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# Remote sensing of the energy of auroral electrons in Saturn's atmosphere: Hubble and Cassini spectral observations

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ABSTRACT

Saturn's north ultraviolet aurora has been successfully observed twice between March and May 2011 with the STIS long-slit spectrograph on board the Hubble Space Telescope. Spatially resolved spectra at ~12 Å spectral resolution have been collected at different local times from dawn to dusk to determine the amount of hydrocarbon absorption. For this purpose, the HST telescope slewed across the auroral oval from mid-latitudes up to beyond the limb while collecting spectral data in the timetag mode. Spectral images of the north ultraviolet aurora were obtained within minutes and hours with the UVIS spectrograph on board Cassini. Several daytime sectors and one nightside location were observed and showed signatures of weak absorption by methane present in (or above) the layer of the auroral emission. No absorption from other hydrocarbons (e.g. $C_2H_2$) has been detected. For the absorbed spectra, the overlying slant $CH_4$ column varies from $3 \times 10^{15}$ to $2 \times 10^{16}$ cm$^{-2}$, but no clear dependence on local time is identified. A Monte Carlo electron transport model is used to calculate the vertical distribution of the $H_2$ emission and to relate the observed spectra to the energy of the primary auroral electrons. Assuming electron precipitation with a Maxwellian energy distribution into a standard model atmosphere, we find that the mean energy ranges from less than 3 to ~10 keV. These results are compared with previous determinations of the energy of Saturn's aurora based on ultraviolet spectra and limb images. We conclude that the energies derived from spectral methods are higher that those deduced from the nightside limb images using current atmospheric models. We emphasize the need for more realistic model atmospheres with temperature and hydrocarbon distributions appropriate to high-latitude conditions.


## 1. Introduction

Saturn's aurora and magnetospheric dynamics are different from both the solar wind driven case of the Earth and the dominance of corotating plasma at Jupiter. Unlike Jupiter or the Earth, the magnetic dipole of Saturn is closely aligned with the planetary spin axis with an offset angle less than 1 degree. The morphological and spectral characteristics of Saturn's aurora were reviewed by Kurth et al. (2009). The original detection of Saturn's FUV aurora was based on spectra collected with the Ultraviolet Spectrometer (UVS) during the Voyager 1 and two flybys of Saturn in 1980. They showed the presence of the HI Lyman-α and $H_2$ Lyman and Werner bands in the polar regions of both hemispheres. Saturn's aurora appeared in the Voyager data as a narrow circumpolar region (Broadfoot et al., 1981; Sandel and Broadfoot, 1981), probably originating from the distant magnetosphere. Outbursts of Lyman-α emission were intermittently observed with the International Ultraviolet Explorer (IUE) over a decade (Clarke et al., 1981; McGrath and Clarke, 1992). The Faint Object Camera on board the Hubble Space Telescope (HST) provided the first image of the north Saturn aurora, with all images co-added to increase the signal to noise ratio (Gérard et al., 1995). A set of Wide Field Planetary Camera (WFPC2) FUV images (Trauger et al., 1998) with a higher limiting sensitivity (~5 kR) showed more details of the northern auroral arc. The brightness of the emission was quite variable (<5–90 kR), but the morning sector was consistently enhanced in comparison with the afternoon sector. Gérard et al. (2004) and Grodent et al. (2005) analyzed two sets of FUV images of the north and south polar regions obtained with the Space Telescope Imaging Spectrograph (STIS). They found that the morphology and brightness

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distribution of the aurora vary on time scales of hours or less. They also tentatively identified the optical signature of the dayside cusp near local noon and pointed out the occasional presence of a spiral structure of the main oval. The dayside main oval lies between 70° and 80° and is generally brighter and thinner in the morning than in the afternoon sector. The brightness of the main oval ranged from below the STIS threshold at ~1 kR of $H_2$ emission up to about 75 kR. The total electron precipitated power was found to vary between 20 and 140 GW, that is comparable to the Earth's active aurora but about two orders of magnitude less than on Jupiter (Gérard et al., 2005; Nichols et al., 2010). Based on images from the Ultraviolet Imaging Spectrograph (UVIS) instrument on board Cassini, Grodent et al. (2011) observed that what appears as a continuous oval on low resolution images could actually be formed of small scale structures in the noon and dusk sectors. Furthermore, Radioti et al. (2011) and Badman et al. (2012) identified bifurcations of the main oval followed by an expansion of this oval. By analogy to the Earth, this behavior was attributed to large-scale reconnections on the dayside magnetopause. Saturn's aurora shows large intensity and morphological variations of the main oval in response to changes in the solar wind dynamic pressure (Clarke et al., 2009). Infrared emissions from the ionospheric $H_3^+$ ion, whose density is significantly enhanced by auroral precipitation, have also been spectroscopically detected (Geballe et al., 1993) and imaged from the ground (Stallard et al., 2007). Badman et al. (2011) analyzed images obtained with the Visual and Infrared Mapping Spectrometer (VIMS) on board Cassini and showed that the average location of the infrared oval is similar to that of the ultraviolet main emission.

The aurora of giant planets potentially exerts a major influence on the thermal structure and the chemistry of the planets' upper atmosphere (Müller-Wodarg et al., 2006; Melin et al., 2007), although meridional heat transfer to mid- and low-latitudes is not fully understood (Smith et al., 2007). Effects on thermal structure are very dependent on the energy of auroral electrons and the altitude of deposition of heat by particle precipitation and Joule heating. Cowley et al. (2008) suggested that the auroral oval at Saturn corresponds to a ring of upward current bounding the region of open and closed magnetic field lines. Their model estimated that the aurora is produced by magnetospheric electrons accelerated to energies in the range of a few keV to a few tens of keV. Coordinated HST-Cassini observations have indicated that field-aligned currents and potential acceleration play a key role in Saturn's aurora (Bunce et al., 2008) and their in situ signatures have been statistically analyzed by Talboys et al. (2011).

Information on the energy of the precipitated auroral electrons has only been obtained through spectroscopic remote sensing. For example, the altitude of the aurora relative to the hydrocarbon homopause has been derived from the comparison between the observed spectra and a reference $H_2$ laboratory spectrum without any absorption. The methane column providing the best fit allows the determination of the altitude of the auroral emission peak relative to the hydrocarbon homopause, which is linked to the energy of the precipitating electrons. This method is based on the shape of the $CH_4$ absorption cross sections, which partly absorbs the $H_2$ emissions at wavelengths less than 1400 Å but leaves the longer wavelength $H_2$ emissions unattenuated. Low spectral resolution Voyager-UVS spectra provided indications on the nature and energy of the auroral energetic particles interacting with Saturn's atmosphere (Sandel and Broadfoot, 1981; Sandel et al., 1982; Shemansky and Ajello, 1983). Spectra generally appeared to originate near the exobase (near 2500 km) and showed no signature of hydrocarbon absorption, with the exception of the brightest spectrum which was best fitted with an overlying methane column of $8 \times 10^{15}$ cm$^{-2}$. The STIS spectrograph on board Hubble offered the possibility to obtain spatially resolved spectra together with images of the auroral emission morphology measured a few minutes before or after the spectra. Six STIS FUV auroral spectra collected in December 2000 with a 12-Å spectral resolution in the noon sector were compared with a synthetic model of electron-excited $H_2$ emissions. The wavelengths below 1400 Å were weakly absorbed by methane with column densities ranging between $7 \times 10^{15}$ and $2 \times 10^{16}$ cm$^{-2}$. These results suggested that the aurora is emitted near the homopause, located at ~800 km in the model atmosphere developed by Moses et al. (2000) based on low-latitude Voyager solar occultation. The mean energy of the primary auroral electrons was estimated in the range 12 ± 3 keV. A comparison of FUV spectra observed with STIS-HST on one hand and with the UVIS spectrograph on board Cassini on the other hand was presented by Gustin et al. (2009). They found that the vertical column of $CH_4$ overlying the principal layer of auroral emissions ranges from $1.4 \times 10^{15}$ to $1.2 \times 10^{16}$ cm$^{-2}$, corresponding to a mean energy of 10–18 keV, using the Moses et al. (2000) model adapted to the value of gravity at 75°N.

Another useful remote sensing technique to estimate the depth of the auroral emission Gustin et al. (2004) is based on absorption of the EUV $H_2$ bands. Self-absorption was observed with Voyager-UVS in a bright spectrum (~100 kR) (Sandel et al., 1982; Shemansky and Ajello, 1983). High resolution (0.2 Å) EUV spectra collected with the Far Ultraviolet Spectroscopic Explorer (FUSE) satellite showed that the 1090–1180 Å spectrum was not self-absorbed and characterized by a temperature of 400 K at the altitude of the bulk of the auroral EUV emission (Gustin et al., 2009), in agreement with the values obtained from $H_3^+$ infrared polar spectra (Melin et al., 2007). A FUSE spectrum between 1030 and 1080 Å including transitions connecting to the $v = 0$ or 1 vibrational levels of the electronic ground state was also analyzed by Gustin et al. (2009). It exhibited self-absorption by a $H_2$ vertical column of $3 \times 10^{19}$ cm$^{-2}$ above the aurora, which locates the auroral layer near 660 km in the atmospheric model at 75°N. If this $H_2$ column is used to determine the energy of precipitating electrons, it corresponds to primary electrons of ~10 keV, in good agreement with the STIS results. The total electron energy range of 10–18 keV deduced from the STIS and FUSE observations sets the auroral emission peak close to the 0.1 μbar pressure level, that is slightly above the methane homopause. FUSE spectra could not provide any spatial resolution, so that the temperature and the auroral pressure level refer to global average values integrating emission from all local times and different view angles.

A third, less model dependent, source of information on the energy of the auroral electrons is the altitude of the peak of the $H_2$ emission observed in FUV images beyond Saturn's high latitude limb. Gérard et al. (2009) analyzed more than 176 radial light curves collected with the Advanced Camera for Surveys (ACS) on board Hubble. They found that the peak of the nightside emission is statistically located at 1145 ± 305 km above the altitude of the 1-bar level. The altitude of the $H_3^+$ infrared auroral emission was also found to be 1155 ± 25 km, in close agreement with the FUV emission (Stallard et al., 2012). Gérard et al. (2009) suggested that the spectral and the imaging results can only be reconciled if the thermal structure of the high-latitude thermosphere is different from the reference model used for their analysis. They proposed an alternative empirical model meeting the observational constraints for auroral latitudes. In this alternative model, the stratospheric temperature gradient is maximum near 10 μbars, compared to $7 \times 10^{-3}$ μbar in the standard model. As a consequence, the 0.1 μbar auroral level derived from the FUSE spectrum is located near 1200 km in this model, in agreement with the HST limb images. The characteristic energy of the auroral electrons reaching this level was estimated in the range 1–5 keV using the 75° latitude model adapted from Moses et al. (and 5–30 keV in case of the modified model). These observational results are synthesized in Table 1