Auroral Processes on Jupiter and Saturn

John T. Clarke

Center for Space Physics, Boston University, Boston, Massachusetts, USA

This chapter will give an overview of the auroral emissions observed at Jupiter and Saturn and describe the general level of understanding of the physics behind the emissions and controlling electrodynamic processes. Topics include the observed distribution and variations in auroral emissions, the different auroral emission regions on Jupiter, our understanding of the locations within the magnetospheres controlling the auroral emissions, and our understanding of the auroral physics for the different regions and emissions. Relevance to the large-scale structure of the magnetospheres and interaction with the solar wind will also be discussed.

1. INTRODUCTION

Decades of space- and ground-based measurements of the Earth's aurora and magnetosphere have shown that auroral activity is largely controlled by the interaction with the solar wind. The nature of this interaction has been discovered by concentrated measurements from earth-orbiting spacecraft, in parallel with auroral and ionospheric observations from the ground. It is instructive to compare the conditions in the Earth's magnetosphere with those at the giant planets, as listed in Table 1. The size scales of the magnetospheres of the Earth, Jupiter, and Saturn are vastly different, and this has important implications for how their magnetospheres must operate. In particular, the flow of the solar wind past each magnetosphere happens over very different time scales. While the solar wind moves from the magnetopause to the Earth in a few minutes, the corresponding times are an hour for Saturn to a few hours for Jupiter. The time scale for solar wind flow down Jupiter's magnetotail is days to weeks, a period over which the solar wind conditions can change dramatically. The corresponding times to fill the magnetotails with open flux range from a few hours on the Earth to many days on Jupiter and Saturn. This suggests that the interaction of the solar wind with the Jovian and Saturnian systems will proceed along much longer time scales, and with different processes, than on the Earth.

Auroral Phenomenology and Magnetospheric Processes: Earth and Other Planets
Geophysical Monograph Series 197

10.1029/2011GM001199

2. JUPITER'S AND SATURN'S MAGNETOSPHERES

In contrast to the Earth's magnetosphere, with the strong influence of the solar wind, Jupiter's magnetosphere is dominated by corotating plasma originating from Io [*Dessler*, 1983]. Io's volcanoes and surface sublimation produce a collisionally thick atmosphere, from which ions and electrons are picked up and brought to corotation speed with Jupiter's magnetic field. This hot plasma forms the Io plasma torus, and the resulting impact of plasma on the upstream side of Io releases more plasma [*Bagenal et al.*, 1980]. The plasma energy is mainly perpendicular to the field as a result of the pickup direction, and it is thus closely confined to the centrifugal equator. Plasma slowly drifting outward from Io's orbit fills the magnetosphere with high-β plasma, and neutral sheet currents strongly flatten the overall shape of the magnetosphere. Field-aligned currents needed to enforce corotation of the plasma lead to strong field-aligned potentials in Jupiter's upper ionosphere, and the accelerated particles produce the main auroral oval [*Cowley and Bunce*, 2001; *Ray and Ergun*, this volume]. This maps to regions in the middle magnetosphere close to the distance of breakdown of corotation, and the main aurora is thus not directly connected with the solar wind boundary [*Hill*, 2001].

Table 1. Comparison of Magnetospheres and Aurora

Planet/Rotation Period (h)	Magnetic Moment/ Equatorial Field Strength (G)	Magnetosphere Cross-Section Radii/Diameter (km)	Solar Wind Travel Time, Bow to Planet at 500 kms^{-1} (min)	Average Auroral Brightness/Input Power (W)
Earth/24	1 (normalized)/0.3	17 R_E 2×10^5	2	1–100 kR (1–100 $\times 10^9$)
Jupiter/10	20,000/4	140 R_J 200×10^5	200	10–1000 kR (few $\times 10^{13}$)
Saturn/11	580/0.2	20 R_S 40×10^5	40	1–100 kR (1–10 $\times 10^{11}$)

Saturn's magnetosphere is intermediate between the cases of the Earth and Jupiter. The corotating plasma from the rings and icy satellites gives a $\beta \sim 1$, so that the influence of the solar wind should be comparable to that of the internal plasma [*Kurth et al.*, 2009]. Saturn's magnetic field is also coaligned with the rotation axis. Estimates of the auroral brightness that would be produced by the Jupiter-like process of field-aligned currents from corotating plasma suggest that this process would not lead to the observed bright main auroral oval, suggesting that Saturn's aurora could originate closer to the boundary with the solar wind like the Earth's [*Cowley and Bunce*, 2001].

By contrast with the detailed measurements on the Earth, observations of the aurora on Jupiter and Saturn have only occurred a few times a year, with in situ spacecraft measurements even less often. As a first step to determine the physical cause and effect of planetary aurora, a large Hubble Space Telescope (HST) observing program was initiated, with simultaneous measurements by Cassini on Saturn, the New Horizons flyby of Jupiter, and extrapolation of solar wind conditions from 1 AU to Jupiter and Saturn. These results will be summarized after a brief introduction to the history of the observations and our present understanding of the two planets.

3. OBSERVATIONS OF THE AURORA ON JUPITER AND SATURN

Jupiter's intense nonthermal radio emissions were well known in the 1950s and implied a strong magnetic field and likely auroral processes. Jupiter's auroral emission was first clearly detected at FUV wavelengths in 1979 by the Voyager 1 ultraviolet spectrometer instrument [*Broadfoot et al.*, 1979]. Subsequent observations with the IUE satellite in Earth orbit for 16 years established the basic properties of the distribution of the UV auroral ovals, the spectrum of the emissions, and the relatively constant nature of Jovian auroral activity [*Clarke et al.*, 1980; *Skinner and Moos*, 1984; *Livengood et al.*, 1992]. IR thermal emissions of CH_4 and C_2H_2 from the lower auroral atmosphere were discovered in the 1980s [*Caldwell et al.*, 1988; *Kostiuk et al.*, 1993], and bright near-IR emissions from the auroral regions were identified and associated with previously unknown spectral features of H_3^+ in 1989 [*Trafton et al.*, 1989; *Drossart et al.*, 1989; *Stallard et al.*, this volume]. The Earth-orbiting Einstein X-ray observatory discovered soft X-ray emissions from Jupiter [*Metzger et al.*, 1983], and further observations with Röntgen satellite [*Waite et al.*, 1994] and Chandra [*Gladstone et al.*, 2002] established the locations and spectra of the X-ray emissions [*Cravens and Ozak*, this volume]. The Galileo spacecraft imager has been used to capture high-resolution visible wavelength images of nightside auroral emissions [*Ingersoll et al.*, 1998]. Much progress has been made since the early 1990s through increasingly sensitive observations with the HST (Figure 1). These observations have established the morphology of Jupiter's multiple auroral processes with high spatial and time resolution. Reviews of the many observations are given by *Bhardwaj and Gladstone* [2000] and *Clarke et al.* [2004]. Jupiter's auroral processes are far more energetic than on the Earth or even

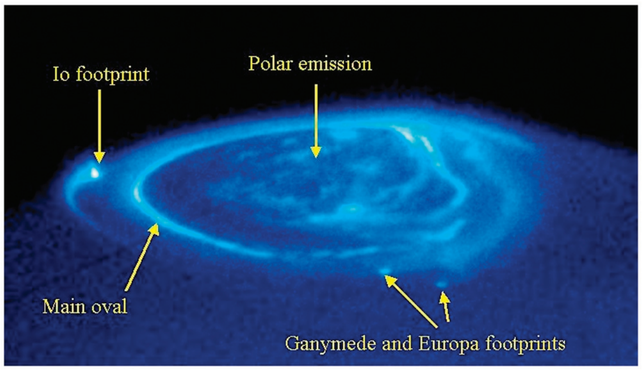

Figure 1. Hubble Space Telescope (HST) UV image of Jupiter's northern auroral zone, showing the three different emission regions. From *Clarke et al.* [2004]. Copyright © 2004 Cambridge University Press. Figures 1 and 3 are both log stretches in intensity to emphasize the fainter emissions.

on Saturn (Table 1), while typical energies of the incoming particles are several tens of keV [*Grodent et al.*, 2001; *Gérard et al.*, 2002].

UV observations of Saturn by the Pioneer 10 and IUE spacecraft gave indications of UV auroral emissions from the polar regions [*Judge et al.*, 1980; *Clarke et al.*, 1981], and Voyager 1 again provided the first clear spectral and spatial evidence for auroral emissions [*Broadfoot et al.*, 1981]. Continued IUE observations indicated that bright aurora on Saturn are infrequent, while spectra from Voyager showed that the auroral emissions were relatively unabsorbed leaving the atmosphere, limiting the energy of the incoming particles in the range of 1–10 keV. Saturn's auroral emissions are much fainter than Jupiter's, and IR auroral emissions have proven difficult to detect from ground-based observations. Faint H_3^+ emissions are now observed on a regular basis [*Stallard et al.*, 1999], while thermal hydrocarbon emissions have not been observed, and only faint X-rays have been detected from Saturn. More recently, the Cassini mission has led to many new insights into the workings of the Saturnian magnetosphere from both UV observations and in situ particle and field data [*Gombosi et al.*, 2009].

The excitation of the auroral emissions from the hydrogen atmosphere of Jupiter has been modeled [*Grodent et al.*, 2001; *Gustin et al.*, 2009], and information about the energy of the incoming particles can be derived from the degree of atmospheric absorption of the outgoing UV emissions in addition to the relative intensity of H_2 band emissions. The stronger the absorption, the deeper the particles penetrate, and the larger their initial energies, although most of the emission is produced by secondary electrons. Typical energies of the incident particles are a few tens of keV for Jupiter and 1–10 keV for Saturn, comparable to or more energetic than on the Earth. Values for the total auroral energy are derived by summing the auroral emissions across the polar regions and assuming an ~10% efficiency of production of UV emission from the total incident particle energy, as implied by detailed modeling of the degradation of energy of the incoming particles. The energy is distributed between collisional ionization, dissociation, heating, and the production of emissions at all wavelengths.

4. AURORAL PROCESSES AT JUPITER

The earliest IUE spectral observations showed that Jupiter's main auroral emissions rotated with the planet, since the observed auroral intensity varied as the highly nondipolar and tilted magnetic field carried the auroral zones in and out of the line of sight from the Earth with the planet's rotation. With the advent of UV images of Jupiter's aurora taken with HST, it became clear that there are three independent regions of auroral emissions, in the sense that the emissions vary independently of each other and map to clearly different regions in the magnetosphere [*Delamere*, this volume; *Vogt and Kivelson*, this volume]. The degree of correlation of emissions from different latitude ranges has been presented by *Nichols et al.* [2009]. Auroral emissions have been detected from the magnetic footprints of Io, Europa, and Ganymede [*Connerney et al.*, 1993; *Clarke et al.*, 2004; *Bonfond*, this volume; *Hess and Delamere*, this volume]. These emission features remain at the magnetic footprints of the satellites, rather than rotating with the planet (as the main oval does), thus their location reveals the geometry of Jupiter's local magnetic field. They also exhibit variations in intensity as each satellite moves in and out of the corotating torus plasma [*Gerard et al.*, 2006; *Serio and Clarke*, 2008; *Wannawichian et al.*, 2010]. There is a clear "main oval" in the auroral emissions, although in contrast with the Earth's main oval, this oval maps to the middle magnetosphere, *not* to the vicinity of the boundary with the solar wind. These emissions are fairly steady on time scales of minutes to hours and clearly rotate with the planet rather than being roughly fixed in local time, as on the Earth. In contrast, the emissions that appear poleward of the main oval are rapidly variable, with several discrete features identified including the polar flares described below.

4.1. Jupiter's Main Oval

Since the Pioneer and Voyager spacecraft flybys of Jupiter, the basic structure of the magnetosphere has been known [*Dessler*, 1983]. The magnetosphere is enormous and loaded with plasma originally from Io. The corotating plasma flattens the shape of the magnetosphere and dominates the energy of the system [*Vasyliunas*, 1983]. It was proposed early on that strong field-aligned currents were needed to maintain the corotation of the plasma and that these currents with associated field-aligned potentials could accelerate particles to produce bright auroral emissions [*Cowley and Bunce*, 2001; *Hill*, 2001; *Southwood and Kivelson*, 2001; *Ray and Ergun*, this volume] (see Figure 2). Observational confirmation that the incident particles producing the main oval originate in the middle magnetosphere came from observations of auroral emissions from the magnetic footprints of three satellites. Jupiter's magnetic field has not been mapped close to the planet, thus there are substantial uncertainties in connecting latitudes with distances from the planet. The satellite footprints permit one to accurately trace the distance of the main auroral oval in comparison with the latitudes of these footprints. The mapping of the main auroral oval to distances of 20–30 R_J in the middle magnetosphere is consistent with the relatively constant auroral emissions,

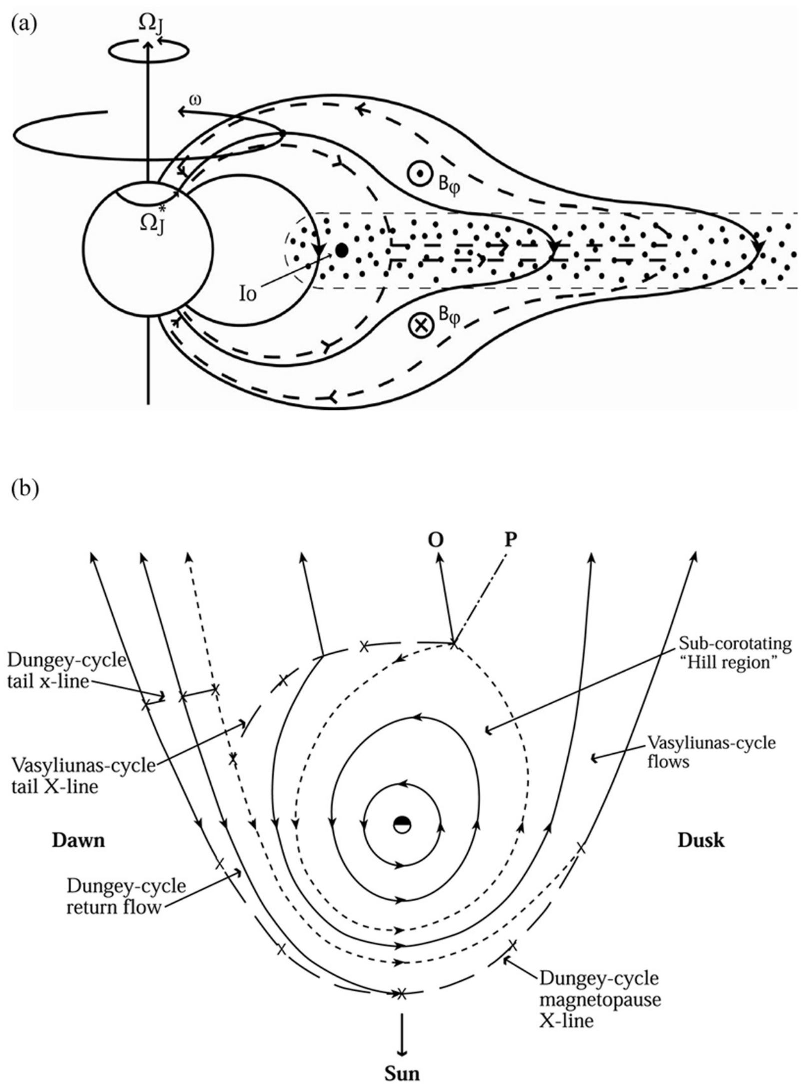

Figure 2. (a) Cross section of the configuration of the Jovian magnetosphere. Reprinted from *Cowley and Bunce* [2001], with permission from Elsevier. Currents are indicated by dashed lines, magnetic field by the solid lines, and induced magnetic field from plasma corotation is shown in and out of the plane. (b) Polar view of the mapping of different regions in Jupiter's north auroral zone into the magnetosphere. From *Clarke et al.* [2004]. Copyright © 2004 Cambridge University Press.

since the plasma is constantly produced and drifts slowly outward [*Grodent et al.*, 2003a]. Even if the solar wind was to diminish to near zero, this auroral process would continue. This is in marked contrast to the Earth's auroral processes, which are closely related to the interaction with the solar wind.

4.2. Satellite Magnetic Footprints

The locations of the auroral emissions from the satellite magnetic footprints can be used to help "map" the geometry of the magnetic field near the planet [*Connerney et al.*, 1998]. In particular, one region in the north appears to indicate a localized region of low field, likely due to a magnetic anomaly (the "Dessler anomaly") [*Grodent et al.*, 2008]. Studies of the location and brightness of Io's auroral footprint have shown a persistent pattern of brightness increases when Io is center in the plasma torus [*Gérard et al.*, 2006; *Serio and Clarke*, 2008; *Wannawichian et al.*, 2010]. However, the implied vertical scale height of the plasma does not appear to be consistent with other measurements; thus, while the trend has been consistent over a decade's time, the data are not fit well by simple models. The footprint auroral emissions show an interesting structure, especially in the case of Io, which can be related to the details of the electrodynamic interaction near the satellite [*Bonfond et al.*, 2009].

4.3. Auroral Storms and Polar Emissions

Extremely bright auroral emissions have frequently been observed along Jupiter's main oval near local dawn. The emissions rise to several MRayleighs in brightness over a period of ~ 1 h and persist for a few hours. These "dawn storm" emissions remain centered along the main oval near magnetic dawn, while other main oval emissions rotate past. If the main oval maps to the middle magnetosphere (20–25 R_J), then how do the conditions in the solar wind control the location of these storms? One suggestion has been a Kelvin-Helmholtz instability at the solar wind boundary [*Prangé et al.*, 1998], but this should map to higher latitudes than where the dawn storms are observed.

Another persistent feature of the Jovian polar aurora observed in high time resolution data are the bright "polar flares" observed in the polar regions both north and south [*Waite et al.*, 2001]. These emissions rise from near background to tens of MRayleighs on a time scale of tens of seconds, then fade away on a somewhat longer time scale. The emissions often appear near local noon, but there is an observational bias toward detecting features on the dayside in the oblique observing geometry from the Earth. These flares have a duty cycle on the order of 15%, they can be accompanied by strong X-ray emissions, and it has been proposed that they map to the dayside magnetopause boundary [*Waite et al.*, 2001]. The polar auroral emissions are generally more rapidly variable than either the main oval or satellite footprints, coming and going on time scales of tens of seconds. These emissions may be related more closely to the open/closed field line boundary or to regions in the magnetotail that are relatively devoid of plasma [*Grodent et al.*, 2003b].

4.4. Dependence of Jovian Aurora on Solar Wind Conditions

Jupiter's overall auroral power is driven mainly by the brightness of the main oval, with increases seen from specific regions at different times. Based on two historical events and six events from 2 month long HST auroral observing campaigns in 2007, the arrival of a solar wind shock appears to be consistent with a brightening of the main oval, subject to some uncertainty in the arrival times of solar wind features at the planet [*Gurnett et al.*, 2002; *Pryor et al.*, 2005; *Clarke et al.*, 2009; *Nichols et al.*, 2009]. By contrast, solar wind velocity increases with a pressure *decrease* have *not* been seen to correlate with auroral brightening (based on three events from the campaign). Dawn storms can occur at times of quiet solar wind conditions, based on two events from the campaign, raising serious questions about the nature of the processes (see below). It appears that Jupiter's auroras are relatively more constant than those on the Earth and on Saturn, yet they still show some apparent response to solar wind conditions.

5. SATURNIAN AURORAL PROCESSES

On Saturn, the auroral morphology is dominated by a main oval, which is often not symmetric but does appear more or less centered about the combined rotational and magnetic poles. Bright emission regions observed along the ovals come and go on a few hour time scales and appear to move at a fraction of Saturn's rotation rate [*Gérard et al.*, 2004]. The main oval appears nominally near 75° latitude, but drifts a great deal from day to day. The overall auroral oval has been found to be offset by ~2° toward midnight and ~1° toward dawn, while no significant offset from the rotation axis in a frame of reference fixed to Saturn has been discovered [*Nichols et al.*, 2008]. The oval has been further seen to "wobble" about the average center location, and fits to this motion have resulted in periods consistent with the Saturn kilometric radiation (SKR) rotation period and changing with time, also similar to the SKR period. With regard to the satellites, auroral emissions have been detected only from the magnetic footprint of Enceladus, and those are faint and variable [*Pryor et al.*, 2011; *Gurnett and Pryor*, this volume]. Without the footprint evidence of the mapping distance into the magnetosphere, one cannot accurately determine from the auroral images the distance to which the main ovals map. In one case, Cassini measurements of field-aligned currents were obtained with simultaneous auroral images, indicating auroral processes near the solar wind boundary [*Bunce et al.*, 2008; *Cowley et al.*, 2008]. Overall though, it is not well established from the auroral observations alone where the open/closed field line boundary falls in the auroral regions on either Jupiter or Saturn. This is in clear contrast to that of the Earth's auroral regions, where the auroral oval appears slightly equatorward of the open/closed field line boundary.

In the case of Saturn, theoretical estimates of the strength of currents in and out of the ionosphere required to enforce plasma corotation led to the conclusion that the associated field-aligned potentials would not be sufficient to produce the observed auroral brightness [*Cowley et al.*, 2004; *Bunce*, this volume]. It was concluded that the main auroral oval was likely to map to the open/closed field line boundary and be produced by the interaction with the solar wind. The higher variability of Saturn's aurora compared with the case on Jupiter is generally consistent with this hypothesis. These authors further suggested associations between various regions in the auroral zone and mapped regions in the magnetosphere. Observations of energetic neutral atom events in the middle magnetosphere have suggested that at least, at times, auroral processes closer to the planet are also important [*Mitchell et al.*, 2009].

An interesting line of research involves the discovery of clear correlations between the arrival of shock fronts in the solar wind and the intensification of both Saturn's UV auroral emissions and the nonthermal SKR (Figure 3). Coordinated HST observations of the aurora with Cassini measurements of the solar wind as it approached Saturn in late 2003 and early 2004, plus Cassini measurements of the SKR, have shown a clear correlation between the UV aurora and the SKR emissions [*Kurth et al.*, 2005]. Increases in both emissions also were recorded at the arrival times of two solar wind shocks at Saturn, suggesting a causal connection [*Clarke et al.*, 2005; *Crary et al.*, 2005]. During the 2 month long HST observing campaigns in 2007 and 2008, there was

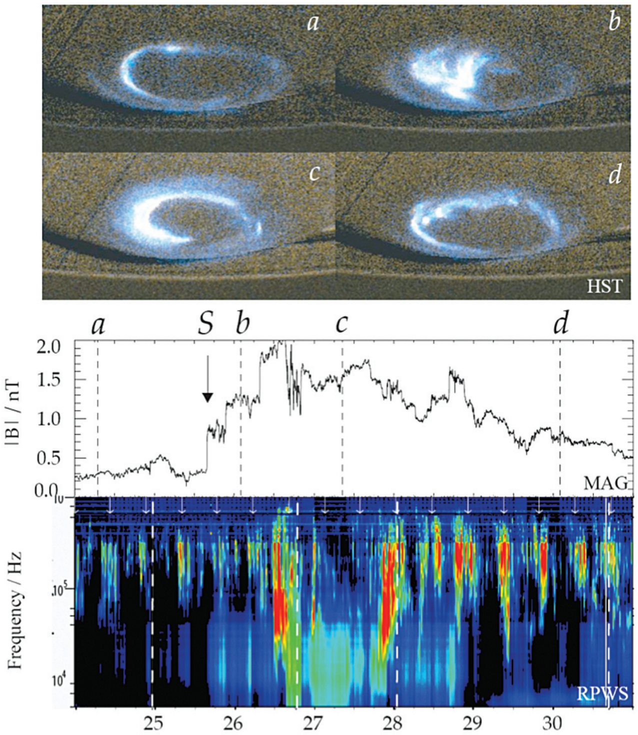

Figure 3. (top, a–d) HST UV images of Saturn in January 2004 showing the progression of an auroral storm. The storm in Figure 3b was shortly after the arrival of a solar wind shock, (middle) marked "S" in the measurement of interplanetary magnetic field. (bottom) The event also corresponded with an intensification of the SKR emission. From *Kurth et al.* [2009].

a one to one correspondence between auroral activity, SKR emission, and size of the oval [*Clarke et al.*, 2009]. From combined observations now covering almost 3 months duration, UV emission and SKR radiation are correlated with solar wind pressure, and auroral brightenings begin at times of solar wind shocks (six events have been observed). A strong connection to solar wind pressure is consistent with a source region in the outer magnetosphere, unlike the case on Jupiter, yet there is the added evidence for the importance of processes in the middle magnetosphere. There is clearly more to be learned about Saturn's auroral dynamics.

6. CHALLENGES FOR PHYSICAL UNDERSTANDING

There are many areas in which our understanding of auroral processes on the giant planets falls short. A few outstanding questions are highlighted below:

Why would both Jupiter and Saturn aurora brighten in response to solar wind pressure increases? Jupiter's main oval maps to the middle magnetosphere, while Saturn's maps in theory to the outer magnetosphere, yet both respond with brightenings when solar wind shock fronts arrive on each planet. During a period of enhanced auroral activity, Jupiter's main oval gets brighter and at times more extended in latitude, with patchy clumps of emission along the oval. The overall brightening sometimes starts with a dawn storm, which may begin with a brightening observed poleward of the main oval. The observed time scale for auroral events on Jupiter is 1–2 days. During an auroral intensification on Saturn, the main oval gets brighter, and the brightest emission is shifted poleward of the quiet oval latitude. The dawnside initially fills in with bright emissions, with an observed time scale for auroral events of 2–4 days. A weaker event may accompany a smaller increase in solar wind pressure. The extent to which these characteristics relate to the interaction with the solar wind is unclear.

What is the principal driving physics of the Jovian main ovals? Jupiter is the prototype of a magnetosphere controlled by internal plasma and planetary rotation, yet the aurora appears to be at least somewhat affected by the solar wind. How does the solar wind exert any effect on the region producing the main oval, deep within the magnetosphere? If the main oval is driven by corotation breakdown currents, it has been predicted that the outward drifting plasma content would decrease with increased solar wind pressure, giving weaker currents and fainter auroral emissions [*Southwood and Kivelson*, 2001]. Yet the opposite is observed, with shock intensifications in the solar wind and compression of the Jovian magnetosphere corresponding to increases in total auroral power. For Saturn, it has been proposed that the main oval maps out close to boundary with solar wind, but this has yet to be established by measurement. The distance to which the main oval maps was determined from satellite footprint emissions on Jupiter, but emission has only been detected from the footprint of Enceladus on Saturn, too close to Saturn to be helpful.

How do we explain the other types of auroral storms observed mainly on Jupiter? Jupiter's dawn storms start near local dawn close to the latitude of the main oval, which maps into the middle magnetosphere far from the boundary with the solar wind. In addition, these storms have been seen more than once to evolve into an overall brightening of the main oval. There is evidence from modeling that Kelvin-Helmholtz instabilities form easily on the dusk flank of the magnetosphere. Could a disturbance on the flank propagate inward and disturb conditions in the middle magnetosphere? The current sheet could build up over time until such a disturbance scattered energetic particles into the loss cone, leading to bright aurora. These storms are detected roughly once every few weeks and last a few hours. Jupiter also displays active region flares, with low-level flares in the polar region that occur all the time, and high-intensity events with a ~10% duty cycle. These events appear at a consistent location in the polar region, implying a mapping to a consistent location within the magnetosphere. Whether this location is fixed in local time has not yet been well determined.

What controls Saturn's auroral storms? Is there more than one kind of auroral storm on Saturn? How does the solar wind influence the auroral activity?

To what distance in the magnetosphere does the auroral oval map? On Jupiter, we used satellite footprints to determine the mapping. Is there anything on Saturn that will serve this purpose, perhaps in measurements from the Cassini spacecraft?

Understanding these different auroral storms on Jupiter and Saturn is critical to help us understand auroral processes both on the Earth and on exoplanets. Please note that all the HST imaging data from the 2007/2008 campaigns can be viewed and downloaded from the Planetary Atmospheres and Space Sciences Group website (http://www.bu.edu/csp/PASS/main.html).

Acknowledgments. This work is based in part on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by AURA for NASA. The work was supported by grants HST-GO-10862.01-A and HST-GO-12176.01-A from the Space Telescope Science Institute to Boston University.

REFERENCES

Bagenal, F., J. D. Sullivan, and G. L. Siscoe (1980), Spatial distribution of plasma in the Io torus, *Geophys. Res. Lett.*, *7*(1), 41–44.

Bhardwaj, A., and G. R. Gladstone (2000), Auroral emissions of the giant planets, *Rev. Geophys.*, *38*(3), 295–353, doi:10.1029/1998RG000046.

Bonfond, B. (2012), When moons create aurora: The satellite footprints on giant planets, in *Auroral Phenomenology and Magnetospheric Processes: Earth and Other Planets*, *Geophys. Monogr. Ser.*, doi:10.1029/2011GM001169, this volume.

Bonfond, B., D. Grodent, J.-C. Gérard, A. Radioti, V. Dols, P. A. Delamere, and J. T. Clarke (2009), The Io UV footprint: Location, inter-spot distances and tail vertical extent, *J. Geophys. Res.*, *114*, A07224, doi:10.1029/2009JA014312.

Broadfoot, A. L., et al. (1979), Extreme ultraviolet observations from Voyager 1 encounter with Jupiter, *Science*, *204*, 979–982.

Broadfoot, A. L., et al. (1981), Extreme ultraviolet observations from Voyager 1 encounter with Saturn, *Science*, *212*, 206–211.

Bunce, E. J. (2012), Origins of Saturn's auroral emissions and their relationship to large-scale magnetosphere dynamics, in *Auroral Phenomenology and Magnetospheric Processes: Earth and Other Planets*, *Geophys. Monogr. Ser.*, doi:10.1029/2011GM001191, this volume.

Bunce, E. J., et al. (2008), Origin of Saturn's aurora: Simultaneous observations by Cassini and the Hubble Space Telescope, *J. Geophys. Res.*, *113*, A09209, doi:10.1029/2008JA013257.

Caldwell, J., H. Halthore, G. Orton, and J. Bergstralh (1988), Infrared polar brightenings on Jupiter IV. Spatial properties of methane emission, *Icarus*, *74*, 331–339.

Clarke, J. T., H. W. Moos, S. K. Atreya, and A. L. Lane (1980), Observations from Earth orbit and variability of the polar aurora on Jupiter, *Astrophys. J.*, *241*, L179–L182.

Clarke, J. T., H. W. Moos, S. K. Atreya, and A. L. Lane (1981), IUE detection of bursts of H Ly α emission from Saturn, *Nature*, *290*, 226–227.

Clarke, J. T., D. Grodent, S. W. H. Cowley, E. J. Bunce, P. Zarka, J. E. P. Connerney, and T. Satoh (2004), Jupiter's aurora, in *Jupiter: The Planet, Satellites and Magnetosphere*, edited by F. Bagenal, T. E. Dowling, and W. B. McKinnon, pp. 639–670, Cambridge Univ. Press, Cambridge, U. K.

Clarke, J. T., et al. (2005), Morphological differences between Saturn's ultraviolet aurorae and those of Earth and Jupiter, *Nature*, *433*, 717–719.

Clarke, J. T., et al. (2009), Response of Jupiter's and Saturn's auroral activity to the solar wind, *J. Geophys. Res.*, *114*, A05210, doi:10.1029/2008JA013694.

Connerney, J. E. P., R. L. Baron, T. Satoh, and T. Owen (1993), Images of excited H_3^+ at the foot of the Io flux tube in Jupiter's atmosphere, *Science*, *262*, 1035–1038.

Connerney, J. E. P., M. H. Acuña, N. F. Ness, and T. Satoh (1998), New models of Jupiter's magnetic field constrained by the Io flux tube footprint, *J. Geophys. Res.*, *103*(A6), 11,929–11,939.

Cowley, S. W. H., and E. J. Bunce (2001), Origin of the main auroral oval in Jupiter's coupled magnetosphere-ionosphere system, *Planet Space Sci.*, *49*, 1067–1088.

Cowley, S. W. H., E. J. Bunce, and J. M. O'Rourke (2004), A simple quantitative model of plasma flows and currents in

Saturn's polar ionosphere, *J. Geophys. Res.*, *109*, A05212, doi:10.1029/2003JA010375.

Cowley, S. W. H., C. Arridge, E. Bunce, J. Clarke, A. Coates, M. Dougherty, J.-C. Gérard, D. Grodent, J. Nichols, and D. Talboys (2008), Auroral current systems in Saturn's magnetosphere: Comparison of theoretical models with Cassini and HST observations, *Ann Geophys.*, *26*, 2613–2630.

Crary, F. J., et al. (2005), Solar wind dynamic pressure and electric field as the main factors controlling Saturn's aurorae, *Nature*, *433*, 720–722.

Cravens, T. E., and N. Ozak (2012), Auroral ion precipitation and acceleration at the outer planets, in *Auroral Phenomenology and Magnetospheric Processes: Earth and Other Planets*, *Geophys. Monogr. Ser.*, doi:10.1029/2011GM001159, this volume.

Delamere, P. A. (2012), Auroral signatures of solar wind interaction at Jupiter, in *Auroral Phenomenology and Magnetospheric Processes: Earth and Other Planets*, *Geophys. Monogr. Ser.*, doi:10.1029/2011GM001180, this volume.

Dessler, A. J. (Ed.) (1983), *Physics of the Jovian Magnetosphere*, Cambridge Univ. Press, Cambridge, U. K.

Drossart, P., et al. (1989), Detection of H_3^+ on Jupiter, *Nature*, *340*, 539–541.

Gérard, J.-C., J. Gustin, D. Grodent, P. Delamere, and J. T. Clarke (2002), Excitation of the FUV Io tail on Jupiter: Characterization of the electron precipitation, *J. Geophys. Res.*, *107*(A11), 1394, doi:10.1029/2002JA009410.

Gérard, J.-C., D. Grodent, J. Gustin, A. Saglam, J. T. Clarke, and J. T. Trauger (2004), Characteristics of Saturn's FUV aurora observed with the Space Telescope Imaging Spectrograph, *J. Geophys. Res.*, *109*, A09207, doi:10.1029/2004JA010513.

Gérard, J.-C., A. Saglam, D. Grodent, and J. T. Clarke (2006), Morphology of the ultraviolet Io footprint emission and its control by Io's location, *J. Geophys. Res.*, *111*, A04202, doi:10.1029/2005JA011327.

Gladstone, G. R., et al. (2002), A pulsating auroral X-ray hot spot on Jupiter, *Nature*, *415*, 1000–1003.

Gombosi, T. I., et al. (2009), Saturn's magnetospheric configuration, in *Saturn from Cassini-Huygens*, edited by M. K. Dougherty, L. W. Esposito, and S. M. Krimigis, pp 203–256, Springer, Dordrecht, Netherlands, doi:10.1007/978-1-4020-9217-6_9.

Grodent, D., J. H. Waite Jr., and J.-C. Gérard (2001), A self-consistent model of the Jovian auroral thermal structure, *J. Geophys. Res.*, *106*(A7), 12,933–12,952, doi:10.1029/2000JA900129.

Grodent, D., J. T. Clarke, J. Kim, J. H. Waite Jr., and S. W. H. Cowley (2003a), Jupiter's main auroral oval observed with HST-STIS, *J. Geophys. Res.*, *108*(A11), 1389, doi:10.1029/2003JA009921.

Grodent, D., J. T. Clarke, J. H. Waite Jr., S. W. H. Cowley, J.-C. Gérard, and J. Kim (2003b), Jupiter's polar auroral emissions, *J. Geophys. Res.*, *108*(A10), 1366, doi:10.1029/2003JA010017.

Grodent, D., B. Bonfond, J.-C. Gérard, A. Radioti, J. Gustin, J. T. Clarke, J. Nichols, and J. E. P. Connerney (2008), Auroral evidence of a localized magnetic anomaly in Jupiter's northern hemisphere, *J. Geophys. Res.*, *113*, A09201, doi:10.1029/2008JA013185.

Gurnett, D. A., and W. R. Pryor (2012), Auroral processes associated with Saturn's moon Enceladus, in *Auroral Phenomenology and Magnetospheric Processes: Earth and Other Planets*, *Geophys. Monogr. Ser.*, doi:10.1029/2011GM001174, this volume.

Gurnett, D. A., et al. (2002), Control of Jupiter's radio emission and aurorae by the solar wind, *Nature*, *415*, 985–987, doi:10.1038/415985a.

Gustin, J., J.-C. Gérard, W. Pryor, P. D. Feldman, and G. Holsclaw (2009), Characteristics of Saturn's polar atmosphere and auroral electrons derived from HST/STIS, FUSE and Cassini/UVIS spectra, *Icarus*, *200*, 176–187, doi:10.1016/j.icarus.2008.11.013.

Hess, S. L. G., and P. A. Delamere (2012), Satellite-induced electron acceleration and related auroras, in *Auroral Phenomenology and Magnetospheric Processes: Earth and Other Planets*, *Geophys. Monogr. Ser.*, doi:10.1029/2011GM001175, this volume.

Hill, T. W. (2001), The Jovian auroral oval, *J. Geophys. Res.*, *106*(A5), 8101–8107, doi:10.1029/2000JA000302.

Ingersoll, A. P., A. R. Vasavada, B. Little, C. D. Anger, S. J. Bolton, C. Alexander, K. P. Klaasen, W. K. Tobiska, and the Galileo SSI Team (1998), Imaging Jupiter's aurora at visible wavelengths, *Icarus*, *135*, 251–264.

Judge, D. L., F. Wu, and R. Carlson (1980), Ultraviolet photometer observations of the Saturnian system, *Science*, *207*, 431–434.

Kostiuk, T., P. Romani, F. Espenak, T. A. Livengood, and J. J. Goldstein (1993), Temperature and abundances in the Jovian auroral stratosphere 2. Ethylene as a probe of the microbar region, *J. Geophys. Res.*, *98*(E10), 18,823–18,830.

Kurth, W. S., et al. (2005), An Earth-like correspondence between Saturn's auroral features and radio emission, *Nature*, *433*, 722–725.

Kurth, W. S., et al. (2009), Auroral processes at Saturn,, in *Saturn From Cassini-Huygens*, edited by M. K. Dougherty, L. W. Esposito, and S. M. Krimigis, pp. 333–374, Springer, Dordrecht, Netherlands, doi:10.1007/978-1-4020-9217-6_12.

Livengood, T. A., H. W. Moos, G. E. Ballester, and R. M. Prangé (1992), Jovian ultraviolet auroral activity, *Icarus*, *97*, 26–45.

Metzger, A. E., D. A. Gilman, J. L. Luthey, K. C. Hurley, H. W. Schnopper, F. D. Seward, and J. D. Sullivan (1983), The detection of X rays from Jupiter, *J. Geophys. Res.*, *88*(A10), 7731–7741.

Mitchell, D. G., et al. (2009), Recurrent energization of plasma in the midnight-to-dawn quadrant of Saturn's magnetosphere, and its relationship to auroral UV and radio emissions, *Planet. Space Sci.*, *57*, 1732–1742, doi:10.1016/j.pss.2009.04.002.

Nichols, J. D., J. T. Clarke, S. W. H. Cowley, J. Duval, A. J. Farmer, J.-C. Gérard, D. Grodent, and S. Wannawichian (2008), Oscillation of Saturn's southern auroral oval, *J. Geophys. Res.*, *113*, A11205, doi:10.1029/2008JA013444.

Nichols, J. D., J. T. Clarke, J. C. Gérard, D. Grodent, and K. C. Hansen (2009), Variation of different components of Jupiter's auroral emission, *J. Geophys. Res.*, *114*, A06210, doi:10.1029/2009JA014051.

Prangé, R., D. Rego, L. Palliser, J. E. P. Connerney, P. Zarka, and J. Queinnec (1998), Detailed study of FUV Jovian auroral features with the post-COSTAR HST faint object camera, *J. Geophys. Res.*, *103*(E9), 20,195–20,215.

Pryor, W. R., et al. (2005), Cassini UVIS observations of Jupiter's auroral variability, *Icarus*, *178*, 312–326, doi:10.1016/j.icarus.2005.05.021.

Pryor, W. R., et al. (2011), Discovery of the Enceladus auroral footprint at Saturn, *Nature*, *472*, 331–333, doi:10.1038/nature09928.

Ray, L. C., and R. E. Ergun (2012), Auroral signatures of ionosphere-magnetosphere coupling at Jupiter and Saturn, in *Auroral Phenomenology and Magnetospheric Processes: Earth and Other Planets*, *Geophys. Monogr. Ser.*, doi:10.1029/2011GM001172, this volume.

Serio, A. W., and J. T. Clarke (2008), The variation of Io's auroral footprint brightness with the location of Io in the plasma torus, *Icarus*, *197*, 368–374.

Skinner, T. E., and H. W. Moos (1984), Comparison of the Jovian north and south pole aurorae using the IUE observatory, *Geophys. Res. Lett.*, *11*(11), 1107–1110.

Southwood, D. J., and M. G. Kivelson (2001), A new perspective concerning the influence of the solar wind on the Jovian magnetosphere, *J. Geophys. Res.*, *106*(A4), 6123–6130, doi:10.1029/2000JA000236.

Stallard, T., S. Miller, G. E. Ballester, D. Rego, R. D. Joseph, and L. M. Trafton (1999), The H_3^+ latitudinal profile of Saturn, *Astrophys. J.*, *521*, L149–L152.

Stallard, T., S. Miller, and H. Melin (2012), Clues on ionospheric electrodynamics from IR aurora at Jupiter and Saturn, in *Auroral Phenomenology and Magnetospheric Processes: Earth and Other Planets*, *Geophys. Monogr. Ser.*, doi:10.1029/2011GM001168, this volume.

Trafton, T., D. F. Lester, and K. L. Thompson (1989), Unidentified emission lines in Jupiter's northern and southern 2 micron aurorae, *Astrophys. J.*, *343*, L73–L76.

Vasyliunas, V. M. (1983), Plasma distribution and flow, in *Physics of the Jovian Magnetosphere*, edited by A. J. Dessler, pp. 395–453, Cambridge Univ. Press, Cambridge, U. K.

Vogt, M. F., and M. G. Kivelson (2012), Relating Jupiter's auroral features to magnetospheric sources, in *Auroral Phenomenology and Magnetospheric Processes: Earth and Other Planets*, *Geophys. Monogr. Ser.*, doi:10.1029/2011GM001181, this volume.

Waite, J. H., Jr., F. Bagenal, F. Seward, C. Na, G. R. Gladstone, T. E. Cravens, K. C. Hurley, J. T. Clarke, R. Elsner, and S. A. Stern (1994), ROSAT observations of the Jupiter aurora, *J. Geophys. Res.*, *99*(A8), 14,799–14,809.

Waite, J. H., Jr., et al. (2001), An auroral flare at Jupiter, *Nature*, *410*, 787–789.

Wannawichian, S., J. T. Clarke, and J. D. Nichols (2010), Ten years of Hubble Space Telescope observations of the variation of the Jovian satellites' auroral footprint brightness, *J. Geophys. Res.*, *115*, A02206, doi:10.1029/2009JA014456.

J. T. Clarke, Center for Space Physics, Boston University, Boston, MA 02215, USA. (jclarke@bu.edu)