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Characteristics of Saturn’s FUV airglow from limb viewing spectra obtained with Cassini-UVIS

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Abstract

This study reports the analysis of far ultraviolet (FUV) limb spectra of the airglow of Saturn in the 1150-1850 Å spectral window, obtained with the Ultraviolet Imaging Spectrograph (UVIS) onboard Cassini, spanning altitudes from –1200 to 4000 km. The FUV limb emission consists of three main contributions: 1) H Ly-α peaking at 1100 km with a brightness of 0.8 kilo-Rayleighs (kR), 2) reflected sunlight longward of 1550 Å which maximizes at –950 km with 16.5 kR and 3) H$_2$ bands in the 1150-1650 Å bandwidth, peaking at 1050 km reaching a maximum of 3.9 kR.

A vertical profile of the local H$_2$ volume emission rate has been derived using the hydrocarbon density profiles from a model of the Saturn equatorial atmosphere. It is well matched by a Chapman function, characterized by a maximum value of 3.5 photons cm$^{-3}$ s$^{-1}$ in the 800-1650 Å UV bandwidth, peaking at 1020 km.

Comparisons between the observed spectra and a first order synthetic airglow H$_2$ model in the 1150-1650 Å bandwidth show that the spectral shape of the H$_2$ bands is accounted for by solar fluorescence and photoelectron excitation. The best fits are obtained with a combination of H$_2$ fluorescence lines and 20 eV electron impact spectra, the latter contributing ~68% of the total H$_2$ airglow emission.

Keywords: airglow, Saturn, spectroscopy, ultraviolet observations
1. Introduction

The first observations of Saturn’s ultraviolet (UV) emissions were obtained by the Voyager encounters in the early eighties. Comparisons between the emissions at Jupiter and Saturn showed that they are qualitatively similar (Broadfoot et al. 1981). The most intense emission at Saturn detected by the ultraviolet spectrometer (UVS) onboard Voyager 1 (V1) was the aurora, with ~10 kilo Rayleighs (kR) for both the Hydrogen Lyman α (Ly-α) and the H₂ bands, followed by dayside Ly-α with ~1.5 kR and H₂ dayglow with ~0.7 kR in the Lyman and Werner bands (Broadfoot et al. 1981). The latter value is four times lower than the Jupiter value, consistent with the factor of ~3 reduction in the solar flux from Jupiter to Saturn. This fact, among others, pleaded for a dayglow stimulated by the solar flux. Several UVS spectra were examined by Shemansky and Ajello (1983). They compared the observed dayside H₂ bands with electron-excited synthetic spectra that includes the B¹Σ⁺, E,F¹Σ⁺, C¹Π, B³Σ⁺, D¹Π, B¹³Σ⁺, and D¹¹Π vibronic transitions and confirmed that, as for Jupiter, H₂ emission from electronic collisions makes a significant contribution to the observed UV intensity. They also pointed out that the emission longward of 1500 Å is dominated by reflection of solar radiation. Although the electron impact excitation and the solar flux control suggest that the H₂ dayglow is produced by photoelectrons, this idea has been, at first, partially rejected for energy budget considerations (Broadfoot et al. 1981). Precipitation of magnetospheric electrons has been proposed several times (Strobel, 1979, Chen, 1981), but never been considered as an appropriate mechanism to account for the various features of the dayglow phenomenon.

As for Jupiter and Saturn, the dayglow observed after the Voyager Uranus encounter was found to exceed the available photoelectron energy, assuming that 15% of the total solar EUV energy goes into photoelectron excitation of FUV emission (Cravens et al. 1975). A
process called “electroglow” was proposed by Broadfoot et al. (1986). As many UVS
dayglow spectra were well fit by electron excitation models, it was considered that
electroglow consisted of soft (~50 eV) charged particle excitation in the presence of sunlight.
Since the dayglow demonstrated correlation with solar zenith angle and the heliocentric
scaling, it was supposed that electroglow was completely controlled by the incident solar flux
(Yelle et al. 1987). Several mechanisms were considered. For example, Yelle et al. (1987)
proposed that electroglow was produced by fluorescence or H⁺ photolysis. Since electroglow
was created to explain the emission in excess of available solar energy, Clarke et al. (1987)
objected that electroglow was not a direct consequence of solar input, but produced by in-situ
electric field acceleration of photoelectrons and ions through an atmospheric dynamo. This
mechanism was neither satisfactory, as it should have a strong dependence of magnetic
coordinates, which was not observed. Yelle, (1988) suggested that solar fluorescence could
significantly contribute to the observed outer planet dayglows. He built two independent
models of H₂ emission, excited by photoelectrons and solar fluorescence, and first pointed out
significant differences between the emission due to the two excitation sources: the electron-
excited spectrum consists of a large number of vibronic transitions distributed relatively
smoothly with wavelength, while the solar fluorescence H₂ spectrum mainly consists of a
series of bright emission lines produced by the absorption and reradiation of solar lines into
H₂ bands. Using a combination of photoelectron-excited and solar fluorescence-excited
spectra, he was able to obtain a good fit to a Jovian Voyager UVS spectrum without the need
for additional sources. As the Saturn UVS spectra appear very similar to that of Jupiter, he
also predicted that Saturn’s dayglow emission could be accounted for by a combination of
fluorescence and photoelectron excitations. He however indicated that his simple model
suffered from substantial uncertainty. Combined with the uncertainties in the solar flux he
used, UVS calibrations, and low UVS spectral resolution (~30Å), he was not able to
determine the respective contribution of fluorescence and photoelectron and univocally state
that fluorescence and photoelectron excitations can account for the total observed brightness.

This controversy was finally cleared out by Liu and Dalgarno, (1996), who compared
a ~3 Å resolution Jovian dayglow spectrum obtained by the Hopkins Ultraviolet Telescope
(HUT) at solar maximum with a self-consistent model of the airglow of H₂, excited by the
absorption of solar EUV radiation. The much higher spectral resolution of HUT spectra (than
UVS) and more accurate calibrations provided a very convincing demonstration that solar
fluorescence and photoelectron excitation could explain the H₂ dayglow emissions. Their
model took into account the absorption of EUV solar radiation < 500 Å, which ionizes H, H₂
and HD, producing an energy spectrum of photoelectron flux, exciting UV H₂ bands by
collision, as described in Shemansky and Ajello (1983). The fluorescence part of the UV
emission is produced by the strong wavelength coincidences between solar emission lines and
absorption lines of H₂ in the 900-1100 Å bandwidth. They found that the UV spectrum of the
Jovian dayglow can be accounted for in both brightness and spectral shape by solar
fluorescence and photoelectron excitation, without other energy source. In particular, Fig. 3 of
Liu and Dalgarno (1996) shows that the majority of photoelectrons producing the UV photons
are confined below 60 eV, with a maximum flux at 25 eV and an average energy of 33 eV.
These values lie near the maximum of the excitation cross-section of the EF cascade (~20 eV)
and B. C (~40 eV) (Ajello et al. 1982). With a maximum flux at 25 eV, it is likely that the
cascade process which populates the B^1Σ_u^+ electronic state through E, F^1Σ_u^+, has a important
contribution in the photoelectron-excited spectrum. This point was raised by Prangé (1986),
who observed a small peak near 1300 Å in a low resolution V1 UVS Saturn’s disk spectrum,
which may indicate a enhancement of EF cascade in the dayglow emission compared to the
aurora. Liu and Dalgarno (1996) estimated solar fluorescence to contribute 57% to the total
2.3 kR of the Jovian dayglow HUT spectrum. Since the airglow brightness depends on solar
conditions and gas temperature, these values may not be readily applied to our Saturn
observations. Yet, the work by Liu and Dalgarno (1996) gives a good overview of the
processes responsible to the observed dayglow UV emissions.

The Saturn limb profiles from V1 and Voyager 2 (V2) have been re-analyzed by Yelle
et al. (1986). At that time, the source of the UV dayglow emission was still controversial, but
some interesting conclusions should be emphasized. First, they noticed that the limb profile of
Ly-\(\alpha\) and \(\text{H}_2\) band peaked at about the same altitude, near the homopause, at \(~60000\) km
minimum ray height (MRH) for the V2 limb drift. As they assigned the 1 bar level at \(~59000\)
km, it situates the \(\text{H}_2\) emission near 1000 km above the 1 bar level. The uncertainty is
determined by the slit width, which was \(~400\) km. The line of sight (LOS) measurements
must be inverted to yield the emission rate variation with altitude. Yelle et al. (1986) used a
forward technique, consisting of modeling the volume emission rate (VER) and adjusting the
model to get the best fit to the observed limb profile. Using the \(\text{CH}_4\) densities from Smith et
al. (1983) to take into account the extinction due to methane, their best VER was a
combination of two exponentials. A first one with a scale height of 1500 km, which best fit
the observed brightness above 60500 km and a second one with a scale height of 200 km, best
fitting the observed brightness below 60500 km. This vertical VER produced \(~2\) photons cm\(^{-3}\)
\(\text{s}^{-1}\) at the merging 60500 km. As the scale heights they used is from five to ten times the
ambient gas value from Smith et al. (1983), Yelle et al. (1986) concluded that the airglow
emission was present throughout the entire thermosphere. They also mentioned that similar
results had been achieved with an inversion technique calculations.

In terms of composition, a first model of Saturn’s upper atmosphere has been derived
by Smith et al. (1983) from the analysis of V2 UVS occultation measurements, providing
temperature and \(\text{H} \), \(\text{H}_2\) and \(\text{CH}_4\) density profiles. Until recently, most of the Saturn’s
photochemical models were based on photochemical processes operating on Jupiter and
extrapolated to Saturn. The first comprehensive model of Saturn’s atmosphere was published by Moses et al. (2000). It used the latest hydrocarbon reaction rates, absorption cross sections, and photolysis quantum yields as well as observational constraints from infrared to ultraviolet. As for Jupiter, they found that the main hydrocarbons are CH₄, C₂H₆ and C₂H₅, in that order of abundance.

In this study, we analyze limb-viewing spectra of Saturn obtained with the UltraViolet Imaging Spectrograph (UVIS) onboard Cassini, obtained at a continuous set of MRH altitudes. In contrast to Voyager UVS limb observations, obtained at ~30 Å spectral resolution with a spatial resolution of ~400 km, UVIS provides high signal to noise spectra at ~5.5 Å resolution with a spatial resolution of ~300 km. The goal of this paper is to 1) derive the vertical VER of the H₂ dayglow, taking into account the absorbing hydrocarbons attenuating the signal along the LOS, 2) provide a spectral analysis of the FUV airglow limb spectra and 3) establish limb profiles of the sources of the observed emissions.
2. Observations and data reduction

The data examined here consist of six sets of observations listed in Table 1. The first two sets were collected on 29 October 2005 and the other four ones on 27 November 2005, i.e. near solar minimum. Fig. 1a shows the projection of the UVIS FUV slit near Saturn’s disk for the first set and Fig. 1b gives a general outlook of the viewing geometry. The UVIS instrument has been thoroughly described by Esposito et al. (2004). In brief, UVIS includes a two-channel imaging spectrograph, from 1115 to 1912 Å in the FUV, and from 563 to 1182 Å in the EUV. Three slits are available: a high resolution slit (75 and 100 µm slit width for the FUV and EUV channel, respectively), a low resolution slit (150 and 200 µm slit width for the FUV and EUV respectively), and an occultation slit of 800 µm width, identical for both channels. The data discussed here were obtained with the low resolution slit and FUV channels, providing spectra at ~5.5 Å spectral resolution. The detector is a Codacon (CODed Anode array CONverter), consisting of 1024 pixels in the spectral direction and 64 pixels in the spatial direction. The spectral dimension was compressed by two pixels throughout the observation sequences to reduce data volume. The distance between Cassini and Saturn at the tangent point varied from $2.7 \times 10^5$ to $3.0 \times 10^5$ km, leading to a spatial resolution of about 300 km per pixel, assuming a spatial pixel field of view of 1.0 mrad. The average phase and incidence angles of all spatial pixels at the tangent point along the LOS are 96.0 and 24.7 degrees respectively, with a constant emission angle of 90 degrees.

Taking into account the illuminated spatial pixels only (56 pixels for all observations except observation number two which has 57), the dataset consists of 14133 spectra. The first step of the reduction process is to sort all the spectra by MRH and add them up into bins of 50 km, in order to examine the dayglow variations with altitude. This procedure has been applied by Stevens et al. (2010) in the analysis of Titan’s UVIS limb spectra. Assigning the central
altitude value for each 50 km bin, we obtain a total of 109 spectra, spanning a continuous
altitude range from ~1325 to 4125 km MRH. Negative values of the MRH correspond to
altitudes where the tangent point of the line of sight is situated below the 1 bar level. The
spectra are then calibrated, using a procedure already applied to other UVIS analysis (Ajello
et al. 2008, Gustin et al. 2009, Stevens et al. 2010). It consists in a subtraction of the
background noise due to the radioisotope thermoelectric generator onboard Cassini, a flat-
field correction, and conversion from counts to Rayleigh Å⁻¹ using the time-dependent
sensitivity curve prescribed by the UVIS team. The last three high-altitude spectra at 4025,
4075 and 4125 km have been used as background reference and have been subtracted from all
spectra. Another source of background signal that affects the recorded spectra is scattering of
the H Ly-α line on the detector. This wavelength-dependent background, directly proportional
to the Ly-α intensity, has been modeled, scaled to the observed Ly-α and subtracted from the
data. Fig 2a shows the variations of the spectral contents and intensity for several altitude
bins. It is seen that a strong solar reflectance structure longward of 1500 Å dominates the
overall intensity for lower altitude spectra (~1325 to ~425 km) and spectra above ~ 425 km
contain strong H₂ Lyman and Werner bands. Limb spectra above 2700 km start to be very
noisy and structureless. Fig. 2b shows the brightness variations of the reflected sunlight
emission in 1700-1880 Å, plus the 1250-1300 and 1550-1620 Å spectral windows, used to
define the H₂ color ratio (CR), which is a measure of the absorption by methane (Gustin et al.
2004). The limb reflected solar profile has a maximum of 16.5 kR, peaking at ~1075 km. The
1230-1300 and 1550-1620 Å profiles exhibit the same trend at high altitude up to 1100 km,
where the 1250-1300 Å brightness starts to reveal the effect of methane absorption, active
shortward of 1400 Å. The integrated limb brightness in 1550-1620 Å peaks near ~825 km and
1230-1300 Å one peaks near ~975 km. The altitudes scale used in Fig. 2a and 2b is provided
by the nominal pointing in the NAIF SPICE C kernel toolkit. It will be demonstrated later that
219  an upward offset of 125 km will be applied to the altitude scale in order to obtain better
220  agreement between the data and model.
3. FUV solar reflectivity

The main goal of the study is to describe the characteristics of the H₂ dayglow. Between –1325 and 775 km, the spectra in the 1500-1650 Å bandwidth are a combination of the H₂ bands and reflected sunlight. The first natural step is to model the reflected sunlight emission in order to separate the two contributions. The reflected emission is the result of the solar radiation scattering by atmospheric H₂ and He and absorption by the hydrocarbons along the photon trajectory. First, we calculate Saturn’s FUV reflectivity in the 1500-1880 Å window using a procedure previously applied by Ajello et al. (2008), based on a multiple scattering formalism designed for limb-viewing geometry (Wallach and Hapke, 1985). Each spectrum we analyze is the sum of all spatial pixels into 50 km MRH bins. Since the solar incidence and phase angles can be very different for each pixel into a 50 km bin, we calculated the reflectivity for each individual pixel and then computed a weighted averaged reflectivity, based on each pixel intensity between 1700 and 1880 Å. The modeled reflectivity so calculated is then multiplied by a solar spectrum which accounts for the angle between Saturn, the Sun and the Earth to correct for the solar rotation and the resulting delay between the solar photon flux reaching the Earth and Saturn. The solar flux is then corrected for the distance between the Sun and Saturn. Since the datasets have been obtained 29 days apart, two solar spectra should be considered. We retrieved solar spectra obtained from the TIMED/SEE database (Woods et al. 2005), measured on 21 October 2005 and 22 November 2005, related to the 29 Oct. 2005 and 27 Nov. 2005 limb observations respectively. As both spectra were found identical, we chose the 21 Oct. 2005 spectrum in our calculations. Because of the limb-viewing geometry, the path crossed by the light is much larger than for disk observations. Therefore we chose to include in the modeled reflectivity, in addition to C₂H₂ and C₂H₆, nine minor hydrocarbons which may have an effect on the total attenuation:
C\textsubscript{2}H\textsubscript{4}, C\textsubscript{3}H\textsubscript{6}, CH\textsubscript{2}CCH\textsubscript{2}, C\textsubscript{4}H\textsubscript{2}, C\textsubscript{4}H\textsubscript{8}, CH\textsubscript{3}C\textsubscript{2}H, C\textsubscript{3}H\textsubscript{8}, C\textsubscript{4}H\textsubscript{8} and C\textsubscript{4}H\textsubscript{10}. Since this high number of parameter may lead to unstable results, we chose to tie some hydrocarbon mixing ratios to others. We first choose the hydrocarbons whose number density altitude profiles follow the same trend in the Moses et al. (2000) model and tied them to the most abundant one, which can vary freely. In our selection of hydrocarbons, C\textsubscript{2}H\textsubscript{2} and C\textsubscript{2}H\textsubscript{4} vary freely. C\textsubscript{3}H\textsubscript{6}, CH\textsubscript{2}CCH\textsubscript{2}, C\textsubscript{4}H\textsubscript{2} and C\textsubscript{4}H\textsubscript{8} are tied to CH\textsubscript{3}C\textsubscript{2}H, and C\textsubscript{3}H\textsubscript{8} and C\textsubscript{4}H\textsubscript{10} are tied to C\textsubscript{2}H\textsubscript{4}. The average abundance ratios between the “free” and “tied” hydrocarbons along the vertical profile are used to relate the tied hydrocarbons to the free ones. After multiple tests, we added C\textsubscript{6}H\textsubscript{6} in the model, whose important absorption cross-section near 1780 Å improved the fit. Since the H\textsubscript{2} emission significantly contributes in the 1500-1650 Å bandwidth, we also included in the regression a synthetic H\textsubscript{2} airglow spectrum in that spectral region as a free parameter. This synthetic H\textsubscript{2} spectrum, provided by J. T. Hallet (personal communication, from Hallet et al., 2005), is described in more details in section 4.1.a. It is used in the present paragraph as an all-around airglow spectrum simulating the influence of H\textsubscript{2} within the reflected sunlight signal. It will be the base of our VER determination presented in section 4.1 and 4.2. A least-square fit between the observed and modeled spectra in 1500-1880 Å minimizing chi squares (χ\textsuperscript{2}) is then applied, yielding the best parameters, which are the mixing ratios of the absorbing components and the scale factor of the synthetic H\textsubscript{2} spectrum. Two examples of fits are shown in Fig. 3, illustrating the strong variation of the H\textsubscript{2} contributions compared to reflected sunlight in the 1500-1700 Å spectral region. Figure 4 shows the C\textsubscript{2}H\textsubscript{2} and C\textsubscript{2}H\textsubscript{6} mixing ratios of the best fits for the low altitude spectra up to the 1x10\textsuperscript{4} mbar level (~800km) along with the Moses et al. (2000) values and other published measurements. The Moses et al. (2000) profiles show the mixing ratios averaged along the LOS. Data points from disk viewing observations obtained by other studies are also shown. The UVIS C\textsubscript{2}H\textsubscript{2} profiles below ~1 mbar and C\textsubscript{2}H\textsubscript{6} below ~1x10\textsuperscript{2} mbar do not exhibit a strong
altitude dependence. This is an effect of the limb-viewing geometry, which averages the hydrocarbon local density profiles along the LOS and smoothes their variations with the MRH. It should be noted that the UVIS values reflect, for a given MRH, the product of the local solar illumination by the optical depth, summed on each point along the LOS. Therefore, they cannot be readily compared with other published values, since the unattenuated vertical profile of the solar flux is not known, which make it unfeasible to simulate the average mixing ratios that would be obtained in limb-viewing geometry. This is not essential to our analysis, since our goal is to subtract the modeled reflected sunlight component from the observed spectra in order to get the \( \text{H}_2 \) emission free of solar contamination. Once a best synthetic spectrum is obtained for each MRH, the solar reflected component is then removed from the observations to retain the airglow \( \text{H}_2 \) emission only.
4. Spectral Analysis

4.1. Overview

The emergent brightness $B$ at $Z_0$ MRH is the sum of the $\text{H}_2$ emission on each point $S$ along the LOS, attenuated by hydrocarbons (Fig. 1b):

$$B(Z_0) = \int_{-\infty}^{+\infty} v(S) e^{-\tau(S)} dS \quad (1) \quad \text{with}$$

$$\tau(S) = \int_{s}^{\infty} n_{\text{HC}} (S') \sigma_{\text{HC}} dS' \quad (2) \quad \text{where}$$

- $v(S)$ is the vertical VER of the $\text{H}_2$ airglow intercepted at distance $S$ along the LOS
- $\tau(S)$ is the optical depth due to absorption by hydrocarbon HC, of density $n_{\text{HC}}$ at $S'$

The VER and hydrocarbon density profiles are unknown a-priori. Since they both significantly influence the emergent signal and are independent unknowns, we chose to fix the vertical hydrocarbon density profiles by using the values from the Moses et al. (2000) model. To determine the VER, we evaluate equations (1) and (2) using the Moses et al. (2000) atmospheric model, with a Chapman-type function to model the vertical VER:

$$v = v_m \exp\{f(1 - \alpha - e^{-\alpha})\} \quad (3) \quad \text{where}$$

- $\alpha = (Z - Z_m)/H$ is the reduced height,
- $v_m$ is the maximum of $v$ at the altitude $Z_m$. 
- f is the shape factor, defining a α-Chapman when f=0.5 and a β-Chapman when f=1.
- H determines the thickness of the emission profile. In the case of a β-Chapman profile, H is the scale height of the emission, i.e. the height range in which the topside VER changes by a factor of e (~2.718). The β-Chapman is chosen a-priori in our study.

We adopt the following steps in the spectral analysis:

a. Determination of the VER

Using equations (1), (2), (3), the parameters of the Chapman function are derived from a least-squares fit between the calculated and observed profile of B(Z0) in the integrated 1550-1620 Å spectral window. We chose this bandwidth to avoid the effects of CH₄, the most abundant hydrocarbon, which has a strong absorption cross-section shortward of 1400 Å. Nevertheless, simulations have shown that the 1550-1620 Å range is not free of absorption because of the long path along the LOS. The optical depth in the model thus includes all the hydrocarbon species used in paragraph 3, with C₂H₂ and C₂H₆ as the stronger absorbers in this spectral band. To account for the wavelength dependence and spectral shape, we incorporate in the model the synthetic spectrum of Saturn’s airglow as described by Hallet et al. (2005).

This H₂ synthetic spectrum is composed of transitions due to both direct excitation by photoelectron and solar photon of the X ground electronic state to B, C, B’, D, B”, D’ states, and cascade from the excited singlet-gerade states EF, GK, HH, I and J. It uses solar conditions of April 2005 with incidence and emission angles set at 0 deg. This synthetic spectrum is normalized in the 1550-1620 Å bandwidth, multiplied on each point S along the LOS by the intercepted VER, and attenuated by τ(S). The model uses 10 km steps along the LOS, from ~30000 to 30000 km and altitude bins of 50 km MRH from ~115 km (minimum altitude tabulated in the Moses et al. (2000) model) to 3025 km, where the dayglow tends to zero. The resulting 1550-1620 Å brightness profile is compared to the data and the best fit provides the best parameters of the Chapman function.
b. Spectral comparison

From the best VER determined in a) from the 1550-1620 Å brightness profile, we calculate for each altitude bin an emergent synthetic spectrum in the 1150-1650 Å bandwidth, with the CH₄ profile from Moses et al. (2000) added back to the procedure. The VER has been adapted to this wider spectral range by multiplying the best $v_m$ parameter by 4.0. At this stage, a line-by-line comparison between the synthetic and observed spectra is not practical because we have to consider a hundred of spectra. A good way to evaluate the quality of the modeled emergent spectra (and thus the VER and density profiles used in the previous step) is to compare the observed and synthetic CR. This brings a overall view on the ratio between two bandpasses of the spectra and on the CH₄ absorption. If the synthetic CR profile is not satisfactory, the procedure in step a) is performed again, with modified hydrocarbon profiles and/or VER. Once a satisfactory CR profile is obtained, the observed and modeled spectral shape in the 1150-1650 Å are compared to possibly make further adjustments. For example, the examination of the absorption at 1520 Å gives an information on the quantity of C₂H₂ and may allows a fine-tuning of the model.

c. Photoelectrons and fluorescence contributions

In order to estimate the proportion between the emission due to photoelectrons and solar pumping contributing to the airglow, the synthetic spectrum by Hallet et al. (2005) is replaced in paragraph 4.3. by an electron-impact H₂ laboratory spectrum, associated with individual H₂ fluorescence lines found in Table 2 of Liu and Dalgarno, (1996). The best fit between the observed and modeled emergent spectra provides a first estimate of the contribution of each excitation process.

4.2. Volume emission rate
Applying the procedure described in 4.1., the first synthetic CR profile we derived was too high and did not match the observed one at all (see the orange curve with diamonds in Fig. 7). A natural way to decrease the CR is to reduce the amount of CH₄ in the model. A lowering of CH₄ by a factor of 100 (compared to the Moses model) was needed to match the synthetic and observed CR, which does not seem realistic. An other way to adjust the CR is to modify the VER altitude profile. This can be achieved by modifying the hydrocarbon profiles in 4.1.a or by using another profile than the Chapman function defined in equation (3). Many combinations have been tried (lowering or increasing the hydrocarbon density profiles, using Gaussian, generalized Gaussian, asymmetric Gaussian or Epstein profiles), which did not provide a satisfactory result. Finally, we obtained a very good fit of the CR profile by shifting the UVIS observations upward by 125 km, using a Chapman function and the Moses et al. (2000) density profiles, without additional modification. In a study of Titan’s limb spectra obtained by the Composite InfraRed Spectrometer (CIRS) onboard Cassini, Vinatier et al. (2007) showed that an altitude offset corresponding to a spacecraft altitude-control pointing uncertainty of ~2 mrad (Hasas et al. 2004) was also required to fit their observations. The 125 km offset we need, which corresponds to 0.4 mrad, is therefore well within Cassini pointing uncertainties. Figure 5a shows the shifted UVIS brightness profile in the integrated 1550-1620 Å bandwidth with the best fit in red. The model, calculated every 50 km MRH, has been smoothed over 7 pixels to account for the slit spatial resolution (300 km). The blue points show the 1550-1620 Å brightness before subtraction of the reflected sunlight component and illustrate well the requirement to separate the H₂ from the reflected sunlight components to study the airglow. The effect of the hydrocarbon absorption is illustrated in Fig. 5b, which shows the unsmoothed synthetic brightness, with and without the effect of the hydrocarbon absorption. It is seen that the attenuation is effective below 900 km, with a 50% reduction of
the signal at 50 km MRH. The brightness peaks near the homopause level, as already noted by Yelle et al. (1986). The best vertical VER displayed in Fig. 5c is a β-Chapman profile, characterized by a maximum value of 0.67 photons cm\(^{-3}\) s\(^{-1}\) at 1020 km and a scale height of 284 km. This solution is not unique, as a range of shape factors can be attributed to the Chapman function. Comparable fits to the 1550-1620 Å brightness have been experimented with a shape factor fixed to 0.5 or varying freely in the regression. In the case of shape factor fixed to 0.5, the best VER is characterized by a maximum of 0.71 photons cm\(^{-3}\) s\(^{-1}\) at 1000 km. When left free, the best shape factor is 2.1, with a maximum of 0.65 photons cm\(^{-3}\) s\(^{-1}\) at 1038 km. Compared to the best β-Chapman, this gives \(v_m\) and \(Z_m\) variations of 6% and 2%, respectively. The 1550-1620 Å VER can be extended to the entire H\(_2\) UV bands in 800-1650 Å by multiplying \(v_m\) by 5.27, which is the factor between the integrated intensities in these two bandwidths in the synthetic H\(_2\) airglow spectrum.

As mentioned previously, two factors affect the emergent spectra. The first one is the absorption by hydrocarbons which partly attenuates the emission between the emitter and the observer. The second one is the shape of the VER, which puts more or less weight on some portion of the LOS, as illustrated in Fig. 6. Figure 6a shows the average optical depth \(\tau(S)\) in the 1150-1650 Å bandwidth for \(Z_0=50\) km, while Fig. 6b shows the corresponding VER intercepted by the LOS. It is seen that the unabsorbed emission (black curve) has two separate components. The one with \(S<0\) is completely absorbed and does not contribute to the observed emission. As the MRH increases, the two portions of the intercepted VER come near each other and start to merge at ~ 450 km to form a one-block bulk of emission. Figure 6c and 6d demonstrate this merging in the case of \(Z_0 = 700\) km. The hydrocarbon attenuation is weaker and a substantial portion of the emission at \(S<0\) starts to contribute to the total signal. At \(Z_0 = 900\) km, the average optical depth is less than unity all along the LOS and the emission in each point contributes to the observed signal. This figure demonstrates that a
large increase/decrease of the hydrocarbon number densities may not have a noticeable effect on the emergent brightness. At 50 km MRH for example, a large increase of the hydrocarbon densities will not influence the emission at S<0, as the optical depth is already much larger than unity. This increase would only affect the region where \( \tau(s) \) is near unity, i.e around \( S=7000 \) km. As the intercepted VER has a minor contribution in this portion of the LOS, the emergent signal would not be significantly modified.

Taking into account the 125 km shift, the lowest probed altitude is \(-1200 \) km MRH. As the hydrocarbon density profiles start at \(-115 \) km in the Moses et al. (2000) model, we need to extend these profiles to lower altitude to examine the full dataset. The Moses hydrocarbon density profiles have been extended to \(-1200 \) km by keeping their first value at \(-115 \) km constant throughout the lower altitudes until \(-1200 \) km. Figure 7 shows a comparison between the observed CR (black curve) and the CR deduced from the best synthetic emergent spectra (red curve). The CR for the unabsorbed synthetic airglow spectrum is 1.5, higher than the 1.1 value pointed out for an auroral (i.e. electron impact) \( \text{H}_2 \) spectrum (Gustin et al., 2006).

Starting from the top, it is seen that the synthetic CR is constant at 1.5 between 4000 and 950 km, as all spectra are unaffected by hydrocarbons. At 950 km, the modeled CR starts to increase as the hydrocarbon layer is reached. The CR maximizes at 850 km and then decreases at lower altitudes. This effect is due to the intercepted VER, which starts to separate into two components. The emission with \( S<0 \) starts to be completely absorbed for all wavelength, while the emission for \( S>0 \) is less and less affected by hydrocarbons, because 1) the path from \( S \) to infinity is too short to create a significant optical depth 2) the VER shifts towards the right, i.e. towards lower values of \( \tau(s) \), leaving the low altitude emergent spectra practically unabsorbed. In other words, the absorption at low altitude does not affect much the spectral shape of the emergent emission but essentially attenuates the overall integrated brightness by a factor of \(~2\). Between 4000 and 2500 km MRH, the observed CR are scattered
around the theoretical value because of the low S/N ratio. Between 2500 and 1100 km, the observed CR is significantly lower than the theoretical value. This is due to an unidentified feature at 1255 Å peaking in this portion of the atmosphere, which gives more weight to the denominator of the observed CR. Below 1100 km, the synthetic and observed CR fit well down to ~500 km, where the observed CR are lower than expected, likely because the low-altitude spectra longward of 1500 Å is strongly influenced by the reflected sunlight emission. This component has been removed from the data, but the residual of the subtraction may lead to a significant uncertainty on the remaining H₂ signal.

We experimented other methods to extend the hydrocarbon density profiles to the lower altitudes, basically in lowering the density profiles. As expected, these attempts did not notably change the resulting synthetic CR profiles because of the position of the intercepted VER along the LOS, as discussed before. At this point, a visual comparison between the observed and best synthetic emergent spectra has been performed for all altitude bins. The fits were found very satisfactory in terms of general shape, overall intensity and hydrocarbons absorptions. However, a few individual lines in some best fits were found too intense or too weak depending on the altitude bin examined. This is illustrated in Fig.8a for the emergent spectrum at 300 km, which shows that the overall fit to the data is good, but presents a few over-bright lines at specific wavelengths. Figure 8b shows a comparison between the Hallet et al. (2005) airglow spectrum used in this study and a laboratory H₂ spectrum obtained from impact of 20 eV electrons (Dziczek et al. 2000). It is seen that the main differences between the two spectra are due to several individual lines, and correspond to the discrepant peaks observed in Fig. 8a, as indicated by the arrowed lines. They correspond to H₂ transitions excited by fluorescence and are identified by using Table 2 of Liu and Dalgarno (1996), which lists the principal fluorescence H₂ lines resulting from the absorption of EUV solar
radiation obtained from the study of the Jovian airglow. The transitions determined in Fig. 8 generally correspond to the most intense fluorescence lines of this table.

4.3. Electron-impact and fluorescence contributions.

The H$_2$ spectrum from Hallet et al. (2005) used in the previous sections represents an average airglow emission and is composed of a fixed combination of electron impact and solar fluorescence excitations. The ratio between the contribution of electron impact and fluorescence on the emergent emission may vary with altitude. In order to evaluate the magnitude of both contribution with MRH, the spectral analysis in the 1150-1650 Å bandpass is performed again here, with the Hallet et al. (2005) spectrum replaced by the blending of an e-impact H$_2$ spectrum obtained in the laboratory and individual fluorescence H$_2$ lines arising from solar EUV pumping. Two e-impact laboratory spectra at 300 K have been tested. The first one has been obtained from impact of 100 eV electrons (Liu et al. 1998) and the second one from 20 eV electrons (Dziczek et al., 2000). The main differences between the 100 eV and 20 eV spectra are due to the EF cascade, which populates the B electronic state through E, F $^1\Sigma_u^+ \rightarrow B^1\Sigma_u^+$ transitions. The cascade is enhanced for low energy excitation and maximizes for 20 eV electrons (see Fig. 10 of Ajello et al. 2005). This enhancement can be detailed by the examination of a spectrum resulting from the EF cascade process only (without direct excitation), obtained with a time-resolved electron-impact technique (Dziczek, et al. 2000). The EF spectrum shows that cascade has emission bands all over the EUV and FUV bandwidth. The cascade process most strongly populates the v=0 vibrational state of B, whereas direct excitation mainly populates v=6, 7 of B. The EF spectrum is more intense in the FUV, with a maximum contribution of the L(0,3) band at 1276Å, L(0,4) at 1335 Å and L(0,5) and 1395 Å, followed by well-defined peaks near 1436, 1458, 1488, 1518, 1546, 1578 and 1608 Å.
For both e-impact spectrum, an emergent spectrum is calculated for each 50 km altitude bin following equations (1), (2) and (3), with the hydrocarbons from the Moses et al. (2000) model and the best VER obtained in the previous paragraph. We add to this spectrum the strongest solar fluorescence lines reported in Table 2 of Liu and Dalgarno (1996). Each line is convolved to the UVIS spectral resolution and is allowed to vary freely in the fitting procedure. Five additional lines have been included in the procedure to improve the fit: Ly-\(\alpha\) at 1215.7 Å, the OI triplet at 1302.2, 1304.09 and 1306.0 Å and the mystery feature at 1255 Å. The combination of these contributions forms a new synthetic airglow spectrum that is compared to the observed spectra at each MRH. The least-squares regressions have been performed for altitudes from \(-1200\) to \(3000\) km MRH. The results reveal that the best fits with \(100\) eV and \(20\) eV spectra are very similar, with a slight preference for the \(20\) eV spectra. It is however difficult to point out a particular spectral region with systematic improvement, because of all the individual lines varying freely included in the regression. In fact, because of the medium resolution of the data \((5.5\) Å), some intense pumped \(H_2\) lines included in the regression coincide with lines enhanced by the EF cascade: the 1276 Å line coincides with the pumped lines at 1272.81 Å and 1279.10 Å \([L(11,7) R(1)+P(3)\) from CII and OVI\], the 1335 Å line coincide with the 1334.28 Å pumped line \([L(5,6) R(1)\) from CII and OVI\] and the 1395 Å line coincide with the pumped 1394.25 Å line \([L(11,10) R(1)\) from Ly-\(\gamma\)]. This means that a specific observed peak enhanced by the EF cascade can be fitted as well with the \(20\) eV spectrum alone or a combination of the \(100\) eV spectrum with solar pumped lines. Still, the overall fit with the \(20\) eV spectrum are found slightly better when compared to the data. Examples of best fits at \(-700\), \(50\) and \(1050\) km MRH are shown in Fig. 9. For all spectra, the \(20\) eV electron impact component dominates the total emission, along with a few fluorescence lines. The most intense fluorescence \(H_2\) lines, clearly apparent in Fig. 9, are found at 1265.68 Å \([L(6,5) P(1)\], 1362.04 and 1365.66 Å \([L(11,9) P(3)\) and \([L(6,7) P(1)\], 1369.0 Å \([L(2,5)\]
P(6)], 1461.97 Å [L(6,9) P(1)], 1546.72 Å [L(6,13) P(1)], 1607.50 and 1607.90 Å [L(6,11) P(1)] and [L(5,12) R(1)]. The contribution of the 1255 Å mystery feature is weak for the spectra at ~700 and 50 km MRH in Fig. 9 but clearly visible for the 1150 km spectrum. In order to determine the contribution of the different EUV solar lines in the pumping process, the individual H₂ lines due to the same solar source have been added up for each best synthetic spectrum and plotted versus MRH in Fig. 10. This figure also shows the Ly-α line limb profile and presents the contributions of e-impact and fluorescence to the total airglow emission. Some relevant number from the plots in Fig. 10 are tabulated in Table 2. It is seen that the Ly-α line maximizes at 1100 km with 802 R, which corresponds to the altitude of the airglow peak within 50 km (i.e. below the spatial resolution of one UVIS pixel), as already noticed for V1 and V2 limb scans (Yelle et al. 1986). The total emission due to fluorescence peaks at 900 km with 1445 R and the emission due to electron impact peaks at 1150 km with 2743 R, for a total airglow emission of 3943 R peaking at 1050 km. Taking into account the 11 years solar cycle, these numbers can be readily compared to the limb values obtained from the two Voyager encounters with Saturn. The Ly-α line is about two to three times weaker for UVIS compared to Voyager, while the total H₂ emission compares well. The much higher Ly-α brightness observed during the Voyager observations is attributed to the tilted Saturn’s rings reflecting a significant amount of emission into the detector, while the rings appeared horizontal during the UVIS observations. Table 2 also gives the intensity of the pumped line used in the analysis of a HUT disk spectrum of the Jovian dayglow (Liu and Dalgarno, 1996), converted to our observation conditions. The Liu and Dalgarno figures have been derived from a disk spectrum and thus cannot be readily compared to ours, which have been obtained from limb-viewing observations. Yet, comparisons between the Liu and Dalgarno values and the UVIS pumped lines brightness averaged from ~1200 to 2500 km show that the main contributor to fluorescence for both planets is Ly-β, followed by solar OVI, CII, and NII in
that order. The main lines contributing to fluorescence are the L(6,13) P(1) and L(5,12) R(1) transitions at 1607.50 Å and 1607.90 Å respectively. This contribution is clearly seen in the fits presented in Fig. 9. The fits require the addition of the OI triplet at 1304 Å for the low-altitude spectra, and a mystery feature at 1255 Å which peaks at 1200 km. The altitude profile of the 1255 Å line displayed in Fig. 10 looks triangular, quite different from the fluorescence lines. It should be stressed out that the fluorescence lines from Table 2 of Liu and Dalgarno (1996) used in our regression correspond to the main features of the pure fluorescence spectrum. However, they only represent 28% of the total integrated fluorescence spectrum presented in Liu and Dalgarno (1996), as the fluorescence emission exhibits a continuous emission in the UV. If we then multiply the intensity of the pumped lines used in our regression by 3.57 and remove this total fluorescence contribution from the best fits, we find that the electron impact excitation process dominates the emission, with a maximum contribution of 80% at 1400 km and an average contribution of 68% in the ~1200 to 2500 km range. The technique we use to evaluate the fluorescence and electron impact contributions to the total airglow should be considered as a first order survey, as it bears two main weaknesses. First, the contribution of the main fluorescence lines listed in Table 2 of Liu and Dalgarno (1996) somewhat depends on the gas temperature and second, we scaled the electron impact spectrum component to the calculated VER and added the fluorescence lines afterwards in the regression, which may lead to an overestimate of the electron impact contribution. On the other hand, the comparison between the e-impact laboratory spectra and the airglow synthetic spectrum from Hallet et al. (2005) in Fig. 8 shows that the airglow spectrum can be very well reproduced by combining the e-impact spectra with the fluorescence pumped solar lines. We thus find this method appropriate in our airglow simulations.
5. Conclusions

A total of 109 UVIS limb spectra at ~5.5 Å resolution of the Kronian airglow, spanning the altitude range ~1200 to 4000 km at the tangent point have been analyzed. The limb brightness in the 1150-1850 Å range is dominated by Ly-α, peaking at 1100 km MRH with 802 R, reflected sunlight maximizing at ~950 km MRH with 16.5 kR and H₂ Lyman and Werner bands which peak at 1050 km MRH with a maximum of 3.9 kR. The UVIS integrated H₂ brightness at the altitude peak compares well with the values obtained with the UVS V1 and V2 spectrometers, taking into account the EUV solar flux ratio at the time of the observations. The Ly-α brightness peaks at the same altitude as the H₂ bands, near the homopause level, but our value is significantly lower than the V1 and V2 observations (Yelle et al. 1986), probably because of the reflection of interplanetary Ly-α by Saturn’s rings, more inclined towards the instrument during the Voyager observations.

A model of the airglow emission taking into account hydrocarbon absorption along the LOS has been developed, based on a H₂ synthetic airglow spectrum (Hallet et al. 2005) and the Moses et al. (2000) model of the Saturn equatorial atmosphere. A vertical profile of the H₂ volume emission rate has been derived from fits between the observed and modeled H₂ limb brightness in the 1550-1620 Å bandwidth. We find that the best agreement is obtained by shifting the data upward by 125 km, within the pointing uncertainty related to our observations. Our best representation of the vertical volume emission rate is a β-Chapman function which peaks at 1020 km and emits 3.5 photons cm⁻³ s⁻¹ in the 800-1650 Å bandwidth. The scale height of the Chapman function is 284 km, which is five times the scale height of the neutral atmosphere (H=~53 km assuming a temperature of 130 K). This result, already pointed out by Yelle et al. (1986), shows that the source of excitation extends throughout the entire upper atmosphere of the planet.
A comparison between the observed and synthetic spectra has been carried out using a first-order hybrid model of airglow, consisting of a free combination between an electron impact H\textsubscript{2} spectrum and intense fluorescence H\textsubscript{2} lines reported by Liu and Dalgarno (1996). Laboratory spectra excited by 20 eV and 100 eV electrons have been tested. The main differences between these two spectra are due to the EF cascade process, which increases the population of the v=0 vibrational level of B and enhances specific H\textsubscript{2} emitted lines. This effect is maximum for 20 eV electrons and is used to discriminate between 20 eV and 100 eV spectra. However, the spectral lines enhanced by cascade coincide with fluorescence lines, which makes it difficult to choose between the modeled emergent spectra obtained with the 20eV and 100 eV spectra. Nevertheless, the emergent synthetic airglow spectra built with the 20 eV spectrum provided overall better fits to the observations. This suggests that the airglow is principally due to low-energy photoelectrons, as was already suggested by the study of the Jovian UV airglow by Liu and Dalgarno, (1996). The photoelectron flux spectrum they derived from XUV solar excitation had energies mostly lower than 60 eV, with an average of 33 eV and a peak at 25 eV. We find that electron impact process dominates Saturn’s airglow emission, with an average contribution of ~ 68% in the –1200 to 2500 km MRH range.

This study provides the first study of recent UV spectra of the Kronian airglow, which is scarcely described in the literature. A next step in the study of airglow would be to use a self-consistent spectral model of H\textsubscript{2}, based on the incident XUV and EUV solar flux. This would help to univocally determine 1) the mean energy of the photoelectrons responsible of the airglow, 2) the relative contribution of photoelectron and fluorescence excitation to the total emission and 3) that the airglow at Saturn, as for Jupiter, can be solely attributed to solar fluorescence and photoelectron excitation without the need of an additional energy source.
Acknowledgements

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References

Ajello, J. M., Srivastava, S. K., Yung, Y. L., 1982. Laboratory studies of UV emissions of H$_2$

Ajello, J. M., W. Pryor, L. Esposito, I. Stewart, W. McClintock, J. Gustin, D. Grodent, J.-C.
Gérard, J.T. Clarke, 2005. The Cassini Campaign observations of the Jupiter aurora by the
Ultraviolet Imaging Spectrograph and the Space Telescope Imaging Spectrograph, Icarus,

Ajello, J. M., Gustin, J., Stewart, A. I. F., Larsen, K., Esposito, L., Pryor, W., McClintock,
Ultraviolet Imaging Spectrograph: FUV disk analysis, Geophys. Res. Lett., 35, L06102,

McConnell, J.C., Kumar, S., Hunten, D.M., Atreya, S.K., Donahue, T.M., Moos, H.W.,
observations from Voyager 1 encounter with Saturn, Science, 212, 206.

Broadfoot, A. L. and 18 co-authors, 1986. Ultraviolet Spectrometer Observations of Uranus,


### Table 1: overview of the UVIS limb scan dataset

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<th>Start time</th>
<th>Number of records</th>
<th>Integration per record (s)</th>
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<th>Mean incidence angle (deg)</th>
<th>Mean phase angle (deg)</th>
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<td>3-16.5, 35</td>
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<td>73</td>
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<td>75</td>
<td>-17.5, 133.5</td>
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<td>79</td>
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<td>-18, 140</td>
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<td>-18, 238</td>
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Table 2: Characteristics of the main contributions to the airglow emission.

<table>
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<tr>
<th>Emission</th>
<th>Peak limb brightness from UVIS (R)⁶</th>
<th>Peak altitude (Km)</th>
<th>Main H₂ line contributing</th>
<th>Average brightness from – 1200 to 2500 km MRH (R)</th>
<th>Disk values from Liu and Dalgarno, 1996 (R)⁷</th>
<th>Peak limb values from V1 and V2 (R)⁸</th>
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<tbody>
<tr>
<td>H Ly-α</td>
<td>802</td>
<td>1100</td>
<td>-</td>
<td>441</td>
<td>V1: 1936, 2543, V2: 1845</td>
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<tr>
<td>L(6,x)³ P(1) from H Ly-β</td>
<td>120</td>
<td>1000</td>
<td>L(6,11) P(1) at 1546 Å</td>
<td>42</td>
<td>9.2</td>
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<td>L(11,x)² R(1) + P(3) from H Ly-γ</td>
<td>13</td>
<td>750</td>
<td>L(11,7) P(3) at 1279 Å</td>
<td>6</td>
<td>2.8</td>
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<tr>
<td>L(2,x)³ R(4) + P(6) from NII</td>
<td>35</td>
<td>900</td>
<td>L(2,10) R(4) at 1623 Å</td>
<td>15</td>
<td>3.1</td>
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<td>W(1,x)⁴ Q(3) from NII &amp; OVI</td>
<td>26</td>
<td>1250</td>
<td>W(1,5) Q(3) at 1208 Å</td>
<td>10</td>
<td>2.2</td>
<td></td>
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<tr>
<td>L(5,x)⁵ R(1) + P(3) CII &amp; OVI</td>
<td>60</td>
<td>900</td>
<td>L(5,11) P(3) at 1613 Å</td>
<td>18</td>
<td>7.1</td>
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<td>1607 Å from H Ly-β, CII &amp; OVI</td>
<td>137</td>
<td>950</td>
<td>L(6,13) P(1) and</td>
<td>33</td>
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<td>1255 Å mystery feature</td>
<td>18</td>
<td>1200</td>
<td>L(5,12) R(1)</td>
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<td>OI triplet</td>
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<td>-1000</td>
<td>-</td>
<td>4</td>
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<td>Total H₂ bands from e⁻ impact</td>
<td>2743</td>
<td>1150</td>
<td>-</td>
<td>1054</td>
<td>131⁹</td>
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<td>Total H₂ bands from fluorescence</td>
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<td>900</td>
<td>-</td>
<td>460</td>
<td>173⁹</td>
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<tr>
<td>Total H₂</td>
<td>3943</td>
<td>1050</td>
<td>-</td>
<td>1514</td>
<td>304⁹</td>
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1. x = 3, 5, 7, 9, 11, 12, 13, 14. L stands for Lyman and W for Werner bands.
2. x = 5, 7, 9, 10, 14
3. x = 1, 2, 5, 8, 9, 10
4. x = 4, 5
5. x = 3, 5, 6, 8, 10, 12
6. Value deduced from the fits in the 1150-1650Å bandwidth. The total H$_2$ value must be multiplied by 1.33 to obtain the total H$_2$ brightness in the 800-1650 Å range, giving 5244 R. The V1 and V2 limb values in Yelle et al. (1986) refer to “total H$_2$ bands intensity” without specifying a unambiguous spectral range, which makes it difficult to compare the UVIS and Voyager numbers.

7. Values from fluorescence lines listed in Table 2 of Liu and Dalgarno, (1996), adapted to Saturn at solar minimum. A factor 0.295 is applied to convert the solar irradiance from Jupiter to Saturn and a conversion factor 0.44 is used to account for the solar activity variation between Dec 1990 (HUT) and Nov 2005 (UVIS).

8. Values from Yelle et al. (1986), adapted to Nov 2005 solar activity. A factor of 0.44 and 0.41 is applied to convert from V1 to UVIS and V2 to UVIS, respectively. Two values are associated with V1 because two limb scans have been performed. The V1 Ly-a values have been multiplied by 0.68 to take into account the UVS damages during the Jupiter encounter (Ben Jaffel et al. 1995).

9. According to Liu and Dalgarno, (1996), the solar fluorescence on Jupiter contributes 57% of the total observed dayglow emission.
Figure captions

Figure 1:  a) Projection of the UVIS slit for the limb viewing observation obtained on 29 October 2005 (case 1 in Table 1), showing the four records of the sequence. The long side of the slit represents the 64 spatial pixels of the aperture. A FUV spectrum is associated with each spatial pixel.

b) Viewing geometry for a given impact parameter $Z_0$ (minimum ray height). The observed brightness $B(Z_0)$ is the sum of the $\nu(S)$ intercepted along the line of sight and attenuated by $\tau(S)$ (equations (1), (2) and (3) within the text).

Figure 2:  a) All the raw UVIS spectra have been summed into 50 km altitude bins. The few examples shown here indicate that the emission longward of 1550 Å is dominated by solar reflectance for the low altitude spectra (~1325 to 625 km). The H$_2$ bands prevail from 625 to ~3000 km. The emission above ~3000 km has a very low S/N ratio and is considered as background. The baseline of each spectrum has been incremented for better legibility.

b) Examples of integrated limb brightness profiles for different spectral ranges. The observed solar reflected emission in the 1700-1880 Å range maximizes at ~950 km MRH with 16.5 kR, while the total H$_2$ bands reach a maximum brightness at 1050 km MRH. In particular the ratio of the 1550-1620 Å and 1230-1300 Å bandwidth defines the color ratio and indicates a strong absorption by CH$_4$ shortward of 1400 Å.

Figure 3:  Comparison between the UVIS spectra at ~1025 and 525 km MRH and a model that includes H$_2$ and solar reflected emissions. The best synthetic solar reflected component is then subtracted from all spectra in order to study the H$_2$ airglow. These two
examples illustrate well the dominance of solar reflection at low altitudes (-1025 km spectrum) and the increase of the H2 component at higher altitudes (525 km spectrum). Error bars due to the count statistics are shown at 1765 Å.

**Figure 4:** Mixing ratio profiles of the two main absorbing species obtained from the best fits to the reflected sunlight component between 1500 Å and 1880 Å (solid lines). The acetylene (C2H2) and ethane (C2H6) mixing ratios from the Moses *et al.* (2000) model, averaged along the line of sight, are shown in dashed lines. The various symbols indicate abundances derived from recent observation (adapted from Figure 6 of Sada *et al.* 2005). The error bars reflect the uncertainties in abundances and pressure levels.

**Figure 5:**

a) Best fit to the observed integrated brightness in the 1550-1620 Å range with a Chapman function, following equations (1), (2) and (3) listed in paragraph 4.1. The modeled brightness, calculated every 50 km, has been smoothed over 7 pixels to take into account the spatial extend one UVIS pixel during the observations. The blue squares display the 1550-1620 Å raw profile before the removal of the reflected sunlight component, demonstrating the importance of this step in the analysis.

b) Best synthetic brightness in the 1550-1620 Å bandwidth, unsmoothed, with and without the attenuation by hydrocarbons. It is seen that the signal peaks near the homopause level and is attenuated for MRH below ~900 km.

c) Best β-Chapman vertical profile derived from the fit to the 1550-1620 Å limb brightness. This shows that the emission extends throughout the entire upper atmosphere of Saturn. The listed $v_m$ must be multiplied by 5.27 to extrapolate to the total UV H2 bands in the 800-1650 Å bandwidth.
Figure 6: Examples of the VER intercepted along the LOS and mean optical depth in the 1150-1650 Å bandwidth for two impact parameters. At low altitude, the emission consists of two separated contributions (black curve in panel a), to be multiplied by the cumulated optical depth from each point S to infinity (panel b) The red curve in panel b corresponds to the resulting observed emergent emission. At higher altitudes (panels c and d), the two intercepted VER merge and are more sensitive to the optical depth near S=0.

Figure 7: Color ratio between the integrated brightness in the 1550-1620 Å and 1230-1300 Å bandwidths, illustrating the effect of the CH₄ absorption. The light orange curve shows the synthetic CR obtained before the altitude shift of the observations (see text), and the red curve shows the best synthetic CR obtained after the offset.

Figure 8: a) Example of fit of the airglow emission with the model described in section 4.2, which includes the modeled airglow spectrum of H₂ (fluorescence and electron impact) as described by Hallet et al. (2005) and the HLyman-α line.

b) Comparison between the modeled airglow H₂ spectrum from Hallet et al. (2005) and the laboratory H₂ spectrum obtained from impact with 20 eV electrons from Dziczek et al. (2000). Most of the discrepancies found in Figure 8a are due to the fluorescence lines, clearly apparent in Figure 8b (lines with arrows). See text for details.

Figure 9: Examples of best fit to the H₂ airglow emission, for three altitude bins, obtained from the combinations of a 20 eV electron impact spectrum and individual H₂ fluorescence lines. It is seen that the electron impact component dominates the spectra. The main contributions of fluorescence correspond to the L(6,13) P(1) and L(5,12) R(1)
transitions at 1607.50 Å and 1607.90 Å respectively. A mystery line is added to the regression at 1255 Å. Its effect on the best fit is clearly seen in the 1150 km spectrum.

**Figure 10:** Limb brightness profiles of the main contributors to the H$_2$ airglow emission in the 1150-1650 Å spectral window, derived from the best fits to the emergent spectra. All plots except the H$_2$ brightness and electron impact contribution plots are smoothed over 5 points. A detailed description is provided in Table 2 and within the text.
841 Figures

842

843 Figure 1
Fig. 2
UVIS spectrum at -1025 km

Best synthetic spectrum

UVIS spectrum at 525 km

Best synthetic spectrum

Fig. 3
Fig. 4
Figure 5
Figure 6
Figure 7
Figure 8
Figure 9