Chapter 12
Auroral Processes


Abstract  Cassini has afforded a number of unique opportunities to understand auroral processes at Saturn and to highlight both differences and similarities with auroral physics at both Earth and Jupiter. A number of campaigns were coordinated with the Hubble Space Telescope such that Cassini could provide either ground truth on the impinging solar wind or in situ measurements of magnetospheric conditions leading to qualitative and sometimes quantitative relationships between the solar wind influence on the intensity, the morphology and evolution of the auroras, and magnetospheric dynamics. The Hubble UV images are enhanced by Cassini’s own remote sensing of the auroras. Cassini’s in situ studies of the structure and dynamics of the magnetosphere discussed in other chapters of this book provide the context for understanding the primary drivers of Saturn’s auroras and the role of magnetospheric dynamics in their variations.

Finally, Cassini’s three dimensional prime mission survey of the magnetosphere culminates in high inclination orbits placing it at relatively small radial distances while on auroral field lines, providing the first such in situ observations of auroral particles and fields at a planet other than Earth. The new observations have spawned a number of efforts to model the interaction of the solar wind with the magnetosphere and understand how such dynamics influence the auroras.

12.1 Introduction

As described in Chapter 3, the study of Saturn’s aurora began with Voyager (Broadfoot et al. 1981) and the IUE observatory (Clarke et al. 1981; McGrath and Clarke 1992) and continued with observations by the Hubble Space Telescope (HST), for example (Trauger et al. 1998). However, Cassini’s approach to Saturn in early 2004 and the improved sensitivity of the Space Telescope Imaging Spectrograph (STIS) heralded a new age in understanding Saturn’s auroral processes. In fact, the first of a number of HST-Cassini campaigns occurred in January 2004 which, for the first time, allowed the comparison of the solar wind upstream of Saturn with observations of the ultraviolet (UV) aurora. This campaign showed dramatic changes in Saturn’s auroral intensity and morphology in response to solar wind compression events (in which the dynamic pressure of the solar wind and the embedded magnetic field strength are increased) as demonstrated in Fig. 12.1. This was also the first opportunity to compare the power in the UV aurora with the radiated power of the Saturn kilometric radiation (SKR), commonly thought to be an indicator of auroral activity based on experience with auroral kilometric radiation (AKR) at Earth. Additional campaigns have been carried out with Cassini in orbit at Saturn, enabling another dimension of studies, that of in situ measurements of associated particles and fields in various locations in the magnetosphere that could also be compared to the auroral activity.

Cassini also carries remote sensing instruments that can observe the auroras at UV, visual, infrared (IR), and radio
wavelengths. By the end of the prime mission, Cassini’s orbit carried it to latitudes of \( \sim 75^\circ \) at radial distances as small as 3 Saturn radii (R\(_S\)). While it appears that this is yet too high in altitude to carry the spacecraft through the expected acceleration region, this geometry provides the best opportunity to study auroral processes at a planet other than Earth until Juno arrives in polar orbit at Jupiter.

In this chapter, multi-wavelength observations of Saturn’s aurora both from Cassini and Earth-based platforms are reviewed along with in situ particle and field data obtained on auroral field lines. These observations form the basis of our knowledge about the morphology and variability of the auroras as well as information on their spectrum and intensity. The current ideas on the origin of the aurora are also addressed.

### 12.2 Observations of Auroral Emissions

#### 12.2.1 Pre-Cassini Summary

The history of pre-Cassini observations of Saturn’s aurora has been given in Chapter 3. Until the approach of Cassini to Saturn in January 2004, there had been only a few dozen HST images of the UV aurora and some spectral observations of the IR emissions. Owing to the low intensity, no IR images of the aurora had been obtained. In both wavelength ranges, observers had heavily concentrated their time on the much brighter Jovian aurora, to the extent that relatively little was known about the properties of Saturn’s aurora and the corresponding magnetospheric processes. The arrival of Cassini at Saturn has been accompanied by a surge in Earth-based observations of the auroral emissions, both UV imaging by HST and near-IR observations from ground-based telescopes.

The first observations of Saturn’s aurora were carried out by the Pioneer 11 and Voyager 1 and 2 spacecraft. The spectra obtained by the Voyager UV spectrometer (UVS) revealed emissions from both polar regions near \( 80^\circ \) latitude with no apparent emission present in the polar cap. Typical intensities were in the range 10 to 15 kR (1 kiloRayleigh \( = 10^9 \) photons/s from a 1 cm\(^2\) column of the atmosphere into 4\(\pi\) steradians) with variations up to a factor of 5 (Broadfoot et al. 1981; Sandel and Broadfoot 1981; Sandel et al. 1982). Spectra of the UV auroral emissions indicated little absorption by hydrocarbons, implying relatively low energy incident charged particles (\(< 10\) keV) (see Section 12.2.2.3). Voyager radio observations established a strong correlation between Saturn kilometric radiation and the solar wind dynamic pressure.

#### 12.2.2 Earth-Based Observations Concurrent with Cassini

##### 12.2.2.1 HST-Cassini Campaigns

The first remote observing campaign was conducted by HST using the Space Telescope Imaging Spectrograph (STIS) in January 2004, as Cassini approached Saturn and measured solar wind conditions that could be accurately extrapolated to the planet. This campaign provided evidence of the role of the solar wind in controlling the aurora at Saturn, as described in Section 12.3.1. These HST images were also the first to show the wide range of variability in the aurora as seen in Fig. 12.1.

The properties of Saturn’s faint southern aurora, corresponding to quiet magnetospheric conditions, have been presented based on HST observations in 2005 (Gérard et al. 2006). In addition, in view of the recently discovered large source of plasma from Enceladus, and the known strong interaction of Io, Europa, and Ganymede leading to bright auroral footprints, a sensitive, but unsuccessful, search has been carried out for auroral emissions from the magnetic footprint of Enceladus in Saturn’s atmosphere (Wannawichian et al. 2008). The low upper limits of a few kilo-Rayleighs placed...
on any auroral emission from the Enceladus footprint constrain the mass pickup rate and extent of the mass loading region near Enceladus, and are consistent with a model of the interaction of the extended atmosphere of Enceladus with the corotating plasma (Pontius and Hill 2006).

A large program of HST observations of UV auroral emissions at both Saturn and Jupiter was undertaken over 2007–2008, in part to take advantage of in situ measurements by Cassini at Saturn. Images were obtained using the Solar Blind Channel (SBC) of the HST Advanced Camera for Surveys (ACS), which has properties similar to the STIS instrument, although the ACS sensitivity to auroral emissions is 20–30% higher than STIS. The Saturn observations were concentrated in two campaigns of more or less daily observations, the first in January/February 2007 and the second in February 2008, both carried out when Saturn was close to opposition to optimize the accuracy of propagation of solar wind conditions from measurements obtained at Earth orbit out to Saturn. The initial results from these observations are presented in Section 12.3.1, but this large data set represents a significant resource for future studies. Movies made from images from the 2007 and 2008 HST campaigns are included on the DVD supplied with this book.

There have been several results from a detailed comparison of Cassini in situ data with the HST UV auroral images. Cassini measurements of field-aligned currents near local noon during simultaneous HST images of the auroral emission distribution have given evidence that the UV aurora is associated with these currents near the open/closed field line boundary (Bunce et al. 2008a). A detailed comparison of theoretical models of auroral current systems in Saturn’s magnetosphere and Cassini and HST observations is given in Sections 12.4.2 and 12.5.

### 12.2.2.2 Saturn’s Ultraviolet Auroral Morphology

The analysis of polar projections of HST STIS and ACS images shows that the bright ring of auroral UV emission, the main oval, actually consists of several sub-structures having different latitudinal widths and brightnesses and forming along different paths around the spin axis. Dramatic changes in morphology have been observed during the different HST campaigns. However, some order emerges from this apparent variation; the bulk of auroral emission in groups of images has been shown to fit in a set of characteristic zones (Grodent et al. 2005) fixed in local time, revealing some morphological stability.

The global morphology of the emission varies from an expanded quasi-circular distribution, almost centered on the spin axis and characterized by a mean (southern) latitude of $\sim70^\circ$, to a contracted spiral shape. In most cases, the spiral starts in the midnight to dawn sector at high latitude (values can reach $80^\circ$) and then drifts equatorward with increasing local time down to values as low as $70^\circ$ (Gérard et al. 2004; Clarke et al. 2005; Grodent et al. 2005). Badman et al. (2006) used a selection of HST images obtained from 1997 to 2004 to locate the median poleward and equatorward auroral boundary of the auroral oval using statistical methods. These are shown in Fig. 12.2. Near dusk it connects with the rest of the emission and starts a new, partial, revolution around the pole in the midnight to dawn sector. The spiral shape is likely a consequence of the imbalance between the processes of magnetic field line reconnection occurring at the dayside magnetosphere and in the nightside tail (Cowley et al. 2005). Extreme cases have been reported where most of the emission is concentrated in the morning side. Long term observation campaigns suggest that the global auroral morphology can remain unchanged for almost one week but can also undergo dramatic changes from one day to the next. The bright emission does not form a continuous ring but rather a string of arcs, several tens of degrees long, with variable width, ranging from a few to several thousands of kilometers (up to a few degrees in longitude), and variable brightness.

Smaller features intermittently appear poleward of the main ring of emission. They take the form of individual spots or small arcs which last several minutes and appear distinct from the rest of the auroral emission. Simultaneous remote and in-situ observations with Cassini suggest that these transient features are associated with the dynamical processes taking place in the Saturnian magnetosphere such as injection events (Radioti et al. 2009). They make no attempt to
examine the local time of these features, but focus on HST images that almost overlap Cassini/MIMI (Magnetospheric Imaging Instrument) observations. Other, unpublished, images show transient auroral features at all local times.

While observations accumulated over several hours indicate that the global auroral morphology remains fixed in local time, temporal analysis of the location of individual features forming this global morphology shows that they rotate with the planet at a substantial fraction of corotation (Grodent et al. 2005). A movie showing this rotation is included on the DVD supplied with this book. This is in contrast to a structure truly fixed in local time, as in the case of the Earth. This temporal analysis indicates that the velocity is globally ~65% of corotation with rather large variations of this fraction, but there are uncertainties depending on which reference points in the images are used to determine this velocity. The rotational motion of the auroral emission may seem to contradict the local time nature of the global morphology; however, it should be stressed that the global morphology sets the poleward and equatorward boundaries of the polar region where the auroral emission is likely to occur, regardless of the identity or the previous location of the auroral features that are forming it. Accordingly, the global morphology may be seen as a frame, fixed in local time, but inside which emission (sub-)corotates with the planet’s atmosphere around the pole. This may be related to the behavior of SKR in which the maximum brightness occurs when the subsolar point is near 100° SLS3 longitude (Kurth et al. 2008), yet the emission is thought to be generated on field lines threading bright auroral arcs, which appear to move in the corotational direction.

An important feature of Saturn’s auroral morphology and dynamics is that longitudinal structures at ~65% of corotation have been observed during periods of very quiet solar wind activity. In addition, enhancements of the dawnside oval have been observed when Cassini did not observe any signature in the solar wind activity (Gérard et al. 2006). These observations and the onset of injection of hot plasma in the night or dawn sector in the absence of solar wind activity imply ongoing (but intermittent) dynamical phenomena associated with either the solar wind or planetary rotation through the Dungey or Vasyliunas cycle during relatively quiet intervals.

Closer inspection of a long sequence (~7 h) of images obtained in January 2004 revealed the presence of an isolated bright auroral structure for which the angular velocity constantly decreased with time as it moved across the noon to post-noon sector. The corotation factor of this auroral feature decreased from 55% to 20% and was concomitant with a rapid ~5° poleward shift of the feature. This peculiar feature is probably related to significant enhancements that are regularly observed near 1200 LT poleward of or along the main auroral oval (Gérard et al. 2005). These emissions may then be seen as the signature of the kronian cusp in the noon sector. They present two distinct states; the first is a bright arc-like feature located in the pre-noon sector that appears as an intensification of the main oval. The second is a more diffuse “spot” of aurora lying poleward of the general location of the main auroral oval. The former would be a consequence of pulsed reconnection at the low-latitude dayside magnetopause when the interplanetary magnetic field (IMF) is directed northward (antiparallel to Saturn’s magnetic field lines), while the latter would correspond to the case of southward IMF and high-latitude lobe reconnection (Bunce et al. 2005).

A zone of emission commonly appears at the equatorward boundary of the nightside auroral region. In this sector, faint emission appears clearly equatorward of 70° and is detached from the brighter emission poleward of 70°. This emission is usually tenuous with an intensity only a few kiloRayleighs above the background. It is revealed by the limb brightening of the emission which, in the case of the HST/STIS 2004 dataset, increased the brightness by up to 350% near midnight. Its morphology and mean brightness remain almost constant over the 2004 HST data set, even during the most extreme events. This latter observation suggests that the lower latitude emission is produced by a different mechanism from the rest of the emission, presumably related to inwardly diffusing energetic particles deep into the corotating magnetosphere (Stallard et al. 2008c).

A general trend emerges in the brightness distribution as the dawn to noon sector is generally brighter than the noon to dusk sector, although some images show the opposite trend. The maximum brightness ranges from a few kiloRayleighs to several tens of kiloRayleighs. It usually decreases as the auroral structure rotates from dawn to dusk through noon.

### 12.2.2.3 \( \text{H}_2 \) Auroral Spectroscopy

The auroral emission at Saturn is mainly produced by collision of precipitating energetic electrons with the neutral atmosphere (Shemansky and Ajello 1983). Between 80 and 180 nm, the auroral emission is dominated by atomic H lines from the Lyman series and \( \text{H}_2 \) vibrational lines from the \( B^1 \Sigma_u^+ \rightarrow X^1 \Sigma_g^+ \), \( C^1 \Pi_u \rightarrow X^1 \Sigma_g^+ \), \( B^1 \Sigma_u^+ \rightarrow X^1 \Sigma_g^+ \), \( D^1 \Pi_u \rightarrow X^1 \Sigma_g^+ \), \( B^3 \Pi_u \rightarrow X^1 \Sigma_g^+ \), \( D^1 \Pi_u \rightarrow X^1 \Sigma_g^+ \), \( D^3 \Pi_u \rightarrow X^1 \Sigma_g^+ \) system bands (Gustin et al. 2009). The Lyman \( (B \rightarrow X) \) and Werner \( (C \rightarrow X) \) bands, as well as the Lyman continuum prevail in the far UV (FUV) spectral region, and the extreme UV (EUV) bandwidth results from transitions from the \( B^0 \) and higher Rydberg electronic states.

Once produced, the FUV and EUV auroral emissions interact with the atmosphere through absorption by hydrocarbons and self-absorption by \( \text{H}_2 \). These two mechanisms have been used to estimate the altitude of the auroral emission.
peak by fitting observed spectra with model spectra. A generator of \( \text{H}_2 \) spectra has been developed to simulate the effects of the impact of auroral electrons on the atmospheric \( \text{H}_2 \) molecules. It has been described and used for Jovian spectroscopy analysis by Gérard et al. (2002) and Gustin et al. (2004), and for Saturn’s spectroscopy by Gérard et al. (2004) and Gustin et al. (2009).

Methane is the fourth most abundant substance in the atmosphere of giant planets, after \( \text{H}_2 \), \( \text{H} \) and \( \text{He} \). It is produced in the troposphere and transported to the stratosphere by convection and turbulent diffusion. Methane has a large wavelength-dependent absorption cross-section in the 90–140 nm domain. As a result, it attenuates the \( \text{H}_2 \) emission below 140 nm and leaves the emission above 140 nm mostly unattenuated. Even though ethane (\( \text{C}_2\text{H}_6 \)) and acetylene (\( \text{C}_2\text{H}_2 \)) are known to be present within the atmosphere, only \( \text{CH}_4 \) has been previously detected from auroral UV spectra in the 115–170 nm range near local noon (Gérard et al. 2004). The level of absorption by the methane layer overlying the emitting region is characterized by the color ratio \( CR = I(155–162 \, \text{nm})/I(123–130 \, \text{nm}) \) where \( I \) is intensity in each bandpass, and where brightness in kiloRayleighs is \( 4\pi I \). See Fig. 3 of Gérard et al. (2003) for an illustration of this differential absorption. The color ratio \( CR \) is 1.1 for an unattenuated spectrum, expressed in Rayleighs, and its value increases with attenuation. The color ratio is thus directly associated with the emission altitude, hence, to the penetration depth of the precipitating electrons which depends on the energy of these electrons. Analysis of six HST/STIS spectra of the southern aurora in the 115–175 nm spectral range (Gérard et al. 2004) suggests that the auroral emission is little absorbed by methane, with a nearly constant vertical \( \text{CH}_4 \) column of \( 6 \times 10^{15} \, \text{cm}^{-2} \). Using a model of Saturn’s atmosphere at 30º North (Moses et al. 2000) relating the \( \text{H}_2 \) and \( \text{CH}_4 \) column density profiles, and the Grodent et al. (2001) energy degradation model that links the \( \text{H}_2 \) column density to the mean energy of the precipitated electrons, Gérard et al. (2004) derived an energy of the precipitated primary electrons in the range 12 ±3 keV. More recently, Gérard et al. (2009) used the emission altitude inferred from HST/ACS images of Saturn’s southern auroral region as a constraint for a Monte Carlo electron transport code (Bisikalo et al. 1996). The peak of the auroral nightside emission is generally located 900–1300 km above the 1-bar pressure level which corresponds to a characteristic energy of the precipitating electrons between 5 and 30 keV. This energy depends on the model atmosphere; Gérard et al. (2009) considered a model in which the thermospheric temperature in the auroral region sharply increases at a higher pressure level than in the low latitude model of Moses et al. (2000).

Direct measurement of the \( \text{H}_2 \) column overlying the auroral emission can be obtained independently from EUV spectra. Below 120 nm, the photons connecting to the \( v'' = 0, 1, 2 \) vibrational levels may be partially or totally absorbed by the overlying column of \( \text{H}_2 \) and redistributed to the FUV portion of the spectrum. This self-absorption process provides a measure of the \( \text{H}_2 \) column overlying the UV emission peak and on the population of the ground-state vibrational levels (Gustin et al. 2004).

Gustin et al. (2009) compared synthetic \( \text{H}_2 \) spectra with UV spectra of Saturn’s aurora obtained with HST/STIS, Far Ultraviolet Spectroscopic Explorer (FUSE) and with the Cassini Ultraviolet Imaging Spectrograph (UVIS) instruments. The temperature of the absorbing \( \text{H}_2 \) molecules can also be derived from self-absorption, provided the spectral resolution is sufficiently high, which is the case of the FUSE observations.

STIS and UVIS FUV spectra were found to be very little absorbed by methane, with vertical \( \text{CH}_4 \) columns less than or equal to \( 1.2 \times 10^{16} \, \text{cm}^{-2} \) consistent with primary electron energy lying in the 10 to 18 keV range. This suggests that the peak of the UV auroral emission originates from above but close to the methane homopause, and primary energies near ~18 keV should be considered as an upper limit.

FUSE and UVIS EUV spectra clearly exhibit self-absorbed \( \text{H}_2 \) bands. However, the low spectral resolution of the UVIS EUV spectra does not make it possible to resolve the \( \text{H}_2 \) rotational lines and cannot provide a reliable T/\( \text{H}_2 \) column pair. On the other hand, the high resolution of the FUSE EUV spectra makes it possible to determine a \( \text{H}_2 \) rotational temperature on the order of 400 K and an \( \text{H}_2 \) column of ~6.0 × 10^{19} \, \text{cm}^{-2}, corresponding to a pressure level of ~0.15 \, \mu \text{bar}. The \( \text{H}_2 \) columns deduced from FUSE lead to primary auroral electron energies from 10 to 15 keV. The temperature of 400 K derived from FUSE is in agreement with the 350–500 K range obtained from \( \text{H}_2^+ \) IR spectra measured at the \( \text{H}_2^+ \) peak altitude by Melin et al. (2007). These values are significantly higher than the ~125 K expected from the Moses et al. (2000) equatorial model near 0.15 \, \mu \text{bar}, which suggests that an equatorial temperature profile is not appropriate for polar latitudes.

### 12.2.2.4 Effects of Auroral Energy Input to the Atmosphere

The auroral energy input to the atmosphere of Saturn has been estimated by Gérard and Singh (1982). Their model takes into account the loss of energy of incident energetic particles from collisional processes, tracks the resulting excitation of emissions, and models the radiative transfer of the UV emissions leaving the atmosphere. From this model, the rule of thumb has emerged that the radiated UV power is approximately 10% of the total incident power. The total radiated power from Saturn’s aurora is typically 10–30 GW, corresponding to 100–300 GW input power to the upper atmosphere.
atmosphere. This input power is comparable to the solar input and, when the auroras are bright, exceeds the total input power to the global upper atmosphere from solar UV radiation. The aurora therefore has a strong and potentially dominant influence on the thermospheric dynamics of Saturn’s upper atmosphere. The extent to which this input energy can be transferred from the polar regions to the global atmosphere, and contribute to the high upper atmospheric temperature, is the subject of detailed modeling (Müller-Wodarg et al. 2006). These authors found that while there is ample energy in the auroral zones to yield the global high thermospheric temperatures, the planet’s large size and rapid rotation result in strong zonal winds that limit heat transport to lower latitudes.

12.2.2.5 Ground-Based Observations of Saturn’s IR Aurora

Since the arrival of Cassini at Saturn, the IR aurora from H$_3^+$ emissions has been studied in detail by a long-term observing program based at NASA's Infrared Telescope Facility, using both high-resolution spectroscopy (Stallard et al. 2007a) and emission-line imaging (Stallard et al. 2008a). These observations have begun to categorize both the morphology and magnetospheric origin of infrared auroral emission. In broad structure, the IR emission morphology appears to be similar to that of the UV emission. Just as with the UV main auroral oval, the IR oval is roughly circular. During periods of rarefied solar wind, this appears to be low intensity on both the dawn and dusk sides of the oval, while compressions in the solar wind cause significant dawn brightening. Over the period of the Cassini mission, the overall IR intensity has varied by up to a factor of 50, from $2.56 \times 10^{-15}$ W m$^{-2}$ to $1.32 \times 10^{-13}$ W m$^{-2}$, though the largest change seen over any individual 24-h period was a factor of two increase in intensity.

Equatorward of the main auroral oval, a secondary auroral oval has been detected. Emission from this oval appears to be relatively weak, with an intensity <25% of the main oval. As shown in Fig. 12.3, the ion wind velocities associated with the secondary oval show that it is created by the breakdown in co-rotation within the plasma disk around the planet – a weak Saturnian equivalent of Jupiter’s main auroral oval (Stallard et al. 2008c). There are other significant fine scale differences between the IR and UV auroral emission. Most notable is the significantly raised level of polar emission

![Figure 12.3](image-url)

**Fig. 12.3** (a) shows the H$_3^+$ intensity (thin line) and the associated ion velocity profile (thick line) for a spectrum taken with the slit aligned east–west across the main auroral oval. The dashed line shows the rotation of the planet, which the ions, accelerated by the neutral atmosphere, would follow in the absence of electric currents. The main auroral oval is demarked by the three-dot-dashed lines and the point at which the ions no longer corotate with the planet by the dot-dashed lines. The grey regions show the estimated errors. (b) shows the same intensity profile, corrected for line-of-sight brightening along with a modeled one degree wide circular main auroral oval, positioned at a colatitude of 15°. This model has been subtracted from the H$_3^+$ intensity, with the residual emission also shown. Poleward of the main oval a significant auroral brightening can be seen, which may be analogous to the polar emission seen by the Cassini-VIMS instrument. Equatorward of the main oval, two emission peaks can be seen. These coincide with the location of breakdown in corotation shown in (a), strongly suggesting that this is a secondary auroral oval at Saturn that is caused by the breakdown in corotation, in a similar way to the main auroral oval at Jupiter (from Stallard et al. 2008c))
seen in the majority of IR observations; the relative strength of this raised emission appears to vary with time (Stallard et al. 2007a). In addition, the main auroral oval has been seen to have an extended period of dusk brightened aurora, covering a period of up to five Saturnian days (Stallard et al. 2008b).

Ion wind velocities within the auroral region also show significant structure not seen within the emission morphology. Most notably, while the auroral region generally sub-corotates relative to the neutral atmosphere, a region poleward of the main auroral oval, generally on the dawn side, appears to consistently corotate with the planet. This is a highly unexpected result since this region is typically thought to be associated with field lines open to the solar wind. During periods of compression in the solar wind, when the auroral emission is strongly dawn brightened, this central corotating region disappears and the entire auroral region sub-corotates. It has been suggested that this region may correspond to field lines embedded in the center of the magnetotail that are shielded from the solar wind such that ions in this region are effectively controlled only by the neutral atmosphere and that a major compression in the solar wind closes these field lines (Stallard et al. 2007b).

Observations made using the United Kingdom Infrared Telescope show the overall temperature of Saturn’s polar H$_3^+$ layer should be taken as 400 ± 50 K. The H$_3^+$ emission strength varied by at least an order of magnitude over the 6 year period of these observations. It was shown that this variability was driven by changes in the H$_3^+$ column density and that the increased level of ionization which produced this required a ~20 times variation in the particle (kiloelectron-volt electron) precipitation. However, such increases are insufficient to offset most of the heating due to the extra particle precipitation, indicating that H$_3^+$ does not act as a “thermostat” on Saturn, in the same way that it does on Jupiter (Melin et al. 2007).

### 12.2.3 Cassini Remote Sensing Observations of Auroral Emissions

Cassini can observe auroral and aurora-related emissions in wavelengths ranging from the ultraviolet through radio wavelengths. Cassini has four optically aligned instruments obtaining data relevant to the aurora. Cassini’s Ultraviolet Imaging Spectrometer (UVIS) has a long-slit spectrograph with Extreme Ultraviolet (EUV, 56–118 nm) and Far Ultraviolet (FUV, 110–190 nm) channels with spectral resolution (0.275, 0.48, or 2.49 nm for EUV; 0.275, 0.48, or 1.94 nm for FUV) depending on the selected slit width (Esposito et al. 2004). Each channel has a 1024 pixel (spectral dimension) × 64 pixel (spatial dimension) microchannel plate detector, providing spectral capability and, when slewed appropriately, imaging capability. Cassini’s Imaging Science Subsystem (ISS) has wide (3.5°) and narrow (0.35°) field of view 1024 × 1024 pixel CCD cameras and a set of narrow-band filters providing coverage over the range from 200–1100 nm (Porco et al. 2004). Cassini’s Visual and Infrared Mapping Spectrometer (VIMS) instrument has an internal scan mirror, providing spectral and spatial coverage without additional spacecraft motions (Brown et al. 2004). Finally, Cassini’s Composite Infrared Spectrometer, CIRS (Flasar et al. 2004) uses a pair of Fourier transform spectrometers to make thermal infrared observations at a wavelength range from 7 μm to 1 mm.

While not directly auroral emissions, kilometric radio emissions result from particle distributions existing on auroral field lines and can be used as indicators of auroral activity. The Radio and Plasma Wave Science (RPWS) instrument on Cassini detects waves in the frequency range from ~1–16 MHz, including the SKR spectrum extending from a few kiloHertz to 1.2 MHz and centered between 100 and 400 kHz (Gurnett et al. 2004).

#### 12.2.3.1 UVIS Results

Esposito et al. (2005) presented an initial Saturn UV spectrum and found it indistinguishable from a Jupiter spectrum except 250 times dimmer. In both cases the observed emissions are thought to be due to electron-impact excitation of molecular and atomic hydrogen. In general, the electron energies are lower at Saturn than at Jupiter (Shemansky and Ajello 1983). Gustin et al. (2009) presented comparisons of spectra from FUSE, HST STIS, and Cassini UVIS, and found additional evidence for relatively soft electrons at Saturn.

An early campaign from Saturn orbit was undertaken during a period in which the spacecraft was above Saturn’s equator near 90° phase angle and out in the solar wind on the dawn side. This period is useful for examining the response of the aurora to the solar wind. In this period the auroras are seen as brightenings at the planetary limb. UVIS observed several episodes of brightening (up to a factor of 4 changes in intensity) that took place at both poles in response to solar wind pressure increases (Esposito et al. 2005).

Figure 12.4 shows an image pair of Saturn and its rings from UVIS (2005 day 172; June 21 2005) created by slewing the spacecraft slowly across Saturn and then back. This image was prepared making use of deconvolution techniques and the estimated UVIS point-spread-function. The quality of the deconvolution was controlled by observing the effect on the appearance of the known structures in Saturn’s rings. In this image blue is used to represent auroral emission wavelengths, and orange is used for reflected sunlight at longer FUV wavelengths. The two crossings of the auroral oval are
region using IR emission from the H\textsuperscript{3+} ion. The VIMS instrument has observed Saturn’s infrared auroral oval, as was observed with HST (Gérard et al. 2005). The possible origin of this feature is addressed in Section 12.5. Transient bright features that show up in a single frame are common inside of the main oval. Two of the movies from July 2008 show apparent compression events where the oval contracts in size, broadens in width, and “fills in” with emission inside part of the oval.

12.2.3.2 VIMS Results

The VIMS instrument has observed Saturn’s infrared auroral region using IR emission from the H\textsuperscript{3+} ion. Data from the instrument were combined across several separate wavebands in order to construct images shown in Fig. 12.5 of the infrared aurora at a much higher spatial resolution than had previously been possible using ground-based observations (Stallard et al. 2008a).

Beginning in 2007 UVIS obtained a number of movies showing Saturn’s northern auroral oval with brightness features rotating on Saturn. These provide a good view of both the day and the night side of the oval, unlike most HST images. A processed version of one movie from 2008 day 129 is available on the DVD supplied with this book. This movie showed two bright auroral features on the arc moving nearly corotationally, aligned in longitude with patches of enhanced brightness in MIMI Ion and Neutral Camera (INCA) magnetospheric ring current images. The brightest part of the auroral arc separates into two distinct arcs (Mitchell et al. 2009b). Emission features on the oval in some movies brighten on the dawn side and dim on the dusk side, then rebrighten as they return to the dawn side. This enhanced emission on the dawn side is consistent with SKR observations (Galopeau et al. 1995) and theoretical considerations (Cowley et al. 2004a, b). A number of UVIS movies show a polar cusp emission near noon between the pole and the main oval, as was observed with HST (Gérard et al. 2005). The possible origin of this feature is addressed in Section 12.5. Transient bright features that show up in a single frame are common inside of the main oval. Two of the movies from July 2008 show apparent compression events where the oval contracts in size, broadens in width, and “fills in” with emission inside part of the oval.

12.2.3.3 ISS Results

Saturn’s visible auroras were imaged by Cassini in 2006 and in 2007 on Saturn’s night side in the north polar region near 75° latitude (Dyudina et al. 2007). These data are presented in Fig. 12.6. While the detections are much dimmer than the ultraviolet aurora and have low signal-to-noise, the spatial resolution is better than that of the other Cassini imaging instruments.

ISS observations show that Saturn’s aurora is bright in a few spectral channels (in the broadband infrared channel covering 825–925 nm (~100 R/nm), in the H\textalpha channel covering 651–661 nm (~200 R/nm), possibly in a UV channel covering 300–370 nm (~250 R/nm)), and dark in the other visible channels. The average broadband visible brightness of the aurora for the 300–900 nm 2006 multi-channel observation is ~25 R/nm. This agrees with the line emission predicted in the laboratory spectra of electron impact on molecular hydrogen and atomic hydrogen for the Saturnian aurora by Aguilar et al. (2008). This also agrees with the
visible spectrum of aurora on Jupiter observed by Galileo (Ingersoll et al. 1998; Vasavada et al. 1999). Figure 12.6 shows the auroral arcs and spots near 75° latitude (left panel), and rapid variability in auroral arc features (right panels). The two features labeled 1 and 2 in the images are seen disappearing within half an hour between the observations.

### 12.2.4 Auroral Radio Emissions

Like other magnetized planets, Saturn is a strong radio source at kilometric wavelengths. Zarka (1998) provides a thorough review of planetary radio emissions and serves as a basis for our understanding of Saturn’s radio emissions, particularly the Saturn kilometric radiation. These radio emissions were discovered by Voyager (Kaiser et al. 1980; Warwick et al. 1981). Most interestingly, SKR displays a variable modulation period near 10.7 h, thought to be close to the internal rotation period of the planet. Decades-long studies of the period of modulation of decametric radiation from Jupiter were the basis for the IAU-adopted rotation period of the planet. However, while Jupiter has an offset and tilted magnetic moment, Saturn’s magnetic field is aligned along its spin axis well within 1 degree (Davis and Smith 1990; Dougherty et al. 2005) and it is not understood why there should be a rotational modulation of the SKR. Synoptic studies using the Ulysses spacecraft detected variations in this modulation period of order 1% on time scales of years (Lecacheux et al. 1997; Galopeau and Lecacheux 2000). Cassini has verified
the variation in period of SKR emissions on times scales from years to weeks (Gurnett et al. 2005 2007; Kurth et al. 2007, 2008; Zarka et al. 2007). Possible reasons for the variable SKR period are discussed in Chapter 10, but the result is that Saturn’s rotation period cannot be readily deduced from the modulation of the SKR. The Cassini SKR observations are provided by the High Frequency Receiver portion of the RPWS instrument (Gurnett et al. 2004).

Given that the SKR period varies, it has been useful to define a new longitude system which takes into account the variable modulation period of the radio emissions. Kurth et al. (2007, 2008) have defined the SLS2 and SLS3 longitude systems, respectively, to provide a system that can be used to organize magnetospheric phenomena. In fact, the systems are not predictive, hence, the definition must be extended in time based on empirical models of the period. Numerous magnetospheric phenomena have been found to be organized by these systems, including the so-called ‘cam’ magnetic field signature (Gurnett et al. 2007; Andrews et al. 2008), the plasma density in the inner magnetosphere (Gurnett et al. 2007) and energetic neutral atom (ENA) hot spots in the middle to outer magnetosphere (e.g. Carbary et al. 2007).

Kilometric radio emissions at Earth (Benediktov et al. 1965; Gurnett 1974) were quickly associated with auroral activity by Gurnett. Wu and Lee (1979) suggested that the auroral kilometric radiation was generated by the cyclotron maser instability (CMI) and there has been consensus on this mechanism ever since. It was by analogy with these terrestrial emissions that the cyclotron maser instability was also
believed to be responsible for decametric and hectometric radiation at Jupiter and Saturn kilometric radiation. Hence, it was inferred that SKR had a close association with Saturnian aurora. Voyager observations (Desch 1982) indicated a strong correlation between SKR and the solar wind dynamic pressure; in fact, Voyager 2 found Saturn immersed in Jupiter’s magnetotail around the time of its encounter and Desch (1983) showed that the lack of solar wind input to Saturn’s magnetosphere greatly decreased the SKR activity.

It wasn’t until the 2004 HST – Cassini campaign that evidence was obtained to indicate a direct relation between the UV aurora and SKR. HST campaigns in January and February 2007 and February 2008 have confirmed this association, but the correlation between SKR power observed by Cassini and the power in the UV aurora is not perfect (Clarke et al. 2009). The beaming of the radio emissions means that a spacecraft such as Cassini will not necessarily detect strong SKR emissions, depending on its position, even if the emissions are being generated.

Cassini has found that the general properties of the SKR spectrum are similar to those obtained by Voyager (Galopeau et al. 1989; Lamy et al. 2008b). On time scales of tens of minutes and frequency scales of a few hundred kHz, SKR demonstrates arc-like structures in the frequency–time plane, similar to, but less well defined than, Jovian decametric arcs. Examples of these can be seen in Fig. 12.7, particularly at 2300 on December 23, 2005 centered near 350 kHz; a more complex set of arcs is found between 0900 and 1100 on the same day. These have been pointed out in a number of reports, including some of the earliest Voyager studies. The arcs are discussed most recently by Lamy et al. (2008b, c).

At Jupiter, such arcs have been shown to be consistent with emission on magnetic field lines with beaming angles that vary with frequency such that an observer at a fixed location sees emissions from progressively larger or smaller distances along the field line, hence, at smaller or larger frequencies, respectively. Goldstein and Goertz (1983), for example, attempted to model the arc-like structure of Jovian decametric radiation.

The Cassini RPWS instrument (Gurnett et al. 2004) includes the capability to make high spectral and temporal resolution observations of SKR. Figure 12.8 from Kurth et al. (2005b) shows a progression of spectrograms from those used for normal survey studies to those approaching the ultimate resolution of ~200 Hz and 125 ms (both of which are instrument mode and analysis dependent). These results showed that SKR includes both diffuse emissions, which do not appear to vary rapidly in time or frequency, and bright, narrowband tones with bandwidths of the order of 200 Hz that drift upwards or downwards in frequency. Audio files which enable one to ‘hear’ the complex spectrum of SKR are included on the DVD supplied with this book. Similar spectral structure is observed both in auroral kilometric radiation at Earth (Gurnett and Anderson 1981) and at Jupiter, for example in S-bursts (Carr and Reyes 1999). Since the CMI results in radio waves generated close to the local electron cyclotron frequency, such narrowband emissions imply that (a) there are small active regions emitting radio emissions and (b) these are moving up or down relative to Saturn to explain the falling or rising tones, respectively. The narrow bandwidth of the emissions essentially set an upper limit on the range of magnetic field strengths in the source region,

![Fig. 12.7](image-url) A 24-h interval from the Radio and Plasma Wave Science instrument showing the intensity of SKR (color) as a function of frequency and time. Just over two magnetospheric rotations are shown. The SKR spectrum extends from a few tens of kiloHertz to several hundred megaHertz in this time frame. Note the arc-like features that commonly appear in this frequency–time plane.
Fig. 12.8 Frequency–time spectrograms of SKR showing progressively higher resolution in both frequency and time going from panel (a) to (d) (from Kurth et al. (2005b)). Starting in panel a showing the lowest spectral and temporal resolution, a region is highlighted with a white box that is expanded in resolution in panel (b). Panel (a) comprises observations made in the RPWS survey, or low rate, mode. Panels (b)–(d) utilize the wideband receiver. Panel (c) shows a higher resolution spectrogram of the data in the white box in panel (b). Panel (d) shows the observations in the white box in panel c at approximately the maximum temporal and spectral resolution of the instrument. At each level of resolution, the SKR shows an array of complex structures in the frequency–time plane, usually composed of narrowband tones drifting upwards or downwards in frequency.

Voyager synoptic studies showed that the peaks in SKR intensity were best organized by subsolar longitude (Desch and Kaiser 1981). When the subspacecraft longitude was used, the phase of the peak shifted with the local time of the spacecraft. This characteristic can be explained by a strobe-light model where the SKR emissions are seen to peak at the same time, regardless of the observer’s location. Jupiter’s auroral radio emissions, on the other hand, exhibit a searchlight like pattern, where the peak rotates with the planet and the time at which the peak is observed depends on the observer’s location. In addition, using various indirect methods, the average source location was deduced by Galopeau et al. (1995). This location was centered between dawn and noon at latitudes in the range of 60° to >80°. In spite of this source location, the Voyagers could observe SKR more or less without regard to their (limited) positions in local time.

Lamy et al. (2008b) have utilized approximately 2.75 years of Cassini observations to carry out a comprehensive synoptic study of the occurrence of SKR as a function of observer location with the results shown in Fig. 12.9. This study confirms the spectral range found by Voyager of a few kiloHertz to 1200 kHz. Lamy et al. (2008b) also verify that the bulk of the SKR emissions are emitted in the extraordinary (R-X) mode, that is right hand (RH) emission from the
Fig. 12.9 Statistical properties of SKR (Lamy et al. 2008a). In the top panel, the average power normalized to a distance of 1 AU is given as a function of frequency and local time. The minimum in occurrence in the 15–20 h range is also where Cassini is close to Saturn. Hence, rather than a local time variation, this is indicative of an equatorial shadow zone at small radial distances. Panel (b) represents the average power of SKR as a function of frequency and latitude. For this analysis, north-south hemispherical symmetry was assumed so that all of the emission are assumed to come from the northern hemisphere. Labels in Panel (b) indicate extraordinary (R-X) mode and ordinary (L-O) mode SKR as well as two low frequency narrowband emissions that are not considered auroral radio emissions (after Lamy et al. 2008a).

Northern hemisphere and left hand (LH) from the southern hemisphere. To first order, SKR can be observed at any local time. At very close planetary distances, however, there is an equatorial shadow zone which cannot be illuminated by the high latitude sources as found by Lamy et al. (2008b). Further, there is some indication that at higher latitudes emissions above 200 kHz and below 30 kHz disappear. Lamy et al. (2008b) also find general conjugacy in the emissions between the northern and southern hemispheres. Evidence for ordinary mode SKR emission is also given in Lamy et al. (2008b). Two narrowband emissions labeled n-SKR and n-SMR (narrowband Saturn myriametric radiation) are also shown in Fig. 12.9, but these are generated via mode conversion from electrostatic waves and are not related to the aurora. See Louarn et al. (2007), Wang et al. (2009), and Ye et al. (2009) for discussions of the narrowband emissions and their sources.

Lamy et al. (2008c) subsequently modeled the SKR occurrence by examining radiation from two types of electron distribution functions unstable to the cyclotron maser instability. The first of these is a loss-cone distribution which results in radio beams emitted obliquely with respect to the local magnetic field and the second, is alternately called a shell or horseshoe distribution, the result of electron trapping due to field-aligned potentials on auroral field lines. The shell electron distribution is expected to produce beaming at 90° with respect to the magnetic field. While both distributions produce radio emissions, the latter is more efficient and is thought to be the predominant source of auroral kilometric radiation at Earth (Mutel et al. 2008). Lamy et al. (2008c) modeled the frequency–time characteristics of radio emissions as observed from a virtual observer in an attempt to reproduce the arc-like structures and equatorial shadow zone observed by Cassini in its orbit. Figure 12.10 shows a comparison of a typical periapsis pass of Cassini with a clear shadow zone apparent in the SKR data that is well-modeled by Lamy et al. (2008c). They found that either distribution can reproduce the frequency–time aspects of SKR, but the loss-cone distribution provides a better fit.

A most powerful tool provided by the RPWS instrument is the ability to measure both the direction of arrival and full polarization of radio emissions. The most complete study of SKR using these capabilities was carried out by Cecconi et al. (2008), who determined the three dimensional source of SKR during one periapsis pass of Saturn by Cassini. The source locations are determined over a 24-h interval during which the spacecraft passes from the southern to the northern hemisphere and moves from dawn to dusk through local noon relative to Saturn. This study determines the direction-of-arrival, which places the source at a given frequency \( f \) in the plane of the sky, a two dimensional position. The assumption that the SKR is generated on a surface of constant electron cyclotron frequency \( f_{ce} = f \), according to the theory of the cyclotron maser instability, is used to obtain the third dimension, or distance to the source. The surface of constant \( f_{ce} \) is derived from a magnetic field model, in this case the SPV.
model by Davis and Smith (1990) including the current sheet model by Connerney et al. (1983). Given the source location, the field line threading the source is determined, hence, the magnetic field model can be used to trace that field line to its foot at the top of the atmosphere for comparison with the location of UV auroras.

An example set of source locations determined over a 5-min interval is given in Fig. 12.11 which shows both a perspective plot of the source positions as a function of frequency on the left and the footprints of the source field lines in the right panel. Cecconi et al. (2008) provide a movie composed of such results over the full 24-h interval of analysis. A copy of this movie is included on the DVD supplied with this book. The primary results of Cecconi et al. (2008) are that the SKR sources are located on field lines that map to the ionosphere between ~70 and 80° latitude, consistent with the mean location of the main UV auroral oval. In the northern hemisphere the sources tend to be 2° to 5° higher in latitude than in the south. The sources are also observed over the entire 4 to 16 h local time range visible to Cassini through this particular periapsis pass. Further, the local times of the sources observed at any instant in time are strongly influenced by the local time of Cassini. That is, radio sources clustered on either side of the Cassini central meridian longitude are most often observed. This is a clear manifestation of beaming of the radio emissions.

Lamy (2008a) and Lamy et al. (2009) have, for the first time, shown the direct correspondence between field lines threading the source of SKR and those with their feet embedded in the bright dawnside auroral arc. As shown in Fig. 12.12, these authors have used direction-finding techniques to locate the source of SKR at nearly the same time as an HST image of a bright UV auroral arc on the dawn side on Jan. 17, 2007. Using a model of the magnetic field, the projection of this source along the magnetic field results in the projection of where the feet of the source field lines enter
12.3 Magnetospheric Dynamics and the Aurora

Jupiter’s and Saturn’s magnetospheres are both much larger than the Earth’s, and the time scales for disturbances in the solar wind to move from the bow shock past the planet are hours, compared with minutes at the Earth. A timescale of equal importance in this context is the time it takes to fill the magnetotail with open flux (which is roughly equivalent to the lifetime of an open field line) through reconnection at the dayside magnetopause, versus the rotation rate of the planet. At Earth the polar cap is filled with open flux typically in a few hours, in comparison to the 24 h rotation rate. At the outer planets, however, estimates of the dayside reconnection voltage suggest that it takes ~8 days at Saturn (Jackman et al. 2004), and ~15–25 days at Jupiter (Nichols et al. 2006) to replenish the giant magnetotails, versus the faster ~10 h rotation rate in each case. We would therefore expect the response to the solar wind to be quite different from the situation at Earth. Saturn’s magnetospheric plasma content (mainly from the rings and icy moons) is much lower than Jupiter’s, and the neutral content higher, but the distance

the pole of Saturn. A similar polar projection of the UV emissions lies in the same location. The example in Fig. 12.12 is an individual example of the correspondence between the SKR source and bright UV aurora, but Lamy (2008a) has shown a statistical correspondence, as well. A movie of the SKR radio sources is included on the DVD supplied with this book.

Fig. 12.12 Comparison of the distribution of SKR sources (top) with the location of the main UV aurora imaged by HST on the same day (Lamy et al. 2009). The top left panel shows the location of the SKR source as seen from Cassini while the top right panel shows the locations of the feet of the magnetic field lines threading the radio sources. It is clear that the field lines threading the SKR are those associated with the bright dawnside auroral arc
to which plasma corotates with the magnetic field fills most of the magnetosphere, like Jupiter and unlike the Earth. On
the basis of the mounting body of theoretical and observa-
tional evidence to be discussed in Section 12.5, Saturn’s main
UV auroral emission is probably not produced in a manner
similar to Jupiter’s, rather it seems to be associated with the
flow shear between near-rigidly rotating closed field lines,
and sub-corotating closed field lines. Since no emissions
have been detected from magnetic footprints of the satellites,
there are no direct measurements from UV images of the dis-
tance to which the auroral oval maps.

12.3.1 Response of the Aurora
to Solar Wind Input

The Cassini – HST campaign in 2004, in addition to oth-
ers discussed below, has contributed strong evidence of the
importance of the solar wind in the intensity and morphol-
ogy of Saturn’s auroral emissions. This was the first chance
to see how the auroral displays responded to a large shock-
related compression of the dayside magnetosphere. During
this campaign, the auroral emissions clearly brightened at
the arrival of a large solar wind dynamic pressure increase
(Clarke et al. 2005; Crary et al. 2005). For this event, the
solar wind pressure, velocity, and interplanetary magnetic
field (IMF) were measured by Cassini approaching Sat-
urn. The dawn side auroral emissions brightened the most,
filling the dawn side polar cap, and the main oval radius de-
creased in proportion to the emission brightness as shown
in Figs. 12.1 and 12.13. The SKR emissions (described in
Section 12.2.4), measured by the Cassini RPWS instrument,
also increased in intensity during this event after correct-
ing for the rotational modulation as shown in Fig. 12.14
(Kurth et al. 2005a). In addition to these overall bright-
enings, other diurnal effects were seen in specific auroral
emissions. Isolated emissions appeared to move at 60–70%
of the corotation speed, but some slowed to ~20% after
shifting from the morning to the afternoon sector (Grodent
et al. 2005). In addition, a “comma” shaped distribution
was seen at times when bright emissions from the morning sec-
ton shifted to higher latitudes in the afternoon sector. The
highly-dynamic nature of Saturn’s aurora revealed by the
HST observations (shown in Fig. 12.13) appears to relate
directly to the concurrent solar wind activity measured by
Cassini. Collectively these data provide a unique insight into
the solar wind driving of Saturn’s magnetosphere and con-
sequent auroral response (see Clarke et al. 2005, 2009; Bunce
et al. 2006).

As shown in Fig. 12.15 the January 2004 auroral bright-
enings correlated well with the dynamic pressure of the so-
lar wind, rather than the direction of the IMF which domi-
nates at the Earth, suggesting a different kind of interaction
with the solar wind (Clarke et al. 2005; Crary et al. 2005).
It has therefore been proposed that the brightenings are pro-
duced by shock-compressions triggering rapid reconnection
and closure of open tail flux in the nightside magnetosphere
(Cowley et al. 2005). This effect occurs less frequently at
Earth, but due to the timescales discussed above could well
be the normal mode at Saturn. The local IMF direction,
largely azimuthal due to the Parker spiral configuration, was
also known from Cassini measurements. As discussed this
One of the principal goals of the 2007–2008 HST campaigns was to test the response of Saturn’s aurora and magnetosphere to changes in the solar wind, given the evidence from the 2004 campaign. Two solar wind forward shocks (increased pressure and velocity) of varying strength arrived at Saturn during each set of observations in 2007 and 2008 (Clarke et al. 2009). Linear correlation coefficients were estimated for the nominal arrival times predicted by the MHD model and for the optimal shifted arrival time for an upper limit to the possible correlation. The correlation coefficients between auroral power and solar wind pressure were 0.22/0.51 for the 2007 data and 0.60/0.85 for the 2008 data, in both cases for the nominal and best-correlated shifted arrival times. The linear correlation coefficients between auroral power and rotation-averaged SKR power were 0.30 in 2007 and 0.02 in 2008, and in these cases there were no shifted values since the times were known. In the case of solar wind shocks, the auroral brightenings appeared to persist longer than the solar wind pressure remained elevated. The SKR emission is known to be beamed and is associated with bright auroral emissions (see Section 12.2.4). The intensity detected by Cassini would then depend on the location of the spacecraft with respect to the emission beams, and more detailed modeling is needed to estimate the observing geometry. In terms of individual events, however, there was a one to one correspondence between the arrival of solar wind forward shocks at Saturn and increases in Saturn’s auroral power and SKR emission, and a decrease in the oval radius. At the times of two reverse shocks (increased velocity but decreased pressure) the SKR emission and possibly the UV emission appeared to increase, although the statistics are poor. In addition, no auroral brightenings were observed over several weeks of quiet solar wind conditions. The event data are consistent with a causal relationship between solar wind disturbances and auroral and SKR emission increases.

Both the UV auroral emissions and SKR show brightness patterns that are best organized by local time. Clearly, Saturn’s magnetosphere is strongly affected by pressure variations in the solar wind and it clearly demonstrates the effects via changes in the auroral response. A later section on coupling from the solar wind through the magnetosphere to the ionosphere discusses some of the theoretical ideas of how the dynamics in the solar wind might couple into the magnetosphere and result in the patterns of auroral emissions observed in the remote sensing observations summarized here. In this regard, Saturn’s magnetosphere resembles Earth’s strong response to solar wind input, although there is little evidence that the orientation of the interplanetary magnetic field is as important in this interaction at Saturn as it is at Earth. The reasons for this are twofold. First, the IMF switches back and forth on timescales of tens of minutes to an hour, which for Saturn (unlike the situation at the Earth) is negligible in comparison to the open field convection times discussed above. Second, 2004 was solstice for Saturn, and therefore at this time Saturn presented an apparent lack of dipole tilt in the azimuthal (or B_y) direction. As such, IMF positive B_y is essentially the same as IMF negative B_y. Solar wind effects clearly do play a role in the auroral dynamics at Jupiter, as shown by Gurnett et al. (2002), Pryor et al. (2005), and Nichols et al. (2007), although not to the extent that they do at Saturn from two HST campaigns in 2007. The Cassini – HST campaigns in January 2004, January/February 2007, and February 2008 have contributed strong evidence of the importance of the solar wind in the intensity and morphology of Saturn’s auroral emissions (Clarke et al. 2009).
12.3.2 Response of the Aurora to Rotational Dynamics

Although there is a demonstrable correlation between the solar wind and auroral emissions, it is also clear that Saturn’s rotation plays a major role in its auroral processes. Despite the importance of local time in organizing the morphology of the auroras at Saturn and the brightest SKR sources, there is clear evidence in the images of motion of the auroral bright spots in the corotational sense, albeit at only fractions of the supposed planetary rotation rate. As detailed in Chapter 10 there are numerous features in Saturn’s magnetosphere that rotate at periods statistically identical to or at least similar to the SKR period. While we leave the bulk of this discussion to that chapter, we summarize here work by Mitchell et al. (2009b) which shows a particularly clear linkage between periodic injections and particle acceleration in the midnight to dawn region and SKR and UV auroral brightenings.

Mitchell et al. (2009b), using energetic neutral atom (ENA) images, show that protons and oxygen ions are periodically accelerated once per Saturn magnetosphere rotation, usually in a similar location in the midnight to dawn sector at a radial distance of 15 to 20 Rs. Figure 12.16 is a sketch of this process showing the location of the simultaneous acceleration of both protons and heavy ions and the subsequent gradient drift of the particles as a function of their energy. Mitchell et al. suggest that the acceleration is related to reconnection and plasmoid formation in Saturn’s magnetotail. The acceleration events, appearing as enhancements in the ENA images, correlate with periodic bursts of SKR emissions. A particular example of the intensification of SKR apparently correlated with the ENA enhancement is shown in Fig. 12.17. Further, Mitchell et al. (2009b) show that the enhanced regions of ENA emission rotate in the corotation direction at the same rate as UV brightenings observed by UVIS as shown in Fig. 12.18. A movie included with the book DVD shows the spatial and temporal correlations between the ENA emissions and the UV aurora, as well as the
temporal correlation of the brightening in these two phenomena and the enhancement in the SKR. These authors suggest that the azimuthally asymmetric ring current pressure creates a rotating field-aligned current system linking to the ionosphere through auroral field lines.

The 2007–2008 HST campaign also showed that the auroral oval was periodically shifting with time. A detailed analysis of the locations of the auroral oval in each observation was carried out to give a best fit to the oval center location. It was found that the oval center position oscillated with a period of 10.75 ± 0.15 h (2007) and 10.79 ± 0.13 h (2008), consistent with the SKR period (Nichols et al. 2008). The oval moves around highly eccentric ellipses oriented toward pre-noon and pre-midnight. Provan et al. (2009) suggest that the oval displacements are related to distortions in the magnetic field associated with rotating magnetic perturbations. This technique may in the future yield a more accurate value for the rotation rate of Saturn’s magnetic field and thus its interior.

### 12.4 In-Situ Measurements

#### 12.4.1 Energetic Particles

Although the Cassini spacecraft has not traversed the auroral zone at altitudes where upward field-aligned current mechanisms produce downward accelerated energetic electrons (and so such electrons may only be inferred from the remotely observed auroral emissions), upward traveling particles energized by auroral processes are frequently observed. For example, Mauk and Saur (2007) recently identified electron beams that fit such a description at Jupiter. Near-equatorial field-aligned electron beams with energies starting from ~20 keV up to several hundreds of keV were observed at Saturn by Saur et al. (2006). These electron beams were shown to be consistent with a low altitude source. Electron beams are present in Saturn’s magnetosphere from the magnetopause inward to radial distances
Fig. 12.18 Six images from the day 129, 2008 sequence. UVIS auroral images, each scanned over approximately 15 min, are superposed at a larger scale so they can be more easily seen. A pink line lies on top of the X axis of a coordinate system rotating about Saturn’s spin axis, at the SLS3 (extrapolated) period. This is for reference, to follow the motion of the ENA enhancement and the bright auroral bulge over time. In the bottom left corner of each frame, the SKR data is reproduced, with a vertical pink line indicating the center time of that hour-long ENA accumulation (time given at top of each frame). To the right, each auroral image is reproduced with a superposed latitude–longitude grid (every 10° of latitude). A white line indicates the terminator, and the 70° latitude line turns to white for a segment where it crosses the terminator. An inset in Panel f shows a blow-up of the equatorward bulge at about that time (from Mitchell et al. 2009b).

as close in as 11RS (see Fig. 12.19). Even though pitch-angle coverage of the MIMI Low Energy Magnetospheric Measurement System (LEMMS) instrument did not allow Cassini to establish the existence or non-existence of electron beams along the entire first four orbits, Saur et al. (2006) still demonstrate that the electron beams are only present on parts of Cassini’s orbits within the magnetosphere. Using either a dipole or a model field (Khurana et al. 2005) based on Voyager and Cassini data, the electron beams are shown to map within the general region of the UV aurora (see Fig. 12.20). Magnetospheric electron beams can thus be considered as tracers of auroral activity, assuming these are indicative of downward going return currents associated with upward auroral currents. An analogous conclusion has been reached for Jupiter (Mauk and Saur 2007).

Recently, Stallard et al. (2008c) identified a secondary auroral oval in infrared-observations. This secondary oval subcorotates, is located equatorwards of the main auroral oval, and has been argued to be a weak counterpart of Jupiter’s main auroral oval. Observations of electron beams as deep inside as 11RS may be consistent with the observations of this secondary oval.
Mitchell et al. (2009a) have updated the auroral energetic particle picture at Saturn, showing that in addition to the strongly field-aligned electron beams discussed in Saur et al. (2006), upward moving field-aligned energetic ion conics and/or beams are also frequently observed, both in association with the electron beams, and at many times when simultaneous determination of the presence of electron beams could not be made.

These upward going electron beams are not peaked at a specific energy the way downward-directed auroral electrons typically are, but rather follow a power law in energy, from the lower threshold of the measurement to hundreds of kiloelectron-volts. The electron angular distributions may be either unidirectional upward, or bidirectional. Also as discussed in Saur et al. (2006), events such as these were first observed at Earth (e.g., Klumpar 1990; Carlson et al. 1998), and mechanisms for their generation were proposed by Carlson et al. (1998), Klumpar (1990), Marklund et al. (2001), and Ergun et al. (1998). The FAST satellite measurements described by Carlson et al. (1998) showed a close correspondence between upward-going energetic electron beams, upward-going ion conics, and enhanced broadband electromagnetic noise. The authors showed that all of these phenomena were located within a region of downward field-aligned current in the auroral zone Birkeland current system. At Jupiter, Mauk and Saur (2007) found that the beams mapped to regions of bright aurora, and so concluded that such bright regions, generally accepted to be associated with upward field-aligned current, must have regions of downward current intermixed.

At Saturn Mitchell et al. (2009a) show that the particle energies are higher than those typical at Earth by a factor of up to 100. They show that the composition of the ion conics indicate a likely ionospheric source for the accelerated ions. They describe two classes of field-aligned events; the first class is different from the observations at Jupiter, based on their steady appearance over hours of observation time, and are consistent with extensive, contiguous low altitude acceleration, presumably in regions of downward field-aligned current. A second class of events appears temporally pulsed, with a repetition rate on the order of 1 h.

Figure 12.21 is from an event on day 288 of 2006. Cassini was at 28.3R₉, 42° north latitude, dipole L ~51, and 2220 h local time. During the hours 1900 to 2400 UT the spacecraft was rolling about an axis chosen for fields and particles measurements, which for the measured field orientation allowed both the MIMI LEMMS and INCA sensors to sample nearly complete pitch angle distributions of energetic ions and electrons. In the top panel of Fig. 12.21 we display 100 keV electron counting rates from each end of the double-ended LEMMS telescope. Although this roll permits LEMMS to measure electrons over all pitch angles except those between
Fig. 12.20 Location of electron beams mapped into Saturn’s ionosphere. Auroral images are from Gérard et al. (2004). Yellow data points are calculated with a dipole magnetic field model and red data points are calculated with a magnetic field model from Khurana et al. (2005). Note, for the time intervals when the electron beam measurements were made no simultaneous auroral images are available (from Saur et al. 2006).

~75° and 105°, the only elevated fluxes appear near 0° pitch angle. An electron spectrogram (second panel) shows that the energy of these field-aligned electrons routinely extends to >100 keV, sometimes reaching nearly 1 MeV. Note also that except when the sensor can view near 0° pitch angle, the intensities are at detector background. Mitchell et al. (2009a) show that the electron angular distribution is consistent with an acceleration altitude under 3RS, and likely much closer to 1RS. The electron energy flux in the beam is nearly flat out to ~600 keV, indicating a process in the source region capable of accelerating electrons to that energy. Energetic ion data from the INCA sensor for the same event showed an upward going, field-aligned ion beam with composition consistent with an ionospheric source.

From hour 0700 to 1100 on day 269, 2006 Cassini moved from 8 to 10RS, and from 11 < L < 15. In Fig. 12.22 the top panel shows electrons with energies between 200 keV and 1 MeV. LEMMS is oriented perpendicular to the magnetic field, so the pulsed enhancements are all at 90° pitch angle (not beams). Below that hydrogen intensities measured by INCA are shown. The intensities rise at 0730 as a spacecraft maneuver moves the sun out of the INCA field of view, and the INCA voltages are turned up. Four times over the next 3 h the INCA high energy proton intensities rise (lower energy protons are electrostatically excluded by the ion rejection plates). Below each proton intensification, angle–angle plots of the highest energy channel are displayed. In each case, a distinctly (upward) field-aligned intensification is evident. Below this plot, the magnetic field angles and magnitude appear. The field angles exhibit abrupt changes by ~2° to 3°, then return to their pre-pulse values. This behavior is consistent with the repeated passage of field-aligned current structures. The upward direction of the ions is consistent with upward directed currents and consistent with regions where electrons could be accelerated (at lower altitudes) into the atmosphere exciting the auroral emissions even though the spacecraft is too high to observe the accelerated electrons. The bottom panel shows broadband electromagnetic wave enhancements, again well correlated with the field-aligned currents, upward ion beams, and electron enhancements. Most of the wave energy in these broadband bursts lies below the electron cyclotron frequency $f_{ce}$ signified by the white trace and are electromagnetic, propagating in the whistler mode. The whistler mode cannot propagate above $f_{ce}$, however, so the emissions above $f_{ce}$ in this example cannot be whistler modes. In fact, no magnetic component is measured above the cyclotron frequency, suggesting an electrostatic mode.

A survey of all of the mission data to date reveals many instances where there is correspondence between electron and ion beams, in similar regions of space (high latitude, relatively low altitude, L > 10). In this case, we suggest that the (very weak) electron enhancements, whose timing is slightly later than the onset of the ion beams, are back-scattered from field irregularities much farther out the flux tube, from electron beams similar to those described in Fig. 12.21.

An event on day 284, 2006, unlike the one on day 269, remains steady over periods of an hour or more, and continues to reappear for over 7 h. Again, as in the earlier events, there is no evidence for heavier ions (e.g., oxygen or water
Fig. 12.21 Energetic electron beam characteristics. Top panel shows the time history of 100 keV electrons measured in opposite facing telescopes on the LEMMS sensor as the spacecraft spin sweeps the sensor through various angles with respect to the magnetic field. The sensors are counting near background except when they sample near $0^\circ$ pitch angle. Second panel shows electron intensity as a function of time and energy. Spikes appear when the sensor samples $0^\circ$ pitch angle. Lower left provides a quantitative plot of the electron pitch angles. Since the detector cone has a $7.5^\circ$ half angle, the data are consistent with electrons confined to $<3^\circ$ from the magnetic field. On the lower right, the electron energy flux in the highest spike shows significant energy up to 700 keV (from Mitchell et al. 2009a).

ENA imaging just prior to and just following the event on day 284 reveals a locus of bright hydrogen emission from the south polar region, absent in oxygen. In Fig. 12.23a and b, this emission is clear, along with the usual emission from the ring current beyond the outer edge of the E-ring (cut off by the edges of the INCA field of view). Mitchell et al. (2009a) suggest that the hydrogen emission is generated as protons that are accelerated at low altitude above the auroral zone by wave particle interactions, generating ion conics (the same mechanism invoked in Carlson et al. (1998)). Other instances of this emission have been observed, but only when Cassini is located at latitudes consistent with the pitch angles of upward going proton conics as they charge exchange in products) in these beams. They are consistent with hydrogen, or possibly H$_2$ or H$_3$. As before, they appear as field-aligned, upward moving beams.
Fig. 12.22 Pulsed particle acceleration events, day 269, 2006. Top panel shows energetic electron enhancements, 200 keV to 1 MeV from MIMI LEMMS. Second panel shows time vs average intensity over the INCA FOV for eight hydrogen energy channels. Lower energies are neutrals, but sufficiently energetic ions enter through the INCA ion rejection plates. Angular plots of ion intensity with pitch angle contours appear beneath each peak in intensity. The magnetic field (third panel) shows sharp angular variations associated with each electron and ion enhancement. Broad band electromagnetic (below white line, $f_\omega$) and electrostatic noise (above $f_\omega$) (from RPWS, bottom panel) also aligns with these events (from Mitchell et al. 2009a)
Saturn’s exospheric hydrogen and convert to neutral atoms. The emission is sufficiently weak and localized that it is only seen when Cassini is at relatively low altitudes, as in these cases.

The events presented above are all similar in most respects to the events analyzed by Carlson et al. (1998), which they attributed to perpendicular wave-particle acceleration and electrostatic confinement of ions and upward field-aligned acceleration of electrons in downward field-aligned auroral currents. The whistler mode emissions shown are consistent with VLF saucers found in the FAST observations in downward field-aligned current regimes even though the Cassini observations to date do not have sufficient resolution to show the characteristic saucer-shaped dynamic spectrum. However, Poynting flux measurements show that the waves propagate away from Saturn, consistent with the direction of the electron beams. Although the magnetic field strength in the auroral zone is similar for Earth and Saturn, the distance scale as measured by the planetary radius at Saturn is roughly 10 times that of Earth. Mitchell et al. (2009a) suggest that the magnitude of the total potential drop along an auroral field line is approximately proportional to the square of the distance scale, as the observed peak energies of the accelerated ions and electrons produced by this mechanism are roughly 100 times higher at Saturn than at Earth. At Earth, the up-going electron beams have peak energies in the vicinity of 5 keV, at Saturn up to or above 500 keV. At Earth, the ion conics have peak energies around 100 eV to 2 keV; at Saturn the ion conics have peak energies from 30 to above 200 keV. While the differential energy flux in the events studied by Carlson et al. (1998) is an order of magnitude higher than that in the events at Saturn (consistent with higher electron densities in the events at Earth), the total energy flux integrated over energy for the electron beams at Saturn exceed those at Earth by about one order of magnitude.

Neither the ion nor the electron beams have been observed for dipole L < 9. The electron beams may be either unidirectional upward, or bidirectional (as in Saur et al. 2006), even for large L. Unidirectional downward electron beams have not been observed. The ion beams and conics are exclusively upward.

These observations have been at altitudes of ~6RS and higher. The altitude at which the particles are accelerated is likely to be much closer to the ionosphere, as the reason for the development of the field-aligned potentials responsible for the acceleration of the electron beams is that the magnetospheric circuit is demanding current through what would otherwise be a near-vacuum region. The ionospheric electrons are the only large reservoir of charge carriers available, but they cannot supply the current without an accompanying ion population that can maintain charge quasi-neutrality, and the ionospheric ions are cold and gravitationally bound. A few ions at sufficiently high altitude are accelerated perpendicular to the field by perpendicular stochastic electric field fluctuations and move upward along the field aided by the mirror force. A similar density of electrons can accompany those ions, and the electrostatic shock structure responsible for the field-aligned potential energizes those electrons, until their motion can supply the current required by the system. Of course, that same structure confines the ion conics, so that the ions cannot escape their acceleration region until their parallel energy exceeds the parallel potential that confines them. As discussed in Carlson et al. (1998), this results in a characteristic lower limit to the ion conic energy, and should also result in a larger cone opening angle with increasing energy. In Saturn’s case, the low atmospheric and ionospheric scale heights mean that the ion acceleration process takes place in regions of lower ion density than the equivalent
regions at Earth, so higher potentials are required to provide enough current from the consequently lower density of electrons permitted by quasi-neutrality, hence the much higher energies developed in these populations for downward current regions at Saturn. At the altitudes where most of the ion events have been measured, the conic opening angle is usually too narrow to resolve, and so the conic angle energy dependence has not been well identified in these events.

The ENA images of the ion conic generation region further confirm the process taking place relatively close to the auroral zone. The characteristic ENA emission from this region (Fig. 12.23a and b) cannot constrain the location precisely, because the instrument angular resolution is insufficient at the distances obtained to date. Because the neutral emission decreases with altitude due to decreasing Saturn exospheric gas density that serves as a charge exchange medium, and because as the conic angle collapses about the field with increasing altitude, the trajectories of any ENA produced would no longer intersect the spacecraft. However, it is clear from these images that the light ions reach energies of at least 100 keV in a region not more than 1\( R_S \) above the surface (there is no indication of a heavy ion component, such as water products, methane or nitrogen in either the ion conics or the ENA emission).

### 12.4.2 Auroral Currents

A subset of the January 2007 HST campaign data discussed in Section 12.2.2.1 has been studied by Bunce et al. (2008a), and formed the basis of the subsequent modeling comparison recently discussed by Cowley et al. (2008) and Clarke et al. (2009). These observations are summarized in Fig. 12.24.

![Fig. 12.24](image)

Figure 12.24 shows the HST data from two consecutive observations by the HST (Observation A at \( 05:36\) UT ‘Saturn time’ on 16 January, and Observation B at \( 03:26\) UT on 17 January). During the interval of interest, the magnetically mapped footprint of Cassini traversed magnetic field lines mapping to Saturn’s southern auroral oval, from poleward to equatorward of the auroral oval in the noon sector between the two consecutive observations. Figure 12.25 shows the magnetic field and plasma electron data from Cassini during Revolution 37, for a 48 h interval from 18 UT on 15 January to 12 UT on the 17 January encompassing the HST interval above, as indicated by the vertical dashed lines in the figure. The top panel of Fig. 12.25 shows a thermal electron spectrogram from ELS in the energy range \( \sim 0.5\) eV to 26 keV color coded according to the scale on the right. The four panels beneath this then show the electron bulk parameters, the electron density \( N_e \), the thermal energy \( W_{th e} \), the field-aligned current density associated with the motion of electrons in one direction along the magnetic field lines \( j_{|| e} \), and the corresponding field-aligned electron energy flux \( E_{fe} \). These latter two quantities correspond to the current and energy flux delivered by the precipitating electrons to the ionosphere. The scale on the right hand side of the energy flux panel shows the estimated resulting UV emission, on the assumption that 1 m \( \text{Wm}^{-2} \) produces \( \sim 10\) kR of UV aurora. The Cassini magnetic field data are shown beneath the CAPS-ELS data, and for comparison the red line shows the ‘Cassini’ planetary field model (Dougherty et al. 2005). The UV intensity at the spacecraft footprint in the southern hemisphere obtained at the time of the two observations A and B is shown at the bottom of Fig. 12.25, where the red line
Fig. 12.25 Overview of Cassini plasma electron and magnetic field observations obtained during a 48 h interval on Rev 37 (January 2007), spanning two consecutive HST observations discussed by Bunce et al. (2008a). The top five panels show electron data obtained by the Cassini CAPS-ELS instrument, specifically an electron spectrogram from ~0.6 eV to ~26 keV color-coded according to the scale on the right (the counts at low energies are mainly spacecraft photoelectrons), followed by plots of bulk parameters obtained by numerical integration over the electron distribution assuming the distribution is isotropic. Bulk parameters values are not shown before ~10 UT on 16 January due to low electron fluxes resulting in low measurement signal-to-noise. The bulk parameters shown are the electron density, the thermal energy, the current density of electrons moving in one direction along the field lines, and the corresponding field-aligned energy flux of these electrons. The right-hand scale on the energy flux panel show the corresponding UV auroral emission expected of these electrons precipitate into the atmosphere unmodified by the field-aligned acceleration. The sixth to eighth panels show the three components of the magnetic field in spherical polar coordinates referenced to the planet’s spin and magnetic axis. The red dashed lines in the $B_r$ and $B_t$ panels show the internal field model of Dougherty et al. (2005). The bottom panel shows the UV auroral intensity at the ionospheric footprint of the spacecraft in the southern hemisphere obtained from the two HST image times A (red) and B (blue). Spacecraft position data are given at the foot of the plot. Taken from Cowley et al. (2008)
shows the UV intensity from observation A, and the blue line shows observation B. The peaks in the emission lines indicate where the spacecraft footprint crosses the auroral oval in each observation.

The time between the two observations (indicated by the dashed lines) labeled A and B at the top of Fig. 12.25 thus spans the crossing of the auroral oval. As discussed above, at the time of observation A the spacecraft footprint was well inside the auroral oval on the dawnside, evidenced by the low intensities in the red trace. At this time one sees a lack of measurable electron fluxes, and quiet magnetic field components, as had been the case for some ~40 h previously. These conditions imply the spacecraft was on open field lines in the regions poleward of the main auroral oval, mapping to Saturn’s southern tail lobe. At ~10 UT on 16 January, prior to observation B, the spacecraft detected intense fluxes of warm electrons and the field components became disturbed. First a population of cool magnetosheath-like electrons is observed interspersed with hot keV electrons, followed after ~21 UT by a more continuous population of hot electrons, typical of the dayside outer magnetosphere. These field and plasma data indicate that the spacecraft crossed the open closed field line boundary between the tail lobe and the outer dayside magnetosphere, in the region of the dayside cusp near noon. In addition, throughout the time on open field lines poleward of the cusp a strong positive $B_y$ component of the field is seen, despite the rotational symmetry of the internal planetary field. This positive $B_y$ component may be interpreted as sub-corotation of the open field line region as suggested by Cowley et al. (2004a), and as observed in IR data by Stallard et al. (2004). As the spacecraft moves through the cusp region, the positive azimuthal field component, with significant spatial or temporal structure, drops to near-zero values on the closed side of the boundary. The near-zero values of azimuthal field in the southern hemisphere may then be indicative of near-rigid corotation of the outer magnetospheric closed field region. This is the magnetic signature of a major layer of upward-directed field-aligned current. They show the total current flowing in the layer is ~4–5 MA per radian of azimuth, over an estimated width in the ionosphere of 1.5–2° in the ionosphere, the field-aligned current density just above the ionosphere is estimated to be ~275 nA m$^{-2}$. As can be seen in the fourth panel, this current density value exceeds that which can be provided by the flux of magnetospheric electrons alone, such that an acceleration mechanism is required.

Using Knight’s (1973) kinetic theory Bunce et al. (2008a) show that the minimum accelerating voltages required to produce 275 nA m$^{-2}$ is typically <1 kV for the cool dense sheath plasma, rising to 10 kV for the warm tenuous plasma populations. These voltages are sufficient to amplify the precipitating electron energy flux to values capable of producing emissions of 1–5 kR for cool dense populations, and 10–50 kR for the warm tenuous outer magnetosphere populations. This is excellent agreement with the peak intensities which are observed of ~15–20 kR shown in the bottom panel of Fig. 12.25.

Talboys et al. (2009) have identified seven periapsis passes from the high-latitude phase of the Cassini mission between mid-2006 and mid-2007 during which the azimuthal magnetic field component exhibits similar signatures of field-aligned currents (FACs) flowing between the magnetosphere and ionosphere. In general terms, the southern hemisphere exhibits an intense layer of upward-directed FAC which occurs on closed field lines in the dawn and pre-noon sector immediately adjacent to the open-closed field line boundary as the strongly ‘lagging’ field consistently observed on southern open field lines first declines, and then (usually) reverses to a ‘leading’ configuration. ‘Lagging’ and ‘leading’ fields are generally indicative of plasma sub- and super-corotation, respectively. These ‘leading’ fields then decline sharply to smaller values further inside the boundary, indicative of intense downward FACs as the plasma reverts to near-corotational flow, the magnitude of the field change being dependent on the phase of the planetary-period oscillation in the interior region. Talboys et al. (2009) show that the region of upward current is co-located with the statistical UV auroral oval of Badman et al. (2006), while the downward current immediately equatorward maps to the outer ring current in the equatorial magnetosphere. In the dusk and pre-midnight northern hemisphere, however, only weak azimuthal fields are observed on open field lines, while stronger ‘lagging’ fields are observed immediately equatorward in the closed field region, indicative of downward current just inside the open-closed field line boundary, and upward current in the interior region where this layer interfaces with the region containing the planetary-period oscillations. A similar study of the more recent high-latitude passes is ongoing.

Recent work on Jupiter’s aurora (Ray et al. 2009) uses a Vlasov code to examine the current–voltage relationship in the aurora of Jupiter, which like Saturn, is a rapidly rotating gas giant with centrifugally-confined plasma. The confinement of heavy ions to low latitudes restricts the motion of electrons due to the ambipolar electric field. For the situation at Jupiter, these authors suggest that the Knight relation does not apply and they conclude that the electron density is not a monotone function along the field, leading to a non-linear current–voltage relationship that depends on the high latitude electron density and temperature. The extension of this work to Saturn should add to the discussion of auroral currents and momentum transfer from the ionosphere to the magnetosphere.
12.5 Solar Wind-Magnetosphere–Ionosphere Coupling Currents and Their Relation to Saturn’s Aurora

In this section a theoretical framework into which Saturn’s auroral observations may be placed is discussed, relating directly to the global plasma flows and current systems which are expected to be present in Saturn’s magnetosphere. First, the basic steady-state picture suggested by Cowley et al. (2004a, b) is introduced. Then, subsequent alterations to the model parameters are discussed based on the previous discussion of the high-latitude auroral field-aligned currents during Orbit 37. Finally, the observed highly dynamic nature of Saturn’s aurora and related SKR emissions are compared to particular aspects of the solar wind-magnetosphere interaction at Saturn, and the variations of the model as a consequence of the changing upstream solar wind conditions are discussed.

12.5.1 Proposed Steady-State Theoretical Framework

A global view of a planet’s auroral region provides an instantaneous picture of the state of the magnetosphere, mapped along magnetic field lines into the upper atmosphere. Typically, planetary auroras consist of two components: broad regions (in latitude) of lower intensity “diffuse” emissions produced through unmodified precipitation of magnetospheric plasma, and localized regions of more intense “discrete” auroral arcs associated with field-aligned currents and field-aligned acceleration of the current carrying particles. As such, to build a theoretical framework in which to consider the origin of the overall auroral emission region, one must incorporate a general view of the basic plasma flows and resulting field-aligned current systems that are expected to be present within the magnetosphere, and consider the requirements for field-aligned acceleration. At the giant planets, discrete auroral arcs will appear where field-aligned currents are directed upwards out of the ionosphere in regions where the plasma angular velocity is falling with increasing latitude (or equivalently increasing equatorial radial distance in the magnetosphere).

During the Voyager fly-bys some 30 years ago, it was evident from Saturn kilometric radiation observations from upstream of Saturn that the signal was modulated both by the planetary rotation rate and with solar wind dynamic pressure, and this has been studied more recently with recent joint HST/Cassini campaigns (see Section 12.3.1 and references therein). From a theoretical standpoint therefore, two major aspects of large-scale magnetospheric dynamics must be considered along with their mutual interaction. The first is the dynamics of plasma flows relating to the transfer of angular momentum from the ionosphere to the magnetosphere, associated with planetary rotation, in combination with continuous input of plasma mass to the magnetosphere from moon atmospheres and surfaces, and from ring grains. Such plasma is added into the magnetosphere in the inner regions, and is subsequently picked up by the rotational flow of the magnetosphere. This inner region is shown in the central part of Fig. 12.26a, where the plasma approximately corotates with the planet, as a result of ion–neutral collisions at the ionospheric feet of the magnetic field lines. Voyager observations showed that the flow was near-rigid to $\sim 5R_S$, beyond which the plasma angular velocity falls with increasing radial distance to $\sim 1/2$ of rigid corotation within several $R_S$ of the dayside magnetopause (Richardson 1986, 1995; Richardson and Sittler 1990). Wilson et al. (2008) analyses of Cassini data show similar trends. This fall in angular velocity is thought to be associated with the addition of mass from internal sources as discussed above, and the subsequent outward transport via radial diffusion and loss in the downtail regions. The plasma is subsequently lost by some release process in the outer magnetosphere. Vasyliunas (1983) suggested that the mass-loaded flux tubes in the outer part of the corotating region would be confined by the effects of the solar wind pressure compressing the dayside magnetosphere, but may stretch out into the down-tail regions of the duskside magnetosphere as they rotate around. This subcorotating region is shown in Fig. 12.26a and is bounded on the outside by an outer region (beyond the dashed line), where the variable loss of plasma downtail takes place. This process is commonly referred to as the Vasyliunas cycle, and was first suggested to be an important mass-loss process within the Jovian magnetosphere. Following reconnection of the closed stretched-out field lines in the dusk sector, the mass-reduced flux tubes contract towards the planet due to the tension force and to conserve angular momentum, and thus rotate back to the dayside with increased angular velocity. As they do so, they reload with plasma from the inner regions and subsequently slow once more. The process repeats as the flux tubes reach the dusk sector of the magnetosphere. While in this steady-state picture the Vasyliunas process has been shown as continuous, it seems likely that the reconnection and plasmoid release could be episodic, and possibly triggered by both internal and external mechanisms.

The second aspect of magnetospheric dynamics to be considered is that which is associated with the solar wind interaction with the magnetosphere, producing a large-scale cyclical flow within the magnetosphere. This process was first discussed in the context of the Earth by Dungey (1961), and is known as the Dungey cycle. The outermost region confined to the dawnside in Fig. 12.26a depicts the flows associated with the solar wind interaction, and the Dungey cycle...
Fig. 12.26 (a) Sketch of the plasma flow in the equatorial plane of Saturn’s magnetosphere, where the direction of the Sun is towards the bottom of the diagram, dawn is to the left and dusk is to the right. Arrowed solid lines indicate plasma streamlines, arrowed short-dashed lines show the boundaries between flow regimes (which are also streamlines of the plasma flow), the solid lines joined by X’s the reconnection lines associated with the Dungey cycle, and the dashed lines with X’s representing the reconnection associated with the Vasyliunas cycle. The two lines are shown as contiguous, but this is not necessarily the case. The lines indicated by ‘O’ marks the path of the plasmoid O-line in the Vasyliunas-cycle flow (also a streamline), while ‘P’ marks the outer limit of the plasmoid field lines, which eventually approaches the dusk magnetopause asymptotically. (b) Sketch of the plasma flow in the northern ionosphere, where the direction toward the Sun is at the bottom of the diagram, dawn is to the left, and dusk is to the right. The outermost circle corresponds to ionospheric co-latitudes of $\sim 30^\circ$ from the magnetic pole, which maps to an equatorial radial distance of $\sim 3R_S$. Circled dots and crosses indicate regions of upward and downward field-aligned current, respectively, as indicated by the divergence of the horizontal ionospheric current. Hall currents flow generally anticlockwise round the pole and close within the ionosphere, while Pedersen currents flow generally equatorward and close in the field-aligned current system shown (taken from Cowley et al. 2004a)
for Saturn. Reconnection at the dayside magnetopause occurs principally when the IMF points northward, opposite to Saturn’s southward directed planetary field. Following reconnection on the dayside, open field lines move anti-sunward over the polar cap (out of the plane of the diagram), and eventually sink into the magnetotail. Magnetic flux tubes are expected to remain open for up to ~8 days (Jackman et al. 2004), during which time they expel the mass which was previously trapped on them. Closure of the open magnetic flux tubes takes place via reconnection in the tail, and the newly closed and emptied flux tubes then return to the dayside magnetosphere via dawn due to the presence of the Vasylunias cycle at dusk and the action of the planetary rotational torque exerted. The emptied flux tubes may now rotate through this “corridor” in the outer magnetosphere with an increased angular velocity, and with an admixture of hot magnetospheric and solar wind plasma accelerated into the magnetosphere from the reconnection site (Badman and Cowley 2007). Once the magnetic field lines return to the dayside the process repeats.

Figure 12.26b shows the flow regimes discussed above mapped to the northern ionosphere, where the field-aligned current directions may also be depicted. Beyond a radial distance of ~3R₅ the angular velocity falls from near-rigid corotation with increasing radial distance, and decreasing ionospheric co-latitude, to ~1/2 of rigid corotation at the boundary of the outer magnetosphere containing the Vasylunias cycle on closed field lines. At lower co-latitudes still lies the outer magnetosphere which is bounded by the second dashed streamline, which represents the open-closed field line boundary formed through reconnection at the dayside Dungey-cycle X-line. This outer magnetosphere region contains both the Vasylunias-cycle flow in the lower-latitude portion, and the Dungey-cycle “return” flows at higher latitudes on the dawnside, the latter flowing from the nightside to the dayside reconnection regions (merging gaps) lying on the open-closed field line boundary. In the dawn sector the flows in this region are expected to be higher than in the adjacent magnetosphere due to the lower mass-loading of these flux tubes, but will slow again to the speed of the middle magnetosphere in the dusk sector due to the subsequent refilling of the flux tubes through diffusive mass loading in the Vasylunias cycle.

The central open flux regions in Fig. 12.26b extend from ~15° co-latitude to the pole (e.g. Cowley et al. 2004b). The flows which are expected to exist within the polar cap are due to two effects; the flows associated with rotational circulation driven by ion–neutral collisions in the ionosphere twisting the open field lines (Isbell et al. 1984; Milan et al. 2005), and cyclical flows associated with the Dungey-cycle. Recent ground based Doppler observations of ionospheric IR emissions by Stallard et al. (2004) indicate plasma angular velocities of ~1/3 of rigid corotation, implying a Pedersen conductance of ~0.5–1 mho (compared to values of 1–2 mho derived from Voyager data by Bunce et al. 2003). When the Dungey cycle is also active, anti-sunward flow occurs between the “merging gaps” on the open-closed field line boundary, these flows add vectorially to the sub-corotational flow on open field lines discussed above giving the streamlines shown in Fig. 12.26b. Overall, the Dungey cycle flows are contained within the polar cap region, and coincide with the dashed line at dusk (the open-closed field line boundary) in Fig. 12.26b, while the return flows are confined preferentially to the dawn sector as discussed with reference to Fig. 12.26a. Finally these flow patterns are related to the aurora by considering the field-aligned current patterns which are produced and their relative importance. In Fig. 12.26b a two-ring pattern of upward field-aligned currents is driven by the implied divergence of the horizontal ionospheric current, and one would anticipate the presence of discrete auroral arcs either at the feet of the field lines connecting to the middle magnetosphere (as in the case of the main Jovian auroral oval) or at the open-closed field line boundary (more like the scenario at the Earth).

Figure 12.27 shows the quantitative results of the recently augmented theoretical model of Cowley et al. (2008), based on new Cassini and HST results to be discussed below. Full details of the model are given in the paper, and as such only an outline of the method used will be given here. The basic ingredients of a quantitative analysis of the qualitative picture represented in Fig. 12.26 are essentially simple, based on an initial assumption of axi-symmetry of the magnetic field and plasma flow. First, a model of the plasma angular velocity on magnetospheric magnetic field lines is conceived, based on a combination of results from the Voyager plasma velocity data and theoretical considerations. A simple model of the internal magnetic field (e.g. the Cassini model (Dougherty et al. 2005)) plus ring current contribution (Connerney et al. 1983), provides a mapped angular velocity profile in the ionosphere (shown in Fig. 12.27a). The profile indicates a fall from rigid corotation at lowest co-latitudes (closest to the planet) to approximately 60% of rigid corotation at the boundary between the middle and outer magnetosphere. The profile then rises in the outer magnetosphere (in the region where the flux tubes have been emptied during reconnection episodes in the tail) and peak at 80% of rigid corotation at the outermost regions of the magnetosphere. Across the open closed field line boundary, the angular velocity of the plasma sharply falls, reaching a steady value of 30% of rigid corotation across the polar cap on open field lines.

The ionospheric angular velocity profile is then combined with model ionospheric parameters (i.e. the Pedersen conductivity) to derive the horizontal ionospheric Pedersen current intensity as a function of co-latitude (Fig. 12.27b). With increasing co-latitude from the magnetic pole the Pedersen current intensity increases monotonically to a value
Fig. 12.27 Parameters of the Cowley et al. (2004) model of magnetosphere–ionosphere coupling at Saturn plotted versus co-latitude $\theta_i$ in the ionosphere for the northern (dashed lines) and southern hemispheres (solid lines), the latter relative to the southern pole. Note that the plots shown here employ updated internal magnetic field and angular velocity values compared to Cowley et al. (2004b), as described in Cowley et al. (2008), but that these result in insignificant variations at the 1% level. The panels of the figure show (a) the plasma angular velocity normalized to the planet’s angular velocity, where the horizontal dashed line represents rigid corotation, (b) the equatorward-directed horizontal ionospheric Pedersen current per radian of azimuth, obtained using an effective Pedersen conductivity of 1 mho, and (c) the field-aligned current density just above the ionosphere required by the divergence of the horizontal Pedersen current, where positive and negative values indicate upward and downward-directed currents, respectively, in both hemispheres (adapted from Cowley et al. 2008).

The current intensity then falls rapidly across this boundary, where the angular velocity increases, and then grows once again with increasing co-latitude through the outer and middle magnetosphere regions. As rigid corotation is reached at largest co-latitudes the ionospheric Pedersen current falls to zero.

Taking the divergence of the Pedersen current intensity gives the field-aligned current density just above the ionosphere (Fig. 12.27c) which is required from current continuity. The profile shows that the field-aligned current is directed downward into the ionosphere (negative values) where the Pedersen current is increasing with co-latitude from the pole, and directed upward out of the ionosphere (positive) where the Pedersen current profile is falling. The model estimates show weak downward currents within the region of open field lines across the polar cap at a constant level of $\sim15\text{ nA m}^{-2}$, bounded at the open-closed field line boundary by strong upward directed field-aligned currents across a narrow layer (i.e. between $\sim14^\circ$ and $15^\circ$ co-latitude in the southern hemisphere) at the level of $\sim100\text{ nA m}^{-2}$. Stronger peaks of downward currents ($\sim50\text{ nA m}^{-2}$ near to $\sim17^\circ$–$18^\circ$ co-latitude in the southern hemisphere) are seen further equatorward in the boundary between the outer and middle magnetosphere, followed by a weaker distributed upward current throughout the middle magnetosphere (with a peak value $\sim10\text{ nA m}^{-2}$ at $\sim23^\circ$ co-latitude). The auroral acceleration parameters may be calculated using Knight’s (1973) kinetic theory and a model of the magnetospheric source electron parameters.

Therefore, the modeling studies have concluded that the field-aligned currents in the middle magnetosphere are too weak to require significant acceleration, and will not result in significant auroral output. They also occur at too low a co-latitude to account for the main UV emissions (Clarke et al. 2005; Grodent et al. 2005; Badman et al. 2006). However, Stallard et al. (2008c) have recently shown that at infrared wavelengths a weak oval does exist in regions which map to the middle magnetosphere, and is suggested to be the equivalent of the main auroral oval at Jupiter (see Section 12.2.2.5). Overall though, the large flow shear which occurs at the boundary between open field lines which
strongly sub-corotate (Isbell et al. 1984; Stallard et al. 2003, 2004), and closed field lines moderately sub-corotating in the outer magnetosphere, is at the right co-latitude in the ionosphere to account for Saturn’s main auroral oval (Badman et al. 2005), and is plausible in terms of accelerated electron and auroral parameters (Cowley et al. 2004b; Jackman and Cowley 2006). An opposing theory by Sittler et al. (2006) proposes that the auroral oval is produced by plasma heating and acceleration associated with the interchange instability at the outer edge of the plasma sheet. In this case upward field-aligned currents associated with the main oval should map to the closed field region at ~15R_S in the equatorial plane. However, this distance maps to ~16° in the southern hemisphere ionosphere according to the “typical” model of Bunce et al. (2008b), and thus corresponds to the region of downward field-aligned currents shown in Fig. 12.27c.

As discussed in Section 12.2.2.2, Badman et al. (2006) have determined the average location of Saturn’s main auroral oval in the southern hemisphere from multiple UV images obtained by the HST. Their results indicate that the median location of the oval in the southern hemisphere near the dawn sector is ~14° co-latitude, and thus maps to the outer magnetosphere near the magnetopause, well beyond the middle magnetosphere corotation breakdown region (Bunce et al. 2008b). Therefore, the results of Badman et al. (2006) suggest that the auroral oval is unlikely to be associated with the magnetosphere–ionosphere coupling currents of the middle magnetosphere, but cannot clearly discriminate between the proposed positions of the aurora by Cowley et al. (2004a, b) and Sittler et al. (2006). As discussed in Section 12.4.2, above, during the initial high-inclination phase of the Cassini orbital tour in 2006, the first in situ observations of the high-latitude magnetosphere have been obtained, with coordinated HST imaging. Section 12.4.2 presented an overview of these unique observations and compared the results with the quantitative modeling of Cowley et al. (2004a, b) outlined above.

The observations presented in Section 12.4.2 are in good qualitative agreement with the model of Cowley et al. (2004b). However, Cowley et al. (2008) have compared the model predictions in a quantitative sense, and have found that while the model values are in good general agreement there are three main differences. The first is the location of the open-closed field line boundary, which occurs at ~14° co-latitude in the model whereas the observations place the boundary closer to 12° co-latitude. Second, in the model the switch in the azimuthal B_phi component takes place quasi-monotonically from positive to near-zero, whilst the observations show switching back and forth indicative of multiple spatial structures, or a single oscillating layer. Finally, the magnitude of the B_phi signature in the model peaks at ~2 nT, while the observations show that B_phi grows to a peak value of ~10 nT just poleward of the open-closed field line boundary. As a result the model gives a total upward field-aligned current of 0.8 MA rad^{-1} flowing in a layer ~0.5° wide, producing a field-aligned current density of 150 nA m^{-2}, compared to 4–5 MA rad^{-1}, 1.5–2°, and 275 nA m^{-2} as derived from the magnetic field observations. Cowley et al. (2008) find that simple and realistic alterations to the model achieve excellent results. They relocate the open-closed field line boundary to 12°, widen the current layer to agree with the observations, and to increase the intensity of the field-aligned current they set the angular velocity such that the open field lines do not rotate at all in the inertial frame, and increase the conductivity of the southern ionosphere by a factor of 4 (from 1 to 4 mho). Cowley et al. (2008) suggest that the main difference between the observations and the model is due to the higher conducting summer hemisphere than was previously assumed in the original model formulation. The revised model is now in excellent agreement with the Cassini-HST data, requiring downward acceleration of outer magnetosphere electrons through ~10 kV potential in the current layer at the open-closed field line boundary, giving an auroral oval approximately 1° wide, with UV emission intensities of a few tens of kiloRayleighs.

12.5.2 Time-Dependent Auroral Processes

Assuming this basic scenario, where the main auroral oval is associated with a large upward-directed field-aligned current layer at the open closed field line boundary, one would expect to see a significant modulation of the emissions as a result of changing solar wind conditions, and different levels of Dungey-cycle driving versus internal rotational effects. In particular recent coordinated HST and Cassini campaigns (e.g. January 2004) have shown that the aurora responds strongly to upstream conditions, and specifically the solar wind dynamic pressure (Clarke et al. 2005, 2009; Crary et al. 2005; Grodent et al. 2005; Bunce et al. 2006). This behavior also reflects the modulation observed in the SKR emissions (e.g. Desch 1982; Kurth et al. 2005a).

For example, Jackman et al. (2004) have investigated the reconnection-driven interaction of the solar wind with Saturn’s magnetosphere with particular focus on the consequences for magnetospheric dynamics. In this study, interplanetary magnetic field (IMF) data obtained by the Cassini spacecraft en route to Saturn were collected for 8 complete solar rotations which allow the variation of the field structure to be investigated. They find that the solar wind magnetic field structure is consistent with that expected to be produced by corotating interaction regions (CIRs) during the declining phase of the solar cycle. In general the data show that the IMF structure consisted of two sectors during each rotation of the Sun, with crossings of the heliospheric current sheet
generally embedded within few-day high field compression regions, surrounded by several day rarefaction regions.

During the January 2004 HST campaign (as discussed in Sections 12.2.2.1 and 12.3.1), an impact of a major CIR related solar disturbance was measured by Cassini and the effects on Saturn’s magnetosphere were observed by HST. Cowley et al. (2005) have suggested that the bright auroral displays towards the end of the observation interval are triggered by the collapse of Saturn’s magnetic tail in response to the impact of the compression region on Saturn’s magnetosphere. Figure 12.13 shows the last four visits (a–d) from the January 2004 HST observation set. Following the start of the compression region the magnetic field strength remains high between ~0.5–2 nT, and the solar wind velocity and density were also raised (Crary et al. 2005; Bunce et al. 2006). Image (b) occurred ~10 h after the onset of the compression. Here, one sees that the dark polar cap which was evident in image (a) has now been filled in with bright aurora. The central dark region in image (b) is significantly contracted with respect to that in image (a), indicative of a significant amount of tail flux closure at some point between the two images. Cowley et al. (2005) have estimated that ~15 GWb of open flux was closed during the first ~10 h of this event, by comparison of image (a) and (b). This implies a reconnection rate of ~400 kV over 10 h, which is considerably larger than the several tens of kV of dayside reconnection estimated by Bunce et al. (2006) during this time, implying that tail reconnection was dominant over dayside reconnection. The expansion of the oval from image (c) to image (d) is then suggestive of the cessation of the tail reconnection, as the system ‘recovers’ and the continuation of rapid dayside reconnection, in keeping with the raised magnetic field strength shown. In the bottom panel the SKR frequency–time spectrogram indicates that the planetary modulated signature seems to switch off after the shock-compression, and is replaced by a high-power burst of SKR which extends down to lower frequencies. However, Ulysses did not observe this switch off, and hence, the missing modulated signal is most likely due to beaming as opposed to skipping a rotation. A second burst of SKR is then eventually followed by the recommencement of the planetary modulated signatures, albeit at somewhat higher powers than prior to the compression region, although returning with the same phase. Bunce et al. (2005a) have also shown that a similar major compression impacted Saturn during the Cassini Saturn Orbit Insertion (SOI) maneuver which took place on 1 July 2004, during the period the spacecraft was inside the magnetosphere. They witnessed the effect of this compression inside the magnetosphere, which represents the counterpart of auroral displays of January 2004. During this time a major burst of SKR was observed, indicating the approximate time that the solar disturbance impacted the magnetosphere. At the same time, Cassini measured a major injection of hot plasma into the magnetosphere from the downtail regions, and a substantial reorientation of the magnetic field structure was seen by the magnetic fields instrument. These signatures are consistent with the suggestion that major solar disturbances impacting the magnetosphere induce the magnetotail of Saturn to suddenly collapse, injecting hot plasma towards the planet. It is this hot plasma which is thought to be directly producing the auroral displays. Overall, it has been suggested that the effects of the CIR shock-compression may be one way to produce the equivalent of the terrestrial substorm at Saturn. Russell et al. (2008) have recently suggested that Titan may also play a role in the triggering of some of the substorm-like events that have been witnessed in the Cassini magnetotail data thus far (Jackman et al. 2007, 2008). Likewise, Menietti et al. (2007) have shown that the occurrence of strong SKR has some dependence on the local time of Titan.

As is well known at the Earth, transient “cusp currents” are associated with time-dependent reconnection at the dayside boundary, and are strongly modulated by the orientation of the IMF. During an interval of purely southwards IMF at the Earth, one observes an interval of transient low latitude reconnection (e.g., Milan et al. 2000). For the case of northwards IMF, high-latitude reconnection occurs between the IMF and already-open field lines in the magnetosphere. These two examples lead to two different types of impulsive flows in the ionosphere. For purely southwards IMF at Earth one would expect an impulsive twin-vortical flow localised near noon, leading to an enhanced upward field-aligned current intensity on the duskside of the main oval. During intervals of northwards IMF the impulsive vortical flows are reversed in sense and shifted poleward of the main oval, leading to an enhanced upward field-aligned current density and bright spot of aurora poleward of the main auroral oval. Milan et al. (2000) present two such examples using data from POLAR-UVI and ground-based ionospheric radars to derive the ionospheric flow directions and velocities, and show that the scenarios described above are evident in the data for different orientations of the IMF.

Pulsed dayside reconnection at Saturn then, is expected to produce similar flows across the open-closed field line boundary, as suggested to explain auroral brightening within the main auroral emission region at Jupiter (Bunce et al. 2004), but at Saturn the localised cusp emission would instead modulate the continuously upward current layer present at the open-closed field line boundary due to the flow shear between the two regimes (discussed above). Bunce et al. (2005b) have produced a variety of model scenarios for Saturn’s cusp including the effects of northward and southward IMF, and varying IMF Bz orientations. An example for purely northward IMF conditions is shown on the left hand of Fig. 12.28, during strong Dungey-cycle driving which produces localised twin vortical flows straddling the open-closed field line boundary superposed on the background flows of
Fig. 12.28 On the left hand side we show a stack plot of electrostatic potential contours (i.e., streamlines of the plasma flow) on the left, and field-aligned current density on the right, for the case of the ‘fast flow’ cusp model, taken from the Bunce et al. (2005b) model. The first row in each case corresponds to the case of $B_z > 0$, and the second to the case of $B_z < 0$ as shown. Both are presented on equivalent grids of $-4000–4000$ km in $y$, and $-6000–6000$ km in $x$. The short-dashed line at $y = 0$ indicates the open-closed field line boundary. On the left, in the plasma streamlines grid the dashed lines show contours of negative electrostatic potential. Contours are labeled in steps of 50 kV. On the right, the field-aligned current grids show dotted lines indicating contours of zero field-aligned current density. Solid lines indicate the regions of upward-directed field-aligned current density while the dashed lines indicate the regions of downward-directed field-aligned current density. Contours are labeled 0.05, 0.1, 0.25, 0.5, 0.75, and 1.0, in units of $\mu$A m$^{-2}$. On the right hand side are two examples of the morphology of Saturn’s southern aurora obtained with the HST-STIS SrF2 filter. Images are projected onto the ionosphere, where the pole is to the centre, and circles of increasing size indicate 80°, 70°, and 60° of latitude respectively. The direction to the Sun is at the bottom of the diagram, dusk is to the right and dawn to the left. Longitude meridians are shown at intervals of 10°. Image (a), taken on the 29th January 2001, shows an auroral oval which is brighter at dawn than at dusk, with an additional brightening in the pre-noon sector. Image (b) shows the high-latitude ‘spot’ discussed in the text (taken from Bunce et al. 2005b).

The same basic steady-state background flows are employed but the high-latitude twin vortical flows are reversed in sense due to the reversed polarity of IMF, by simple analogy with the Earth. This produces a field-aligned current spot poleward of the open-closed field boundary and the main auroral oval currents seen in the middle panel on the bottom row. This agrees well with the second state of the ‘cusp’ emission seen in the HST image to the right taken from Gérard et al. (2005), which shows a significant brightening of the aurora to higher latitudes than is typically expected for the main auroral oval (e.g. Badman et al. 2005).

Badman et al. (2005, 2006) and Cowley et al. (2005) have described the overall auroral images collected during this campaign, and related them directly to the steady-state picture of the flows and currents in the ionosphere, discussed by Cowley et al. (2004a) and shown here in Fig. 12.26. Figure 12.29 shows various pictures throughout the January 2004 campaign, and the suggested modified
Fig. 12.29 On the left hand side, we show sketches in the ionosphere in a similar format to Fig. 12.26, where the direction towards the Sun is at the bottom of each diagram, with dawn to the left, and dusk to the right. The solid line shows the boundary between open and closed field lines, while the dashed lines with arrows show plasma streamlines. The patch of newly-closed flux is indicated by the stippled area, bounded on its equatorward side by the short-dashed line. Circled dots and crosses indicate regions of upward and downward field-aligned currents, respectively. The first two diagrams show the ionospheric consequences of intervals of steady magnetopause and tail reconnection, but where the rates are not equal to each other. In (a) the tail reconnection rate exceeds the dayside rate, while in (b) the dayside rate exceeds the tail rate. (c) illustrates the consequences of an interval of rapid reconnection in the tail, in which a significant fraction of the open flux in the tail lobes is closed on a time scale short compared with the typical period of plasma sub-corotation in the outer magnetosphere (after ~20 h). Panel (c) show conditions in the ionosphere after ~20 h. Dayside reconnection is also in progress in this panel at this time. Finally, panel (d) shows the motion of a patch of newly-opened field lines formed by a burst of reconnection at the dayside magnetopause. On the right hand side we show a series of HST images from the January 2004 campaign, which correspond well to the theoretical pictures on the left, and occur during similar conditions in the solar wind according to the in situ solar wind data measured concurrently by Cassini (adapted from Badman et al. 2005 and Cowley et al. 2005).
flows and current patterns in the ionosphere which result which successfully explain the variety of phenomena which were observed. Figure 12.29a shows the flows and currents for the situation of dayside reconnection only, with an absence of tail reconnection. This leads to an enhanced discrete aurora at dawn, and at the mapped location of the dayside “merging gap”, i.e. the transient cusp currents discussed above. This scenario agrees well with the image taken on 23 January 2004. Figure 12.29b shows the flows and currents suggested by Cowley et al. (2005) to occur in response to compression-induced tail reconnection. In this picture a burst of hot plasma is produced in the tail, resulting in enhanced diffuse and discrete auroral features, as seen in the image to the right taken on the 18 January, following the “minor” compression in the middle of the campaign. Figure 12.29c shows the effects of an interval of strong dayside and nightside reconnection which in tandem produce enhanced discrete aurora at dawn and a spiral of diffuse emission on sub-corotating closed field lines. This is in keeping with the image taken on 28 January (image C in Fig. 12.13). Finally, Fig. 12.29d shows an example of the flows and currents expected in the ionosphere during an interval of intermittent tail reconnection on timescales which are small relative to the planetary rotation period. Under such conditions it is proposed that diffuse patches of aurora will sub-corotate around, lying just equatorward of the open-closed field line boundary. This idea is supported by the image to the right, taken on 14 January during the rarefaction conditions in the solar wind when dayside driving is expected to be minimal.

12.6 Summary

Cassini’s prime mission, coupled with a number of joint campaigns with Earth-based remote sensing, has expanded our knowledge of auroral processes at Saturn. Observationally, Earth-based UV and IR observations have provided a consistent morphology of auroral emissions that characterize both quiet and disturbed times. This morphology is focused on the main auroral oval which is almost always present although it is often incomplete, forming a spiral that does not close upon itself. The oval resides near 70° latitude although when the spiral form is present it often begins in the midnight-dawn sector at latitudes as high as 80° and evolves equatorward as local time increases such that the end of the spiral is equatorward of the beginning, again in the region of midnight. Within this framework, there are often dawn brightenings of the oval and these bright arcs corotate at a fraction of the rotation rate of the magnetosphere, often with the bright spots moving poleward in the afternoon as they fade. Particularly in the infrared observations, there are less organized emissions poleward of the main oval. Disturbed conditions, triggered by solar wind compression regions, result in the poleward expansion of the main oval particularly on the dawn side.

Saturn kilometric radio emissions are generated by the cyclotron maser instability on field lines that thread the aurora. To first order, their power correlates with the power in the UV aurora, although the correlation is not particularly strong. Determinations of the source locations of the SKR clearly show a dependence on the observer’s location, meaning beaming of the radio emissions is important. Hence, while the true correlation between SKR and UV auroral power might be very close to one, a single spacecraft cannot accurately integrate over all of the SKR emission, or may even miss the brightest emission because of its location. There is circumstantial evidence that the strongest sources of SKR are associated with auroral bright spots and move in the corotational sense. However, the brightest SKR sources are usually located between dawn and noon. Similar to the situation with UV emissions, there is evidence of rotation of the SKR sources in detail, but the primary SKR source morphology favors the dawn to noon local time quadrant. Further, the integrated intensity of SKR emissions is temporally modulated by the rotation of the magnetosphere such that the brightest SKR emissions occur, statistically, when the Sun is near 100° SLS3 longitude.

SKR can be observed at all local times, but there is evidence of at least two zones where the emission cannot be seen, that is, regions where an observer is shadowed from the SKR sources. The first of these is at low latitudes close to the planet, within a few Saturn radii. The second of these is at high latitudes to where at least the highest frequency emissions apparently cannot propagate. A more complete picture of the high latitude occlusion zone will come when occurrence studies using the high inclination orbits at the end of the prime mission and the beginning of the Cassini Equinox Mission (extended mission) are analyzed.

The ~75° inclination orbits in 2008 at the end of the prime mission and the early Cassini Equinox Mission provide excellent viewing of the aurora by the remote sensing instruments, including ENA imaging as well as increasingly better views of the northern auroral region by Earth-based instruments. Coupled with in situ measurements by the field and particle instruments on Cassini, this time period provides perhaps the best opportunity to understand extraterrestrial auroral processes until Juno arrives at Jupiter in late 2016. Nevertheless, Cassini’s high latitude passes were typically at distances of 5 and above R$_S$ and too high in altitude to fly through the expected auroral acceleration region. Thus, the electrons observed at this location by Cassini are generally upgoing, implying downward-directed field-aligned currents, which are not directly associated with auroral emissions but which may form part of a large-scale circuit, the upward-directed component of which may produce auroral emission. These electrons are in the form of beams moving...
away from Saturn although there are some instances of bimodal distributions moving both up and down the field lines. The electrons in these beams have energies extending to several hundred kiloelectron-volts, compared to the few to tens of kiloelectron-volts observed at Earth. The ENA images provide a glimpse of acceleration processes in the upward current region in the form of light ion (H, H\(^2\), and He\(^{3+}\)) cones. The ions charge exchange and reach Cassini provided they have the proper trajectory after leaving the conic as a neutral. There is currently consideration of putting Cassini into a Juno-like orbit with periapsis between the low-latitude atmosphere and the inner edge of the D ring before dropping the spacecraft into the atmosphere for planetary protection purposes. While the inclination of these orbits will not likely be higher than about 65°, there is a possibility of crossing through the acceleration region associated with the upward auroral currents during these orbits.

Considerable work has gone into placing the Cassini auroral observations into the context of a Vasyliunas cycle moderated by a Dungey cycle and with some success. Unlike Jupiter, the currents associated with the breakdown of corotation do not seem to be strong enough to require a region of parallel acceleration, although infrared observations now suggest a weak auroral oval associated with these currents. The stronger emissions, hence stronger currents, are poleward of those associated with the corotation breakdown. This has led to the suggestion, with some supporting observations, that the main auroral oval at Saturn is associated with the shear at the open-closed field line boundary. However, the situation seems to be not so simple as electron beams can be found from near the magnetopause all the way in to ~11R\(_S\).

Prior to the availability of Cassini observations in the Saturnian system, the natures of the auroral processes at Earth, Jupiter, and Saturn were discussed in terms of ordering by the relative importance of rotation and internal dynamics versus solar wind control. Earth is clearly at the end of the spectrum having predominantly solar wind control. Jupiter has been classified as the rotationally-dominated end-member of the set. This left Saturn as somewhere in between Earth and Jupiter. However, the situation is confused partly by the fact that the solar wind appears to play a reasonably important role in Jupiter’s magnetosphere. It is perhaps more accurate to classify Saturn’s auroral processes as simply unique.

References


