A brief review of ultraviolet auroral emissions on giant planets

Denis Grodent

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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

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

1. Introduction

1.1. General characteristics of the giant gas planets aurorae

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

	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

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

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

One immediate corollary to this domination by the corotation field is the rotating or sub-corotating nature of the auroral features around the poles. Contrary to the Earth, where the bulk aurora is fixed with respect to the Sun, the aurora on Jupiter and Saturn is corotating at a significant fraction of planetary rigid rotation. It is said to corotate with the planetary magnetic field. Deviation from corotation may then be interpreted as the signature of an "unusual" magnetospheric process, where "unusual" means a process capable of disrupting the plasma's rotation around the planet with the magnetic field and/or generate beams of electrons at energies sufficiently large to excite atmospheric H_2 molecules or H atoms through collisions. As will be seen in the following sections, numerous such processes exist in Jupiter and Saturn's magnetospheres and may account for the majority of ultraviolet (UV) auroral emissions.

1.2. First detections of aurora on giant gas planets

The UV aurorae on giant planets were first spotted more than three decades ago by the UVS spectrograph on board the two Voyager spacecraft. During the two flybys of Jupiter in 1979, auroral emissions from H_2 and H were unambiguously revealed [Broadfoot et al., 1979]. A couple of years later, Voyager 2 flew by Saturn and obtained similar evidences of auroral activity [Broadfoot et al., 1981]. The very limited spatial resolution of the UVS spectrograph did not make it possible to determine the precise spatial distributions of these aurorae. It is only thanks to the advent of the UV cameras on board the Hubble Space Telescope (FOC, WFPC1, WFPC2, STIS, ACS) that the accurate determination of the auroral morphology of Jupiter and Saturn became possible (see reviews of Clarke et al. [2004] for Jupiter and Kurth et al. [2009] for Saturn).

1.3. Atmospheric origins of the giant planets UV aurora

Comparisons between observed auroral spectra and models suggest that, on giant planets, auroral emissions observed in the UV range are principally the result of inelastic collisions between atmospheric H_2 molecules and energetic magnetospheric electrons precipitating in the atmosphere along magnetic field lines. These primary electrons gradually lose their energy to the ionosphere through ionization, dissociation and excitation of H_2 molecules. Ionization, the most efficient process, produces numerous secondary electrons that in turn impact H_2 molecules. The primary and secondary electrons interactions with H_2 mainly depend on their energy. They are governed by various cross-sections (ionizations, electronic excitations, vibrational and rotational excitations). In theory, any electron with energy above the excitation threshold of the B state of the H_2 molecule (~10 eV) has a chance to produce a UV photon of interest. The excitation cross section of the various excited states of H_2 maximize in the 20-160 eV range, meaning that primary electrons and mostly secondary electrons colliding with H_2 contribute to the production of auroral UV photons. Above ~50 eV, ionization and electronic excitation cross-sections follow similar electron energy dependences, however, ionization is one to two orders of magnitude more probable than excitation [Gustin et al., 2013].

The bulk of the UV auroral emission in the far ultraviolet (FUV) 70-180 nm range mainly results from electron impact excitation of H_2 to various excited rotational–vibrational–electronic states (see Gustin et al. [2009, 2012, 2013] for a thorough discussion on the origins of the auroral H_2 UV emissions). This process initiates de-excitation of excited H_2 through the emission of UV photons forming the Lyman and Werner bands, Lyman-alpha and continuum emissions. The energy degradation of the primary and secondary electrons in their course towards deeper atmospheric levels continues until they are thermalized in the ambient atmosphere. Direct excitation of atomic H produces Lyman-α emission. However, in the giant planets where H dominates H_2 at very high altitudes, the dominant source of H-Lyman-α emission is related to dissociative excitation of H_2 giving rise to fast-excited H fragments loosing their excess energy through emission of Ly-α as well as Lyman and Balmer series photons. In any case, dissociative excitation dominates the production of the auroral Lyman line and contributes ~99 % of the auroral UV spectrum of Jupiter [Grodent et al., 2001; Gustin et al., 2012] and Saturn.

1.4. Other wavelength ranges

In the following, we focus on ultraviolet emissions that are directly accessible to instruments like the UV cameras onboard the Hubble Space Telescope (the Advanced Camera for Surveys, ACS; the Space Telescope Imaging Spectrograph, STIS) for Jupiter and Saturn, or the Cassini Spacecraft (UltraViolet Imaging Spectrograph, UVIS) for Saturn. Nevertheless, it should be noted that aurorae on the giant planets are also glowing in other wavelengths including the radio [e.g. Lamy et al., 2009], infrared [e.g. Radioti et al., 2013a], visible [e.g. Vasavada et al., 1999] and X-Ray [e.g. Branduardi et al., 2008] ranges. These radiations are more or less directly related to the UV emissions but they deserve specific treatments, beyond the scope of the present review paper, and provide complementary information. The interested reader will find useful information about auroral emissions in other wavelengths in the review paper by Badman et al. (this issue).

2. Jupiter

2.1. Current understanding

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

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

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

2.2. Main components of Jupiter's aurora

2.2.1. Northern and southern polar regions

Gérard et al. [2013] analysed quasi-simulatenous HST images of both hemispheres of Jupiter and found that most morphological auroral features identified in one hemisphere have a conjugate counterpart in the other hemisphere, with some significant differences in the power associated with conjugate regions. Nevertheless, in the following we focus on the northern hemisphere of Jupiter. The main reason for this approach stems from the large hemispheric asymmetries in the internal magnetic field of Jupiter. The northern aurora is more tilted towards the equator than the south and, from Earth orbit, it appears with a better viewing geometry when the field is inclined towards the Earth. Another reason may be linked with the presence of a possible magnetic anomaly in the northern hemisphere [Grodent et al., 2008]. The presence of this anomaly locally perturbs the surface magnetic field and has the effect of a "magnifying glass" on the auroral emissions. In this ionospheric region, magnetic field lines are threading a smaller area in the magnetosphere and the auroral features appear more detached from each other, allowing easier disentangling. Figure 1 shows typical polar projections of ACS FUV images of Jupiter aurora obtained quasi-simultaneously (~3 min apart) in both hemispheres since the field of view (FOV) of ACS and STIS are too small to accommodate both hemispheres in the same image. The southern hemisphere is displayed for an observer looking through the planet from above the north pole. The images were obtained on 22 March 2007 during orbit J8-K8 (visit I8) of program GO-10862. Blue arrows point to the auroral footprints of Ganymede and Europa (Europa's footprint is barely visible). The blue circle points to a systematic discontinuity in the main emission. The green ellipse encircles a possible auroral signature of plasma injection. A small portion of the main emission (main emission) appears near 180°, leftward of the injection. Polar emissions appear in the northern hemisphere near 70° latitude (purple ellipse), no conjugate emission is visible in the south. The influence zone of a likely local magnetic anomaly appears as a white- transparent disc ($B_{anomaly}$). Yellow circles indicate the direction of magnetic noon at 15 R_J (1 Jovian radius = 1 R_J = 71,492 km), which corresponds to the longitude of the footprint of Ganymede when the moon is at 12LT. All longitudes are in System III (S3). Planetocentric parallels and meridians are drawn every 10°. The black line is the region occulted by the repelling wire. In this set of images, the Central Meridian Longitude (CML) is optimized for viewing both hemispheres quasi simultaneously.

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

2.2.2. The main emission (oval)

2.2.2.1. Overall shape and origin

The main auroral oval, more correctly named main emission since it does not form an oval, is structured into a relative stable strip of emission around the magnetic poles. Grodent et al. [2003a] performed a long-term comparison of HST images and showed that the bulk of the auroral morphology is fixed in system-III longitude (SIII), meaning that follows Jupiter's fast rotation. It forms a complex structure mixing multiple narrow arc-like structures, discontinuities, and diffuse patches of emission (orange structures marked "1" in Figure 2). The global statistical shape of the northern aurora has been shown to be influenced by a magnetic anomaly, giving rise to a kink in the main emission (region marked "2" in Figure 2). Such an anomaly has not been reported for the southern hemisphere. In general, the main auroral emissions vary in width between ~100-500 km, though it is even broader at dusk. Its global emission is estimated to contribute almost 75% of the Jovian auroral brightness integrated over the poles. The typical brightness exceeds ~100 kR at UV wavelengths, peaking at up to several MR intensities [Gustin et al., 2006]. In general, the dawnside portion (left side of Figure 2) forms a relatively narrow arc, appearing almost continuous in UV images, the post-noon portion (upper left part of Figure 2) consists of auroral patches and the dusk portion (right side of Figure 2) appears to broaden and break from the main emission. The nightside sector of Jupiter's polar regions is not accessible to Earth orbit observatories like HST. Therefore, current knowledge of the nightside auroral morphology mainly relies on speculations.

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

Recent work has also shown that the main auroral oval and the Ganymede auroral footprint move in latitude over periods of a few months [Bonfond et al., 2012a]. This intriguing motion is not yet explained and could be a subtle combination of moon activity, mass loading rates, magnetodisc configuration, solar wind interaction and ionospheric conductivity.

2.2.2.2. Discontinuity

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

2.2.3. The secondary emissions

2.2.3.1. Overall shape and origin

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

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

At Jupiter, Bhattacharya et al. [2001] suggested that wave particle interactions in a broad region in the magnetosphere (10 to 25 R_J) could lead to electron scattering and precipitation into the ionosphere contributing to the EDE. Tomás et al. [2004] related the transition of the electron pitch angle distribution (PAD) from pancake to bidirectional (observed within 10 to 17 R_J) to a discrete auroral emission equatorward of the main oval, under the assumption of electron scattering in the loss cone due to whistler mode waves. The brightness of the EDE usually ranges from 40 to 100 kR in the north and from 10 to 50 kR in the south. Based on the analysis of a large HST 1997 – 2007 dataset, it appeared that the EDE are almost always present, especially in the dusk side. The persistence of the EDE suggests that its origin is associated with a permanent magnetospheric feature such as the PAD boundary. Radioti et al. [2009a] showed that the PAD boundary magnetically maps to the diffuse auroral emission region in the northern and southern hemisphere. Comparison of the derived precipitation energy flux with the observed brightness of the EDE further showed that the energy contained in the PAD boundary could account for the measured auroral emissions in both hemispheres.

2.2.3.2. Signatures of injections

As stated above, not all components of the EDE may be associated with a transition of the electron pitch angle distribution. Transient isolated auroral patches appearing equatorward of the main emission (purple patches marked "5" in Figure 2) could be related to other mechanisms, such as electron scattering by whistler mode waves associated with anisotropic injection events [Xiao et al., 2003; Mauk et al., 2002] or with field aligned currents flowing along the boundary of a hot injected plasma cloud. These auroral signatures of injections may take the form of quasi-corotating shapeless features detaching from the main emission near the footpaths of Europa and Ganymede. At times, they overlap these satellites footprints, making their detection ambiguous. In the Jovian magnetosphere, the processes of plasma injection and interchange motion are thought to be associated with the radial inward transport of hot tenuous magnetotail plasma, compensating for the continuous opposite outward flow of cold iogenic plasma in such a manner as to conserve magnetic flux. To date, only one HST observation of an auroral injection signature could be unambiguously associated with an in situ Galileo detection of a cloud of injected energetic particles [Mauk et al., 2002]. The fact that this case is unique does not stem from the rarity of the phenomenon; it is actually very frequent both in the HST and Galileo datasets, but from the lack of simultaneous Galileo – HST observations. Bonfond et al. [2012a] reported what appears to be an exceptional event. While the auroral injection signatures are usually confined between the main emission and the Io footpath, in June 2007 a large patch of UV emission was observed with HST in the northern hemisphere as far down as the expected location of the Io footprint. This feature appears to be the remnant of a large injection blob seen in the same sector in the southern hemisphere 34 hours before. Instead of simply overlapping the Io footprint (see below), this feature appears to have triggered a momentary substantial decrease of the Io footprint brightness. This behaviour was suggested to result from the depleted nature of the flux tubes containing the sparse injected hot plasma that may have disrupted the Io-Jupiter interaction.

2.2.4. The satellites footprints

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

The satellite's Ultraviolet auroral footprint appear in Jupiter's ionosphere close to the feet of the field lines passing through the satellites Io, Europa and Ganymede [Clarke et al., 2002] (yellow spots marked "6", "7" and "8" in Figure 2, respectively). The observed morphology consists of either one, for Europa, or several distinct spots for Io and Ganymede [Bonfond et al., 2009, 2013] eventually followed by a trailing tail as is the case for Io and Europa [Clarke et al., 2002; Grodent et al., 2006] (yellow diffuse arc downstream of spots "6" and "7" in Figure 2). It is actually anticipated that with a sufficiently sensitive instrument (which is not yet the case), one should observe the same features for all satellites footprints. Indeed, these small auroral features most probably stem from a common (universal) process in which the slow moving satellites pose obstacles to the fast corotating magnetospheric plasma flow. The magnetic perturbation associated with the continuous collisions of the plasma with the satellites' interaction regions propagates along the magnetic field lines as Alfvén waves. The locus of the perturbed points forms Alfvén wings directed towards both poles. On their way to the planet, the waves probably undergo filamentation (Chust et al., 2005; Hess et al., 2010a) and are partially reflected on plasma density gradients, especially at the plasma torus or the plasma sheet boundaries. The fraction of the waves escaping the torus or the sheet causes electron acceleration in both directions. These electrons ultimately precipitate into Jupiter's atmosphere where they produce the observed auroral signatures. Io's footprint brightness may reach up to 20 MR in the UV, representing a large local input of power to the upper atmosphere [Bonfond et al. 2013]. The emissions from the Ganymede and Europa footprints are generally on the order of a few hundreds of kR in the UV. Bonfond et al. [2008, 2013], Jacobsen et al. [2007] and Hess et al. [2010a] proposed that the combination of Alfvén waves reflection and bidirectional electron acceleration may explain the relative motion of the different spots of the Io and Ganymede footprints, respectively, as well as the presence of electron beams affecting the ionization processes near Io [Dols et al., 2012; Saur et al., 2003].

The brightness of the Io and Ganymede footprint spots varies with the System III longitude of the satellite, i.e. with the location of the moon relative to the plasma torus/sheet center, with a ~10 hr periodicity [Grodent et al. 2009, Bonfond et al. 2013]. At Ganymede, a second time scale for brightness variations ranges from 10 to 40 min and was tentatively associated with interactions between Ganymede's mini-magnetosphere and local magnetospheric inhomogeneities, such as those produced by localized plasma injections. A similar process has been suggested to explain an exceptional drop of the Io footprint brightness [Bonfond et al. 2012a, Hess et al. 2013]. The shortest time scale observed so far is on the order of 1 to 2 min. At Ganymede, these variations were suggested to be triggered by bursty reconnections at the satellite's magnetopause [Jia et al., 2010]. Alternatively, they may be related to double layer regeneration as suggested for the Io footprint [Hess et al., 2010b; Bonfond et al., 2013].

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

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

Although it is very much likely that there is an electrodynamic interaction between Callisto and Jupiter's magnetospheric environment that is similar to those at Io, Europa, and Ganymede (Menietti et al., 2001), so far, there is no strong evidence for a permanent Callisto footprint (Clarke et al., 2011). One possible reason for this lack of observation stems from Callisto orbiting at the distance mapping to the main auroral emission. As a result, the footprint cannot be disentangled from the much brighter main emission.

2.2.5. The polar emissions

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

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

2.2.5.1. Active region

The active region is very dynamic and is characterized by the presence of flares, bright spots, and arc-like features. It is located just poleward of the main emission and maps roughly to the noon local time sector (green patch marked "9" in Figure 2). There have been several interpretations of this region. Pallier and Prangé [2001] suggested that the bright spots of the active region are the signature of Jupiter's polar cusp, or possibly dayside aurora driven by an increase of the solar wind ram pressure. Waite et al. [2001] used the MHD model of Ogino et al. [1998] to map an observed polar flare to near the cushion region, ~40-60 R_J in the morning sector, and postulated that the flare could be produced by a magnetospheric disturbance due to a sharp increase in the solar wind dynamic pressure. Alternately, Grodent et al. [2003b] interpreted the polar flares as the signature of "explosive" magnetopause reconnection on the day side, based on their ~minutes-long characteristic time scale. They also suggest that the arc-like structures could be the signature of a Dungey cycle dayside x-line, following the arguments of Cowley et al. [2003]. Recent observations showed that the flares could re-occur quasi-periodically every 3-2 minutes and this behaviour has been tentatively associated with pulsed reconnections on the dayside magnetopause [Bonfond et al., 2011].

2.2.5.2. Dark region

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

Grodent et al. [2003b] associated the UV dark region with the Stallard et al. [2003] rotating Dark Polar Region (r-DPR), an area of subcorotating ionospheric flows, as measured by the Doppler shifts of infrared emission spectra. The dawn side r-DPR, and thus the dark region, is thought to be linked to the Vasyliūnas-cycle [Vasyliūnas, 1983] sunward return flow of depleted flux tubes [Cowley et al., 2003]. In the Vasyliūnas-cycle, mass-loaded flux tubes are stretched as they rotated into the night side; they eventually pinch off, and reconnection occurs in the midnight-predawn local time sector, releasing a plasmoid that can escape down the tail, while empty flux tubes rotate back around to the day side at a velocity close to that of corotation. Similarly, Southwood and Kivelson [2001] argued that the main oval emissions map to the plasma disk, which would mean that the dark region, just poleward of the main oval, maps to the cushion region. The cushion region is an area of southward-oriented and strongly fluctuating field in the outer magnetosphere in the post-dawn to noon local time sector where the field becomes more dipole-like than in the inner magnetosphere. It has been associated with empty flux tubes that were emptied by Vasyliūnas-type reconnection as they rotated through the night side [Kivelson and Southwood, 2005].

2.2.5.3. Swirl region

The swirl region is an area of patchy, transient emissions that exhibit turbulent, swirling motions. The swirl region is located poleward of the active and dark regions, and is roughly the center of the polar auroral emissions (red features marked "11" in Figure 2). It is generally interpreted as mapping to open field lines. In comparing the UV and IR observations, Grodent et al. [2003b] associated the UV swirl region with the fixed Dark Polar region (f-DPR), an area in which the ionospheric flows are nearly stagnant in the magnetic pole reference frame [Stallard et al., 2003]. The stagnant flows in the f-DPR (swirl region) then suggest that the area maps to open field lines associated with Dungey cycle return flows [Cowley et al., 2003], which are expected to flow across the ionosphere slowly because the Jovian magnetotail is ~hundreds or thousands of R_J in length. A long-lived quasi –Sun-aligned polar auroral filament (PAF) was observed on several occasions in the swirl region in images sequences obtained with HST [Nichols et al., 2009a] (white arc marked "12" in Figure 2). This feature consists of two components: a sunward portion remaining approximately Sun-aligned and an anti-Sunward portion sub-rotating at a few tens of percent. This ~100 kR auroral feature appears to be independent of the local solar wind conditions. It was postulated that PAFs might be associated with large plasmoids slowly drifting down the magnetotail.

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

2.2.5.4. Nightside and polar dawn spots

Several detailed studies based on ultraviolet images taken with HST revealed transient auroral spots appearing in the dawn and midnight sectors along the poleward edge of the main emission [Grodent et al., 2004; Radioti et al., 2011]. These polar auroral emissions take the form of multiple dawn arcs, polar dawn spots, or midnight spots (blue features marked "13" and "14" in Figure 2, respectively). They were found to corotate with the planet, and their sizes, durations, locations, and 2 to 3 days reoccurrence period are consistent with auroral emissions triggered by internally driven tail reconnection. More specifically, based on a recent reanalysis of near simultaneous HST UV images and Galileo magnetic field observations, Radioti et al. [2011] proposed that the nightside spots, like the polar dawn spots, are triggered by the inward moving plasma flow released during magnetic reconnection at Jupiter's tail. These aurorae may then be related to the precipitation of plasma heated in the reconnection region and to the field-aligned currents that couple the changing angular momentum of the flux tubes between the magnetosphere and ionosphere. Radioti et al. [2011] and Kasahara et al. [2013] showed that the energy released by this process is sufficient to account for the observed spots emitted power (a fraction to several GW). Results from Ge et al. [2010], assuming an updated magnetosphere model, provide further direct evidence of a link between Jovian tail reconnection and polar auroral emissions. More precisely, they confirm that the ionospheric footpoints of tail dipolarization events are close to the polar dawn auroras. Vogt et al. (2014) performed an analysis of the magnetic signature of 43 tailward moving plasmoids and showed that their properties are consistent with a typical mass loss rate of ~0.7–120 kg/s, much lower than the mass input rate from Io (suggesting that additional mass loss mechanisms may be significant), and a flux closure rate of ~7–70 GWb/day, confirming that tail reconnection and plasmoids play an important role in flux transport at Jupiter.

3. Saturn

3.1. Current understanding

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

Like Jupiter, Saturn's UV aurora has been studied with the STIS and ACS cameras on board HST. Since, at opposition, the distance from Earth orbit to Saturn is about twice the distance to Jupiter, the spatial resolution is degraded by a factor of ~2, roughly corresponding to 300 km per pixel. The auroral brightness on Saturn is usually one order of magnitude smaller than on Jupiter, with typical values ranging from 10 to 100 kR. The combination of fainter emissions and lower spatial resolution gives rise to images of lesser quality than for Jupiter. However, they are still detailed enough to reveal the complex and changing morphology of the aurora [e.g. Clarke et al., 2005]. One of the most important lessons that we have learned from the HST – Cassini campaign that took place preceding the Saturn orbit insertion of Cassini in Jan. 2004 is the clear influence of the solar wind, most specifically its ram pressure directly measured by Cassini, on the global auroral morphology. During this campaign, the brightness of the aurora significantly increased in response to the arrival of large solar wind pressure pulses (e.g. Crary et al., 2005). On one occasion, the global morphology itself dramatically changed during the compression event. Within a few hours, the main emission ring, that was initially surrounding the pole, collapsed to a bright feature filling in a small region on the dawn side of the polar cap [e.g. Grodent et al., 2005; Badman et al., 2005].

The orbital insertion of Cassini marked the beginning of a new era in the exploration of Saturn. In particular, the UV aurora revealed itself to the ultraviolet imaging spectrograph (UVIS; Esposito et al., 2004). The high latitude orbits provided stunning views of the auroral emissions from almost above the poles. The data captured near Cassini's periapsis showed unexpected fine details of both poles, inaccessible to HST, of the auroral emissions that are greatly helping their interpretation. The UVIS instrument is observing the auroral emissions more frequently than the HST cameras do. Therefore, it is able to sample the auroral dynamics at various timescales. The most important advantage of UVIS stems from the combined use of the different instruments onboard the spacecraft. For example, it makes it possible to observe the auroral emissions from a vantage point threading the same magnetic flux tube [Bunce et al., 2014]. As a result, it is now possible to simultaneously measure the characteristics of the energetic particles giving rise to the aurora and the aurora itself. UVIS is primarily a spectrograph. Its FUV and EUV channels are designed to obtain high-resolution spectra in the 56-191nm range from which one may derive, for example, color ratios indicating the penetration depth of the impinging particles and thus estimate their energy [e.g. Gustin et al., 2012]. Since the FUV and EUV channels both consist of a spectral slit, UVIS is not providing true images of the auroral region. The second spatial dimension is obtained by slewing the spacecraft in the direction perpendicular to the slit length. This motion allows one to spatially scan the auroral regions from which pseudo-2D images may be reconstructed [Grodent et al., 2011]. Figure 3 displays a typical pseudo image of Saturn's FUV aurora obtained with the UVIS camera onboard the Cassini spacecraft. This composite image was reconstructed from a ~1 hr observing sequence during which the UVIS spectral long-slit was scanned twice across the auroral region (the aurora was uninterruptedly accumulated in the spectral slit during 8 sec bins). It was obtained on 6 Jan 2013 from 08:38 (SCT). The sub-spacecraft latitude was close to 48° and the altitude was ~8.6 R_S, which offered an optimum view point of Saturn's north pole.

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

3.2. Main components of Saturn's aurora

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

3.2.1. The main (ring of) emission

Like Jupiter, Saturn's aurora is harbouring one principal component often referred to as the main ring of emission or main oval. It should be noted that, like Jupiter this main component, roughly contributing 2/3 of the total emission, is not forming a circle or an oval, not even a closed structure. Instead, it appears to consist of multiple structures of various sizes, often organized in a broken spiral. In the rest of the text we will refer to it as the main emission. It usually spreads around the poles at northern and southern latitudes larger than 70°, roughly corresponding to equatorial distances mapping to the ring current between ~10 and ~20 R_S (1 Saturnian radius = 1 R_S = 60,268 km; Badman et al., 2006). As stated above, its precise location was shown to respond to the solar wind activity. During quiet periods, the main emission is expanding to lower latitudes and during (or just after) active solar wind episodes, it is significantly contracting to larger latitudes. The expansion/contraction motion is not symmetrically affecting all longitudes simultaneously. As a matter of fact, this dynamical behaviour and the overall spiral shape may be seen as signatures of the processes giving rise to the main emission. It is generally accepted that the main emission is associated with the flow shear between open and closed outer magnetosphere magnetic field lines rather than being directly due to the breakdown of plasma corotation due to mass-loading [Bunce et al., 2008; Talboys et al., 2011]. The distinction between closed and open magnetic field lines points to the role of solar-wind, as suggested in the modeling work proposed by Cowley et al. [2004a, 2004b, 2008b]. The imbalance between dayside magnetopause reconnection with the solar wind, opening magnetic field lines, and magnetotail reconnection, closing field lines, would then explain Saturn's changing auroral morphology and its relation with solar wind activity. In addition to these large morphological modifications, HST-ACS observations obtained near Saturn's 2009 equinox [Nichols et al., 2010], provided images indicating that the location of the overall northern auroral region oscillates, with an amplitude of 1-2° consistent with that of the southern oval observed by Nichols et al. [2008]. It was postulated that the cause of this oscillation is an external magnetospheric current system [Southwood and Kivelson, 2007; Andrews et al., 2010].

The auroral brightness is usually varying from a few kR to several tens of kR and may occasionally reach values in excess of 100 kR. This is roughly one order of magnitude less than Jupiter's aurora. Badman et al. and Crary et al. (2005) showed that the emitted auroral power is directly correlated with the solar wind ram pressure and therefore anti-correlated with the size of the auroral region. During quiet solar wind episodes, the overall brightness may be so small that the auroral region is almost completely fading away [Gérard et al., 2006].

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

As stated above, the main emission consists of several substructures that may be associated with different mechanisms. They are highlighted in Figure 4 (orange features marked "1"). On the dawn side (left side), the emission is usually forming one or more relatively narrow arcs. These arcs can be very bright, they are actually the brightest observed features, and are corotating at 70%. Most of the time, before these arcs rotated past 12LT, new ones replace them, giving the illusion of a permanent dawn side emission. However, on some occasions, the dawn side was not immediately replenished. Owing to the lack of very long observing sequences, it is difficult to ascertain the origin of these arcs. It is possible that they are already present near midnight and light up as they are approaching 06LT. According to Cowley et al. [2005], these features may be explained by magnetotail reconnection near midnight with subsequent corotation of the planetward side of the reconnection accelerated plasma and field reorganization through dawn, then noon and dusk. An alternative mechanism was proposed to explain the direct causal link between ring current enhancements, taking the form of energetic neutral atoms emission (ENA), and auroral UV emissions [Mitchell et al., 2009]. According to this, ring pressure asymmetry may generate sufficiently high currents that field aligned acceleration is required to supply the current carriers, resulting in recurrent bright auroral arcs that would favour the dawn sector. Later on, Nichols et al. [2010b] showed that the northern and southern dawnside auroral power exhibits a statistically significant variation, by factors of ~3, with maximum output occurring during peak Saturn kilometric radiation (SKR) power [Kurth et al., 2007, 2008], while there is evidence for weaker, opposite behaviour in the duskside power. Such behaviour may be indicative of modulation by the same external rotating current system as that postulated to explain the ~2° oscillation in the auroral oval location observed by Nichols et al. [2010a].

Once these rotating arcs leave the dawn sector and approach 12LT, they either continue their revolution around the pole, or give birth to a new kind of sub-structure. In the former case (orange features “1” at the bottom of Figure 4), the arcs will preserve their overall shape but their brightness will continuously decrease. This may explain why the dawnside is usually found to be brighter than the duskside, although on some occasions the dawnside may get much dimmer than dusk, especially when features leaving the dawn side are not replaced with new ones. For the latter case, rotating arcs approaching the noon meridian may evolve into new types of structures, poleward of the main emission (dark green and light green features marked “2” and “’5” in Figure 4), and will be described in the next section. It should be pointed out that this evolution may only be caught during observing sequences spanning several hours. Since these are not very frequent, the association between dawn arcs and noon structures should be considered with caution. UVIS observations obtained on August 2008, when Cassini approached Saturn at an extremely small altitude of ~5 R_S, revealed details of the main emission in the noon to dusk sector at a spatial resolution close to 200 km [Grodent et al., 2011]. These views are showing isolated features as small as 500 km across. They are taking the form of individual spots arranged in a “bunch of grapes” configuration near noon, and small narrow arcs near dusk (pale green spots and arcs marked “3” in Figure 4). The latter arcs were tentatively associated with patterns of upward field aligned currents resulting from non uniform plasma flow in the equatorial plane while the spots were suggested to be the result of field aligned currents associated with vortices triggered by magnetopause Kelvin-Helmholtz waves. These close up views are very rare; therefore, it is currently difficult to ascertain whether the main emission is always formed of small-scale features or if UVIS captured an uncommon event. Alternatively, Merdith et al. (2013) suggested that such isolated patches appearing simultaneously in both hemispheres, as observed with HST, are consistent with field aligned currents associated with a second harmonic ULF FLR wave propagating eastward through the equatorial plasma.

3.2.2. Emissions poleward of the main emission

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

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

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

The same study from Radioti et al. [2011] pointed out transient spot-like structures appearing at the dawn and dusk poleward boundary of the main emission ring, establishing a third category of poleward features (dark blue spots marked "6" in Figure 4). These small, isolated features are somewhat detached from the main emission and are therefore possibly connected to open magnetic field lines. Jackman et al. [2013] demonstrated that dipolarizations in the magnetotail following reconnection events might result in distinct, observable auroral signatures. They estimated that reconnection in the magnetotail can lead to rapid motion of newly closed field lines planetward and the diversion of the cross-tail current through the ionosphere, resulting in discrete auroral emission through hot plasma injection into and around the inner magnetosphere. The expected brightness of associated auroral signatures is on the order of 10 kR, somewhat smaller but still in reasonable agreement with the observed auroral spots of a few tens of kR. Jackman et al. [2013] further pointed out that the observed auroral spot that they considered in their study is a precursor to a larger intensification which followed about an hour later in the Cassini UVIS sequence, and which had previously been reported to be linked with recurrent energisation from the tail (Mitchell et al., 2009).

3.2.3. Emissions equatorward of the main emission

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

3.2.3.1. Spots

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

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

3.2.3.2. Outer emission

Recent observations of Saturn's aurora with the UVIS spectrograph on-board Cassini not only confirm the presence of a quasi-permanent partial ring of emission equatorward of Saturn's main auroral emission [Grodent et al., 2005, 2010] (light blue arc marked "8" in Figure 4), but they also increase the number of positive cases and allow for a statistical analysis of the characteristics of this outer emission. This faint but distinct auroral feature appears at both hemispheres in the nightside sector. It magnetically maps to relatively large distances in the nightside magnetosphere, on the order of 9 R_S.

This auroral feature consists of one or more narrow arcs (~3° of latitude) of emission usually extending equatorward of the main emission from 18LT to 06LT through midnight, although some images show the emission extending down to 09LT. The emission is not uniform in longitude, the presence of patches allows one to estimate the level of corotation of the outer emission to ~70%, similar to the main emission and compatible with a magnetospheric plasma source rotating at 7 to 10 R_S from Saturn.

It was initially thought that pitch angle scattering of electrons into the loss cone by whistler waves would be responsible for the outer auroral emission. Rough estimates suggested that a suprathermal electron population observed with Cassini [Schippers et al, 2008; Lewis et al., 2008] in the nightside sector between 7 and 10 R_S might power this process. However, a new analysis of 7 years of Cassini electron plasma data [Schippers et al., 2012] indicates the presence of layers of upward and downward field aligned currents. They appear to be part of a large-scale current system involving dayside-nightside asymmetries as well as trans-hemispheric variations. This system comprises a net upward current layer, carried by warm electrons, limited to the nightside sector which may as well generate the outer UV auroral emission.

3.2.4. The Enceladus footprint

The detection threshold of the HST UV cameras and the amount of reflected sunlight leaking in these detectors are too large for a possible detection of Enceladus' footprint with STIS or ACS. On the other hand, the UVIS spectrograph is able to detect fainter emissions. On 26 August 2008, UVIS obtained three successive observations of Saturn's north pole unambiguously revealing the auroral footprint of Enceladus at a location consistent with the expected one [Pryor et al., 2011] (yellow spot marked “9” in Figure 4). The spot brightness is on the order of 1 kR, just above UVIS detection threshold. The predicted southern footprint has not yet been detected for it is probably fainter than its northern counterpart, as is the case for the main aurora (Nichols et al., 2009b). The auroral spot size suggests that the emission is connected to an Enceladus interaction region at the equator extending as far as 20 Enceladus radii (R_E) downstream with a radial extent between 0 and 20 R_E, consistent with the extent of the plume resulting from Enceladus’ cryo-volcanic activity. The Enceladus auroral footprint was shown to vary in brightness by a factor of about 3. The most likely cause for this observed large-scale variability is related to the time-variable cryo-volcanism from Enceladus’ south polar vents, suggesting that plume activity was particularly high at the time of the UVIS observations. Two weeks prior this detection by UVIS, the in situ instruments of Cassini detected signatures of magnetic-field-aligned ion and electron beams with sufficient power to produce the observed auroral footprint of Enceladus. Observed changes in the characteristic energy of the field-aligned electron flux were tentatively associated with changes in the magnetic field perturbation suggesting an actual change in the total field-aligned current density. At Jupiter, the multiple components of the ultraviolet footprint of Io have been interpreted as being due to multiple reflections of a standing Alfvén wave current system driven by Io. It is possible that the flickering in energy of the beams observed downstream of Enceladus is the equatorial signature of a standing wave pattern like that observed at the Io footprint, suggesting a possible universal mechanism magnetically coupling a conducting moon to its parent planet’s ionosphere.

4. The ice giants

4.1. Uranus

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

The first unambiguous detection of aurora on Uranus was made possible by the unique flyby of the planet by Voyager 2 (V2) Spacecraft. On January 24, 1986, at the time of Uranus northern summer solstice, V2 was only 81,500 km from the cloud tops. Among the numerous observations performed with V2 instruments during this several-hour encounter, the extreme ultraviolet spectrometer (UVS) measured emissions in the 95-110 nm range near the magnetic poles [Broadfoot et al., 1986; Herbert and Sandel, 1994]. Those were attributed to auroral H_2 Lyman and Werner bands because at these wavelengths sunlight reflected by the uranian atmosphere is relatively weak. On the contrary, the auroral H Lyman α emission could not be discriminated from the much brighter dayside reflected solar H Lyman α light, nor from the nightside reflected interstellar medium H Lyman α.

Reconstruction from individual spatially resolved spectra taken at different times [Herbert, 2009] provided an average map of the auroral emission, assumed to be time invariant. The bulk of the emission forms discrete spots around the north and south AH_5 model magnetic poles and map to closed field line regions near $L=5$ (See Herbert [2009] for precise significance of L which slightly differs from the conventional McIllwain parameter). In addition, a pair of bright spots in the north auroral polar cap appears to map to $L\geq 20$, presumably on open field lines. In both cases, the magnetic longitude is such that the majority of the observed aurora connects to the magnetotail, suggesting substorm-like injection processes, possibly associated with the arrival of an interplanetary shock [Sittler et al., 1987], and an Earth-like partial ring current system.

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

Since the rotation period of Uranus is not accurately known, the magnetic configuration inferred from V2 in 1986 is not sufficient to derive the present location of the magnetic poles. As a consequence, one does not know exactly where to search for the auroral signal, which is challenging new observation planning. Nevertheless, there have been several attempts to observe the uranian UV aurora from Earth orbit with HST, in 1998, 2005 and 2011, around Uranus equinox. Only the 2011 and 1998 HST datasets reveal unambiguous auroral emissions [Lamy et al., 2012]. The 2011 aurora was shown to be potentially associated with a series of powerful CMEs emitted by he Sun two months earlier. These features appeared to form an extremely localised patch of weak emission, only visible in a few HST images. They were described as variable signatures with brightness comparable to that observed with V2. They are taking the form of spots or roughly continuous ring-like structures in the dayside. Lamy et al. [2012] suggested that the spots result from dayside reconnection with the IMF, while the ring-like structures would involve electron precipitation over a wide range of longitudes that might be related to a short-lived twisted configuration of the magnetotail.

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

4.2. Neptune

The dynamo source region of Neptune is likely of the same nature as that of Uranus [Stanley and Bloxham, 2006]. Therefore, it is not surprising that its magnetic field is also highly asymmetric, tilted (-47°) and shifted (~0.5 Neptune Radius). Neptune's obliquity is significantly smaller than Uranus' (29.6°), yet it is still large enough to contribute to the complexity and variability of Neptune's magnetosphere.

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

5. Conclusion

5.1. Jupiter and Saturn

Jupiter and Saturn are gas giant planets with strong magnetic fields and fast rotating H_2 dominated atmospheres. They both harbour conducting moons, one of which (Io and Enceladus, respectively) is a major internal plasma source taping their giant magnetospheres. All the ingredients are present on the two planets, in different proportions, to produce strong UV auroral emissions with, one might think, comparable morphologies. However, Jupiter and Saturn appear to respond differently to the interplanetary magnetic field and to changing solar wind conditions. These different responses are thought to impart noticeable dissimilarities on the UV auroral morphology and on the origin of some auroral features that, at first glance, are looking the same. The most striking case is the main emission. It is present on both planets and is forming a strip of emission around the pole that is partially corotating with the magnetic field. However, closer inspection of this main auroral feature reveals strong dissimilarities, such as the bifurcation of a fraction of the Saturnian main emission, which finds no equivalent in the Jovian aurora. This particular behaviour points to the control of Saturn's main emission by processes related to the interaction of Saturn's magnetosphere with the solar wind. For Jupiter, this interaction appears to be much less important and is eclipsed by the corotation electric field. Despite these major differences, some auroral features appear to be common to gas giants. Among them, satellite magnetic footprints are easily recognizable since they detach from the rest of the emission. Injection of hot plasma in the middle magnetosphere is also a process common to both planets. Therefore, it is not surprizing to find similar auroral signatures. The case of dayside and night side reconnection spot like signatures is less clear-cut since it involves magnetospheric mechanisms that are driven internally (Vasyliūnas-cycle) or externally (Dungey-cycle). The relative importance of these two cycles depends, again, on the significance of corotation enforcement compared to solar wind convection, which is different for Jupiter and Saturn.

5.2. Uranus and Neptune

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

5.3. The Juno mission

Although our understanding of the auroral mechanisms prevailing at the giant planets is improving, thanks to the continuing observing, theoretical and modelling efforts, there are still numerous fundamental questions which need consideration. For example, the auroral particle acceleration processes above the atmosphere need to be confirmed; the actual role of solar wind in driving the magnetospheres is also a crucial point of debate. The NASA New Frontiers Juno mission will directly address some of these questions [Bolton et al., 2010]. Juno will be the first spacecraft placed into an elliptical polar orbit around Jupiter following an insertion-orbit manoeuvre in July 2016. Juno's scientific payload consists of nine instruments, five of which are designed to determine the physical processes occurring in the high latitude magnetosphere of Jupiter, making it possible to directly relate them to auroral activity and to processes taking place in the low-latitude magnetosphere [Bagenal et al., 2014]. Specifically, the magnetometer (MAG) will provide an accurate mapping of the magnetic field from the top of the ionosphere to the deep magnetosphere; the Jupiter Energetic particle Detector Instrument (JEDI) will measure the high energy and pitch angle of plasma sheet ions and electrons while the Jovian Auroral Distributions Experiment (JADE) will make the first characterization of the particles giving rise to aurora and will complement JEDI by observing the lower part of the energy spectrum; the plasma Waves (Waves) instrument will identify the regions of auroral currents and the auroral particles acceleration processes; at the same time, the Ultraviolet Spectrograph (UVS) will obtain spectral images of the UV aurora generated by the particles measured by JADE. In addition, the Jupiter InfraRed Auroral Mapper (JIRAM) will provide key information on the conditions prevailing in the auroral atmosphere and the visible camera (JunoCAM) will also observe the auroral emissions in the nightside sector. Thanks to its polar orbit and instruments suite Juno will be capable of simultaneously measuring key signatures of the efficient magnetosphere-ionosphere coupling at Jupiter. This knowledge will benefit to the case of Saturn and to some extent to Uranus and Neptune, as well as any giant magnetized planet surrounded by plasma.

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Figure captions

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

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

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