sketched on a polar map independent from the observatory and apply to the northern
602 and southern hemispheres. They may be organized as a function of their latitudinal
603 location, local time and dynamical behaviour. Other classifications are possible, but on
604 the simplest level, one may divide the emissions in 4 categories; 1) the main ring of
605 emission, 2) emissions poleward of the main emission, 3) emissions equatorward of the
606 main emission, and 4) the Enceladus footprint.

607

608

609 3.2.1. The main (ring of) emission

610

611 Like Jupiter, Saturn's aurora is harbouring one principal component often referred to as
612 the main ring of emission or main oval. It should be noted that, like Jupiter this main
613 component, roughly contributing 2/3 of the total emission, is not forming a circle or an
614 oval, not even a closed structure. Instead, it appears to consist of multiple structures of
615 various sizes, often organized in a broken spiral. In the rest of the text we will refer to it
616 as the main emission. It usually spreads around the poles at northern and southern
617 latitudes larger than 70°, roughly corresponding to equatorial distances mapping to the
618 ring current between ~10 and ~20 R_S (1 Saturnian radius = 1 R_S = 60,268 km; Badman
619 et al., 2006). As stated above, its precise location was shown to respond to the solar
620 wind activity. During quiet periods, the main emission is expanding to lower latitudes

621 and during (or just after) active solar wind episodes, it is significantly contracting to
622 larger latitudes. The expansion/contraction motion is not symmetrically affecting all
623 longitudes simultaneously. As a matter of fact, this dynamical behaviour and the overall
624 spiral shape may be seen as signatures of the processes giving rise to the main emission.
625 It is generally accepted that the main emission is associated with the flow shear between
626 open and closed outer magnetosphere magnetic field lines rather than being directly
627 due to the breakdown of plasma corotation due to mass-loading [Bunce et al., 2008;
628 Talboys et al., 2011]. The distinction between closed and open magnetic field lines
629 points to the role of solar-wind, as suggested in the modeling work proposed by Cowley
630 et al. [2004a, 2004b, 2008b]. The imbalance between dayside magnetopause
631 reconnection with the solar wind, opening magnetic field lines, and magnetotail
632 reconnection, closing field lines, would then explain Saturn's changing auroral
633 morphology and its relation with solar wind activity. In addition to these large
634 morphological modifications, HST-ACS observations obtained near Saturn's 2009
635 equinox [Nichols et al., 2010], provided images indicating that the location of the overall
636 northern auroral region oscillates, with an amplitude of 1-2° consistent with that of the
637 southern oval observed by Nichols et al. [2008]. It was postulated that the cause of this
638 oscillation is an external magnetospheric current system [Southwood and Kivelson,
639 2007; Andrews et al., 2010].

640

641 The auroral brightness is usually varying from a few kR to several tens of kR and may
642 occasionally reach values in excess of 100 kR. This is roughly one order of magnitude
643 less than Jupiter's aurora. Badman et al. and Crary et al. (2005) showed that the emitted
644 auroral power is directly correlated with the solar wind ram pressure and therefore
645 anti-correlated with the size of the auroral region. During quiet solar wind episodes, the

646 overall brightness may be so small that the auroral region is almost completely fading
647 away [Gérard et al., 2006].

648 The characteristics that makes Saturn's aurora look like Jupiter's and different from the
649 Earth's is its corotating nature. The bulk of the emission is found to rotate with the
650 planet at approximately 70% of rigid rotation (in the S3 longitude system). This velocity
651 may not be representative of the whole emission, since isolated features are also
652 observed to be quasi-fixed in local time (i.e. 0% corotation). Some auroral features were
653 shown to slow down from 70% to ~20% as they were approaching the sub-solar
654 meridian [Grodent et al., 2005]. This deceleration, accompanied with a significant
655 poleward shift of several degrees of latitude, is still unexplained but might be associated
656 with the process of dayside magnetopause reconnection.

657

658 As stated above, the main emission consists of several substructures that may be
659 associated with different mechanisms. They are highlighted in Figure 4 (orange features
660 marked "1"). On the dawn side (left side), the emission is usually forming one or more
661 relatively narrow arcs. These arcs can be very bright, they are actually the brightest
662 observed features, and are corotating at 70%. Most of the time, before these arcs rotated
663 past 12LT, new ones replace them, giving the illusion of a permanent dawn side
664 emission. However, on some occasions, the dawn side was not immediately replenished.
665 Owing to the lack of very long observing sequences, it is difficult to ascertain the origin
666 of these arcs. It is possible that they are already present near midnight and light up as
667 they are approaching 06LT. According to Cowley et al. [2005], these features may be
668 explained by magnetotail reconnection near midnight with subsequent corotation of the
669 planetward side of the reconnection accelerated plasma and field reorganization

670 through dawn, then noon and dusk. An alternative mechanism was proposed to explain
671 the direct causal link between ring current enhancements, taking the form of energetic
672 neutral atoms emission (ENA), and auroral UV emissions [Mitchell et al., 2009].
673 According to this, ring pressure asymmetry may generate sufficiently high currents that
674 field aligned acceleration is required to supply the current carriers, resulting in
675 recurrent bright auroral arcs that would favour the dawn sector. Later on, Nichols et al.
676 [2010b] showed that the northern and southern dawnside auroral power exhibits a
677 statistically significant variation, by factors of ~ 3 , with maximum output occurring
678 during peak Saturn kilometric radiation (SKR) power [Kurth et al., 2007, 2008], while
679 there is evidence for weaker, opposite behaviour in the duskside power. Such behaviour
680 may be indicative of modulation by the same external rotating current system as that
681 postulated to explain the $\sim 2^\circ$ oscillation in the auroral oval location observed by Nichols
682 et al. [2010a].

683 Once these rotating arcs leave the dawn sector and approach 12LT, they either continue
684 their revolution around the pole, or give birth to a new kind of sub-structure. In the
685 former case (orange features “1” at the bottom of Figure 4), the arcs will preserve their
686 overall shape but their brightness will continuously decrease. This may explain why the
687 dawnside is usually found to be brighter than the duskside, although on some occasions
688 the dawnside may get much dimmer than dusk, especially when features leaving the
689 dawn side are not replaced with new ones. For the latter case, rotating arcs approaching
690 the noon meridian may evolve into new types of structures, poleward of the main
691 emission (dark green and light green features marked “2” and “5” in Figure 4), and will
692 be described in the next section. It should be pointed out that this evolution may only be
693 caught during observing sequences spanning several hours. Since these are not very

694 frequent, the association between dawn arcs and noon structures should be considered
695 with caution. UVIS observations obtained on August 2008, when Cassini approached
696 Saturn at an extremely small altitude of $\sim 5 R_s$, revealed details of the main emission in
697 the noon to dusk sector at a spatial resolution close to 200 km [Grodent et al., 2011].
698 These views are showing isolated features as small as 500 km across. They are taking
699 the form of individual spots arranged in a “bunch of grapes” configuration near noon,
700 and small narrow arcs near dusk (pale green spots and arcs marked “3” in Figure 4). The
701 latter arcs were tentatively associated with patterns of upward field aligned currents
702 resulting from non uniform plasma flow in the equatorial plane while the spots were
703 suggested to be the result of field aligned currents associated with vortices triggered by
704 magnetopause Kelvin-Helmholtz waves. These close up views are very rare; therefore, it
705 is currently difficult to ascertain whether the main emission is always formed of small-
706 scale features or if UVIS captured an uncommon event. Alternatively, Merdith et al.
707 (2013) suggested that such isolated patches appearing simultaneously in both
708 hemispheres, as observed with HST, are consistent with field aligned currents
709 associated with a second harmonic ULF FLR wave propagating eastward through the
710 equatorial plasma.

711

712 3.2.2. Emissions poleward of the main emission

713

714 Auroral features appearing poleward of the main emission may fit in three arbitrary
715 categories. The first category comprises auroral features completely detached from the
716 main emission and therefore presumably attached to open field lines. They are usually
717 forming sporadic and faint arcs or branches at latitudes close to 80° (red arcs marked

718 “4” in Figure 4). Their origin is currently unknown, although analogies with similar
719 features in Earth aurora suggest a possible association with Earth’s theta aurora
720 (Radioti et al., submitted). The second category groups auroral structures that are still
721 attached to the main emission (dark green region “2”, light green arcs marked “5” in
722 Figure 4) and appear almost fixed in local time. The majority of these features are
723 located near noon, suggesting that they are related to the process of magnetic
724 reconnection near the nose of Saturn’s magnetopause and were often termed “cusp
725 aurora”. At Saturn, auroral brightenings are frequently observed near noon [e.g. Gérard
726 et al., 2004, 2005] (dark green feature “2” in Figure 4). Following theoretical
727 considerations, they were possibly attributed to reconnection with the solar wind
728 magnetic field on the dayside magnetopause, similarly to the case of lobe cusp spots at
729 Earth [Milan et al., 2000]. Bunce et al. [2005] proposed that pulsed reconnection at the
730 low-latitude dayside magnetopause for northward directed IMF (corresponding to the
731 southward IMF case at Earth) is giving rise to pulsed twin-vortical flows in the
732 magnetosphere and ionosphere in the vicinity of the OCFLB. These vortices build up
733 field-aligned currents sufficient to produce the observed auroral enhancements near
734 noon. During southward IMF conditions, reconnection cannot take place at low latitude,
735 however, high-latitude lobe reconnection pulsed twin-vortical flows, bi-polar field
736 aligned currents are expected and associated with auroral intensifications poleward of
737 the OCFLB. During intermediate conditions, with a small northward and dominating
738 east-west (B_y) component of the IMF, a mixed situation with reconnection at the high
739 and the low latitude region may occur simultaneously. In addition, a non negligible B_y
740 component may also favour reconnection on the flanks of the magnetopause giving rise
741 to auroral brightenings appearing near the pre-noon or post-noon sectors.

742

743 An extended sequence of observations obtained with UVIS in 2008 revealed the
744 evolution of an auroral feature starting as an intensification of the main emission near
745 noon, similar to the cusp aurora described above, gradually detaching from the main
746 emission (the OCFLB) in the poleward direction [Radioti et al., 2011, 2013b; Badman et
747 al., 2013], and finally evolving into two arcs (other shorter UVIS sequences show up to 3
748 arcs) with one end attached to the main emission and the other end intruding the empty
749 polar region at a smaller local time (light green arcs marked “5” in Figure 4). These
750 bifurcations of Saturn’s main emission were tentatively attributed to consecutive
751 reconnection events at the dayside magnetopause and were associated with open
752 magnetic flux. Thorough inspection of the sequence of UV observations showed a
753 concurrent equatorward motion, or expansion of the main ring of emission, such that
754 the increase of the area poleward of the main emission (i.e. the polar cap size) is
755 balanced by the area occupied by the bifurcations, therefore supporting the consecutive
756 reconnections scenario and the possibility that dayside reconnection at Saturn can occur
757 consecutively or simultaneously at several locations on the magnetopause with the
758 reconnection lines following each other as they sweep along the flank of the
759 magnetopause.

760

761 The same study from Radioti et al. [2011] pointed out transient spot-like structures
762 appearing at the dawn and dusk poleward boundary of the main emission ring,
763 establishing a third category of poleward features (dark blue spots marked “6” in Figure
764 4). These small, isolated features are somewhat detached from the main emission and
765 are therefore possibly connected to open magnetic field lines. Jackman et al. [2013]
766 demonstrated that dipolarizations in the magnetotail following reconnection events
767 might result in distinct, observable auroral signatures. They estimated that reconnection

768 in the magnetotail can lead to rapid motion of newly closed field lines planetward and
769 the diversion of the cross-tail current through the ionosphere, resulting in discrete
770 auroral emission through hot plasma injection into and around the inner
771 magnetosphere. The expected brightness of associated auroral signatures is on the
772 order of 10 kR, somewhat smaller but still in reasonable agreement with the observed
773 auroral spots of a few tens of kR. Jackman et al. [2013] further pointed out that the
774 observed auroral spot that they considered in their study is a precursor to a larger
775 intensification which followed about an hour later in the Cassini UVIS sequence, and
776 which had previously been reported to be linked with recurrent energisation from the
777 tail (Mitchell et al., 2009).

778

779 3.2.3. Emissions equatorward of the main emission

780

781 Two types of auroral structures appear equatorward of the main emission; spots and
782 nightside extended arcs (outer emission). Spot features include the Enceladus footprint
783 that will be addressed in the next section.

784

785 3.2.3.1. Spots

786

787 Isolated transient UV auroral spots are occasionally observed in Saturn's ionosphere
788 along the equatorward boundary of the main emission [Radioti et al., 2009b, 2013c]
789 (purple spots marked "7" in Figure 4). Their typical lifetime ranges from several minutes
790 to a few tens of minutes. These relatively faint features – therefore difficult to detect -
791 display typical brightness <10 kR, corresponding to emitted power on the order of 0.1
792 GW.

793 Quasi-simultaneous HST and Cassini observations suggested that these auroral spots are
794 associated with the dynamics taking place in Saturn’s magnetosphere. Most specifically,
795 Cassini’s remote instruments detected signatures of energetic particle injections on
796 magnetic field lines mapping close to the ionospheric region where, on the same day,
797 HST observed the transient auroral spots. Radioti et al. [2009] proposed that the
798 injection region may directly be coupled to Saturn’s ionosphere by pitch angle diffusion
799 and electron scattering by whistler waves, or by the electric current flowing along the
800 boundary of the injected hot cloud. A more recent Cassini UVIS dataset made it possible
801 to model the changing brightness distribution of such UV spot structures [Radioti et al.,
802 2013b]. Comparison of the brightness and size evolution of the simulated ionospheric
803 signature, based on typical injected particles drift and plasma energy dispersion, with
804 observed values demonstrated that these auroral spots behave as auroral signatures of
805 an injection. Simultaneous Cassini observations of energetic neutral atoms (ENA)
806 enhancements, indicative of a rotating heated plasma region, suggest that pitch angle
807 diffusion and electron scattering may not be the only mechanism responsible for the
808 observed auroral spots. Field aligned currents driven by pressure gradients along the
809 boundaries of the injected hot plasma may also give rise to such auroral emissions.

810

811 3.2.3.2. Outer emission

812

813 Recent observations of Saturn’s aurora with the UVIS spectrograph on-board Cassini not
814 only confirm the presence of a quasi-permanent partial ring of emission equatorward of
815 Saturn’s main auroral emission [Grodent et al., 2005, 2010] (light blue arc marked “8” in
816 Figure 4), but they also increase the number of positive cases and allow for a statistical
817 analysis of the characteristics of this outer emission. This faint but distinct auroral

818 feature appears at both hemispheres in the nightside sector. It magnetically maps to
819 relatively large distances in the nightside magnetosphere, on the order of $9 R_S$.
820 This auroral feature consists of one or more narrow arcs ($\sim 3^\circ$ of latitude) of emission
821 usually extending equatorward of the main emission from 18LT to 06LT through
822 midnight, although some images show the emission extending down to 09LT. The
823 emission is not uniform in longitude, the presence of patches allows one to estimate the
824 level of corotation of the outer emission to $\sim 70\%$, similar to the main emission and
825 compatible with a magnetospheric plasma source rotating at 7 to $10 R_S$ from Saturn.
826 It was initially thought that pitch angle scattering of electrons into the loss cone by
827 whistler waves would be responsible for the outer auroral emission. Rough estimates
828 suggested that a suprathermal electron population observed with Cassini [Schippers et
829 al, 2008; Lewis et al., 2008] in the nightside sector between 7 and $10 R_S$ might power
830 this process. However, a new analysis of 7 years of Cassini electron plasma data
831 [Schippers et al., 2012] indicates the presence of layers of upward and downward field
832 aligned currents. They appear to be part of a large-scale current system involving
833 dayside-nightside asymmetries as well as trans-hemispheric variations. This system
834 comprises a net upward current layer, carried by warm electrons, limited to the
835 nightside sector which may as well generate the outer UV auroral emission.

836

837 3.2.4. The Enceladus footprint

838

839 The detection threshold of the HST UV cameras and the amount of reflected sunlight
840 leaking in these detectors are too large for a possible detection of Enceladus' footprint
841 with STIS or ACS. On the other hand, the UVIS spectrograph is able to detect fainter
842 emissions. On 26 August 2008, UVIS obtained three successive observations of Saturn's

843 north pole unambiguously revealing the auroral footprint of Enceladus at a location
844 consistent with the expected one [Pryor et al., 2011] (yellow spot marked “9” in Figure
845 4). The spot brightness is on the order of 1 kR, just above UVIS detection threshold. The
846 predicted southern footprint has not yet been detected for it is probably fainter than its
847 northern counterpart, as is the case for the main aurora (Nichols et al., 2009b). The
848 auroral spot size suggests that the emission is connected to an Enceladus interaction
849 region at the equator extending as far as 20 Enceladus radii (R_E) downstream with a
850 radial extent between 0 and 20 R_E , consistent with the extent of the plume resulting
851 from Enceladus’ cryo-volcanic activity. The Enceladus auroral footprint was shown to
852 vary in brightness by a factor of about 3. The most likely cause for this observed large-
853 scale variability is related to the time-variable cryo-volcanism from Enceladus’ south
854 polar vents, suggesting that plume activity was particularly high at the time of the UVIS
855 observations. Two weeks prior this detection by UVIS, the in situ instruments of Cassini
856 detected signatures of magnetic-field-aligned ion and electron beams with sufficient
857 power to produce the observed auroral footprint of Enceladus. Observed changes in the
858 characteristic energy of the field-aligned electron flux were tentatively associated with
859 changes in the magnetic field perturbation suggesting an actual change in the total field-
860 aligned current density. At Jupiter, the multiple components of the ultraviolet footprint
861 of Io have been interpreted as being due to multiple reflections of a standing Alfvén
862 wave current system driven by Io. It is possible that the flickering in energy of the beams
863 observed downstream of Enceladus is the equatorial signature of a standing wave
864 pattern like that observed at the Io footprint, suggesting a possible universal mechanism
865 magnetically coupling a conducting moon to its parent planet’s ionosphere.
866

867 4. The ice giants

868

869 4.1. Uranus

870

871 Like Jupiter and Saturn, Uranus' fast rotation provides the planet with a strong dynamo-
872 magnetic field. Modelling of the interior of Uranus [Stanley and Bloxham, 2006] suggests
873 that the dynamo source region consists in a convecting thin shell surrounding a stably
874 stratified fluid interior. This configuration is compatible with formation of a highly tilted
875 (58.6°) and shifted (0.3 Uranian radius) magnetic dipole as well as important multipolar
876 components. This intricate asymmetric magnetic topology combines with the oddly
877 inclined spin axis (98°) of Uranus to form a highly distorted magnetosphere interacting
878 with the solar wind in a way that is changing during the course of the uranian day
879 [Arridge et al., 2012]. This complexity complicates the detection of auroral emissions,
880 especially for a distant observer near Earth orbit.

881

882 The first unambiguous detection of aurora on Uranus was made possible by the unique
883 flyby of the planet by Voyager 2 (V2) Spacecraft. On January 24, 1986, at the time of
884 Uranus northern summer solstice, V2 was only 81,500 km from the cloud tops. Among
885 the numerous observations performed with V2 instruments during this several-hour
886 encounter, the extreme ultraviolet spectrometer (UVS) measured emissions in the 95-
887 110 nm range near the magnetic poles [Broadfoot et al., 1986; Herbert and Sandel,
888 1994]. Those were attributed to auroral H_2 Lyman and Werner bands because at these
889 wavelengths sunlight reflected by the uranian atmosphere is relatively weak. On the
890 contrary, the auroral H Lyman α emission could not be discriminated from the much

891 brighter dayside reflected solar H Lyman α light, nor from the nightside reflected
892 interstellar medium H Lyman α .

893 Reconstruction from individual spatially resolved spectra taken at different times
894 [Herbert, 2009] provided an average map of the auroral emission, assumed to be time
895 invariant. The bulk of the emission forms discrete spots around the north and south AH₅
896 model magnetic poles and map to closed field line regions near $L=5$ (See Herbert [2009]
897 for precise significance of L which slightly differs from the conventional McIlwain
898 parameter). In addition, a pair of bright spots in the north auroral polar cap appears to
899 map to $L \geq 20$, presumably on open field lines. In both cases, the magnetic longitude is
900 such that the majority of the observed aurora connects to the magnetotail, suggesting
901 substorm-like injection processes, possibly associated with the arrival of an
902 interplanetary shock [Sittler et al., 1987], and an Earth-like partial ring current system.

903 The brightest UV auroral emissions thread field lines along which strong Uranian
904 kilometric radio emissions (UKR; e.g. Herbert and Sandel, 1994) and whistler mode
905 waves [Gurnett et al., 1986; Kurth and Gurnett, 1991] were also concurrently observed
906 with V2. This coincidence suggests that the auroral precipitation associated with the UV
907 emission might stem from whistler mode plasma waves scattering magnetospheric
908 electrons of several keV into the loss cone.

909 Since the rotation period of Uranus is not accurately known, the magnetic configuration
910 inferred from V2 in 1986 is not sufficient to derive the present location of the magnetic
911 poles. As a consequence, one does not know exactly where to search for the auroral
912 signal, which is challenging new observation planning. Nevertheless, there have been
913 several attempts to observe the uranian UV aurora from Earth orbit with HST, in 1998,
914 2005 and 2011, around Uranus equinox. Only the 2011 and 1998 HST datasets reveal
915 unambiguous auroral emissions [Lamy et al., 2012]. The 2011 aurora was shown to be

916 potentially associated with a series of powerful CMEs emitted by the Sun two months
917 earlier. These features appeared to form an extremely localised patch of weak emission,
918 only visible in a few HST images. They were described as variable signatures with
919 brightness comparable to that observed with V2. They are taking the form of spots or
920 roughly continuous ring-like structures in the dayside. Lamy et al. [2012] suggested that
921 the spots result from dayside reconnection with the IMF, while the ring-like structures
922 would involve electron precipitation over a wide range of longitudes that might be
923 related to a short-lived twisted configuration of the magnetotail.

924

925 Similar efforts were made to detect auroral signatures in the near-infrared wavelength
926 range as part of a long term ground-based monitoring of Uranus' H_3^+ emissions [Melin et
927 al., 2011]. Whilst the aurora remains spatially unresolved in the infrared, probably
928 owing to its small contrast with thermal emissions, observations conducted since 1992
929 show significant short-term variability. This variability is presumably caused by changes
930 in particle precipitation flux and energy rather than by the slower variation of solar
931 input energy. More recently, Melin et al. [2013] presented observations obtained in late
932 2011, simultaneously with HST UV observations, showing that Uranus' upper
933 atmosphere had continued its long-term cooling trend beyond the 2007 equinox. This
934 further suggests that Uranus thermospheric temperature is closely linked to the
935 changing geometry of the solar wind and planetary magnetic field.

936

937 4.2. Neptune

938

939 The dynamo source region of Neptune is likely of the same nature as that of Uranus
940 [Stanley and Bloxham, 2006]. Therefore, it is not surprising that its magnetic field is also

941 highly asymmetric, tilted (-47°) and shifted (~ 0.5 Neptune Radius). Neptune's obliquity
942 is significantly smaller than Uranus' (29.6°), yet it is still large enough to contribute to
943 the complexity and variability of Neptune's magnetosphere.

944 Voyager 2 UVS detected marginal ultraviolet atmospheric emission from the nightside of
945 Neptune [Broadfoot et al., 1989]. This emission, consistent with H_2 band spectrum,
946 forms two distinct features: a broad diffuse region extending from $55^\circ S$ to $50^\circ N$ near
947 $60^\circ W$ and a brighter, narrower region confined to high southern latitudes near $240^\circ W$
948 [Sandel et al., 1990]. This latter feature was tentatively attributed to auroral processes
949 involving precipitation of energetic electrons trapped at L values $\geq 8 R_N$ (Mauk et al.,
950 1994). It was also associated with a partial plasma torus formed by ionization of gas
951 escaping from Triton's atmosphere [Hill and Dessler, 1990]; or, alternatively, with a
952 magnetic anomaly effect [Paranicas and Cheng, 1994]. The latitudinally distributed
953 emission near $60^\circ W$ was suggested to result from precipitation of photoelectrons
954 originating in the conjugate sunlit hemisphere. In any case, these emissions are so faint,
955 a couple of Rayleighs in the H_2 band region shortward of Lyman α , that they were never
956 detected from Earth orbit and are not expected to have any measurable infrared
957 counterpart.

958

959 5. Conclusion

960

961 5.1. Jupiter and Saturn

962

963 Jupiter and Saturn are gas giant planets with strong magnetic fields and fast
964 rotating H₂ dominated atmospheres. They both harbour conducting moons, one of which
965 (Io and Enceladus, respectively) is a major internal plasma source tapping their giant
966 magnetospheres. All the ingredients are present on the two planets, in different
967 proportions, to produce strong UV auroral emissions with, one might think, comparable
968 morphologies. However, Jupiter and Saturn appear to respond differently to the
969 interplanetary magnetic field and to changing solar wind conditions. These different
970 responses are thought to impart noticeable dissimilarities on the UV auroral
971 morphology and on the origin of some auroral features that, at first glance, are looking
972 the same. The most striking case is the main emission. It is present on both planets and
973 is forming a strip of emission around the pole that is partially corotating with the
974 magnetic field. However, closer inspection of this main auroral feature reveals strong
975 dissimilarities, such as the bifurcation of a fraction of the Saturnian main emission,
976 which finds no equivalent in the Jovian aurora. This particular behaviour points to the
977 control of Saturn's main emission by processes related to the interaction of Saturn's
978 magnetosphere with the solar wind. For Jupiter, this interaction appears to be much less
979 important and is eclipsed by the corotation electric field. Despite these major
980 differences, some auroral features appear to be common to gas giants. Among them,
981 satellite magnetic footprints are easily recognizable since they detach from the rest of
982 the emission. Injection of hot plasma in the middle magnetosphere is also a process
983 common to both planets. Therefore, it is not surprising to find similar auroral

984 signatures. The case of dayside and night side reconnection spot like signatures is less
985 clear-cut since it involves magnetospheric mechanisms that are driven internally
986 (Vasyliūnas-cycle) or externally (Dungey-cycle). The relative importance of these two
987 cycles depends, again, on the significance of corotation enforcement compared to solar
988 wind convection, which is different for Jupiter and Saturn.

989

990

991 5.2. Uranus and Neptune

992

993 Compared to Jupiter and Saturn, the UV aurorae on Uranus and Neptune are all
994 poorly documented. The main reason stems from the weakness of the emission, making
995 it extremely difficult to observe from Earth orbit, and from the complexity of the
996 magnetic field and their rapidly changing distorted magnetosphere. Most of the
997 observations were obtained with the Voyager 2 spacecraft that flew by Uranus in 1986
998 and by Neptune in 1989. On Uranus, the aurora forms discrete spots around both
999 magnetic poles and map along closed and open magnetic field lines possibly connected
1000 to the magnetotail, suggesting substorm-like injection processes. On Neptune, the UV
1001 signal was marginally detected on the nightside of the planet. It consists of a broad
1002 diffuse region extending between northern and southern mid-latitudes and a narrower
1003 region confined to high southern latitudes. Only the latter was plausibly associated with
1004 auroral processes. Some recent observations with HST also revealed UV auroral
1005 emission on Uranus. This weak emission forms spots, tentatively attributed to
1006 reconnection with the IMF, or ring-like structures in the dayside possibly related to a
1007 short-lived twisted configuration of the magnetotail.

1008

1009

1010 5.3. The Juno mission

1011

1012 Although our understanding of the auroral mechanisms prevailing at the giant
1013 planets is improving, thanks to the continuing observing, theoretical and modelling
1014 efforts, there are still numerous fundamental questions which need consideration. For
1015 example, the auroral particle acceleration processes above the atmosphere need to be
1016 confirmed; the actual role of solar wind in driving the magnetospheres is also a crucial
1017 point of debate. The NASA New Frontiers Juno mission will directly address some of
1018 these questions [Bolton et al., 2010]. Juno will be the first spacecraft placed into an
1019 elliptical polar orbit around Jupiter following an insertion-orbit manoeuvre in July 2016.
1020 Juno's scientific payload consists of nine instruments, five of which are designed to
1021 determine the physical processes occurring in the high latitude magnetosphere of
1022 Jupiter, making it possible to directly relate them to auroral activity and to processes
1023 taking place in the low-latitude magnetosphere [Bagenal et al., 2014]. Specifically, the
1024 magnetometer (MAG) will provide an accurate mapping of the magnetic field from the
1025 top of the ionosphere to the deep magnetosphere; the Jupiter Energetic particle Detector
1026 Instrument (JEDI) will measure the high energy and pitch angle of plasma sheet ions and
1027 electrons while the Jovian Auroral Distributions Experiment (JADE) will make the first
1028 characterization of the particles giving rise to aurora and will complement JEDI by
1029 observing the lower part of the energy spectrum; the plasma Waves (Waves) instrument
1030 will identify the regions of auroral currents and the auroral particles acceleration
1031 processes; at the same time, the Ultraviolet Spectrograph (UVS) will obtain spectral
1032 images of the UV aurora generated by the particles measured by JADE. In addition, the
1033 Jupiter InfraRed Auroral Mapper (JIRAM) will provide key information on the conditions

1034 prevailing in the auroral atmosphere and the visible camera (JunoCAM) will also
1035 observe the auroral emissions in the nightside sector. Thanks to its polar orbit and
1036 instruments suite Juno will be capable of simultaneously measuring key signatures of
1037 the efficient magnetosphere-ionosphere coupling at Jupiter. This knowledge will benefit
1038 to the case of Saturn and to some extent to Uranus and Neptune, as well as any giant
1039 magnetized planet surrounded by plasma.

1040

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1051

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1554 **Figure captions**

1555

1556 Figure 1: Polar projections of typical ACS FUV images of Jupiter aurora obtained
1557 quasi-simultaneously (~3 min apart) in both hemispheres on 22 March 2007. See text
1558 for detailed description.

1559

1560 Figure 2: Sketch of the typical FUV auroral components of the northern hemisphere of
1561 Jupiter. Planetocentric parallels and System III meridians are drawn every 10°.

- | | |
|-------------------------------------|----------------------------------|
| 1. Main emission (oval) | 8. Ganymede footprint (multiple) |
| 2. Kink region | 9. Polar active region |
| 3. Discontinuity | 10. Polar dark region |
| 4. Secondary emission | 11. Polar swirl region |
| 5. Signatures of injections | 12. Polar auroral filament (PAF) |
| 6. Io footprint (multiple) and tail | 13. Dawn spots and arcs |
| 7. Europa footprint and tail | 14. Midnight spot. |

The upper grey shaded region is not accessible to Earth orbit instruments.

Figure 3: Typical pseudo-image of Saturn's northern FUV aurora obtained with the UVIS camera onboard the Cassini spacecraft on 6 Jan 2013 from 08:38 (SCT). Planetocentric parallels (from 60° to 90°) and local time meridians are drawn every 10°. The local time polar map is showing some of the typical components of Saturn's aurora: a bright dawn section of the main emission, noon feature detaching poleward from the main emission, diffuse dusk side main emission, and nightside outer emission. Dawn (06LT) is to the left; noon (12LT) is to the bottom of the figure. See text for a detailed description of the image.

Figure 4: Sketch of the typical UV auroral components observed at Saturn's poles with both HST STIS and ACS and the Cassini-UVIS spectrograph. The local time polar map displays parallels and meridians every 10°.

1. Main (ring of) emission
2. Cusp emission
3. Small scale spots and arcs
4. Poleward auroral arcs
5. Bifurcations
6. Poleward auroral spots
7. Signatures of injections
8. Outer emission
9. Enceladus footprint