



The Enigmatic Abundance of Atomic Hydrogen in Saturn's Upper Atmosphere

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Abstract

A planet's Ly α emission is sensitive to its thermospheric structure. Here we report joint Hubble Space Telescope and Cassini cross-calibration observations of the Saturn Ly α emission made 2 weeks before the Cassini grand finale. To investigate the long-term Saturn Ly α airglow observed by different ultraviolet instruments, we cross-correlate their calibration, finding that while the official Cassini/UVIS sensitivity should be lowered by $\sim 75\%$, the Voyager 1/UVS sensitivities should be enhanced by $\sim 20\%$ at the Ly α channels. This comparison also allowed us to discover a permanent feature of the Saturn disk Ly α brightness that appears at all longitudes as a brightness excess (Ly α bulge) of $\sim 30\%$ ($\sim 12\sigma$) extending over the latitude range $\sim 5^\circ$ – 35° N compared to the regions at equator and $\sim 60^\circ$ N. This feature is confirmed by three distinct instruments between 1980 and 2017 in the Saturn north hemisphere. To analyze the Ly α observations, we use a radiation transfer model of resonant scattering of solar and interplanetary Ly α photons and a latitude-dependent photochemistry model of the upper atmosphere constrained by occultation and remote-sensing observations. For each latitude, we show that the Ly α observations are sensitive to the temperature profile in the upper stratosphere and lower thermosphere, thus providing useful information in a region of the atmosphere that is difficult to probe by other means. In the Saturn Ly α bulge region, at latitudes between $\sim 5^\circ$ and $\sim 35^\circ$, the observed brightening and line broadening support seasonal effects, variation of the temperature vertical profile, and potential superthermal atoms that require confirmation.

Unified Astronomy Thesaurus concepts: Planetary atmospheres (1244); Upper atmosphere (1748); Atmospheric structure (2309); Radiative transfer (1335); Flux calibration (544); Ultraviolet telescopes (1743); Space telescopes (1547); Chemical kinetics (2233); Planetary ionospheres (2185); Interplanetary medium (825); Solar spectral irradiance (1501); Solar ultraviolet emission (1533)

1. Introduction

The global energy balance in Earth's thermosphere is predominantly a product of solar heating. In contrast, the thermospheres of all the outer planets are several times hotter (500–1100 K) than they would be merely from heating by solar radiation (< 200 K), leading to a very intriguing energy crisis. Analysis of many Cassini UVIS occultation observations of Saturn has confirmed a high temperature for its thermosphere, with a net temperature decrease from polar latitudes (~ 590 K) to the equator (~ 370 K) (Koskinen et al. 2013, 2015; Brown et al. 2020).

Besides the thermal structure diagnostic, atomic H, which is a significant component and sensitive tracer of the upper atmosphere of Saturn, can strongly constrain the composition and energy budget of its thermosphere. However, the H content remains unknown and is poorly constrained by occultation observations (Koskinen et al. 2020). On the other hand, the use of planetary airglow observations should be straightforward for deriving atmospheric properties and composition. For example, the shape of the Ly α line profile bears key information that has been successfully used in the past to study the atmospheres of

all the outer planets and their satellites to help determine composition, thermal structure, velocity distributions, and nonthermal processes operating in the upper atmospheric layers (Clarke et al. 1991; Ben-Jaffel et al. 1995, 2007; Chaufray et al. 2010; Strobel et al. 2019).

For instance, Ly α observation of the disk of Saturn started as early as 1976 during minimum solar activity with both a rocket and the Copernicus satellite (Weiser et al. 1977; Barker et al. 1980). In 1980 and 1981, Voyager encounters with the Saturn system allowed a series of observations of the Ly α airglow of the planet during solar maximum activity (Broadfoot et al. 1981; Sandel et al. 1982). In parallel, International Ultraviolet Explorer (IUE) began in 1980 remote observation of the planet at Ly α with a monitoring that lasted until the end of 1990 (Clarke et al. 1981; McGrath & Clarke 1992). One of the first high-resolution observations of the Saturn Ly α nonauroral emission line was obtained with the Hubble Space Telescope (HST)/Goddard High Resolution Spectrometer (GHRS) in 1996 (Ben-Jaffe & Holberg 2016). When the Cassini mission began in 2004, a large set of observations of the planet's Ly α brightness was obtained until the end of the mission in 2017 September. Finally, during a Cassini/HST joint campaign in 2017, Saturn's airglow was recorded simultaneously by both Cassini/UVIS and HST/STIS echelle spectrometers, offering a rare opportunity to assess the UVIS calibration using the well-



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accepted HST calibration as a reference (Bohlin et al., 1990; Bohlin et al. 2019).

One of the complexities of remote observation of Saturn Ly α dayglow is the absorption by the intervening interplanetary medium (IPM) hydrogen between Saturn and Earth. As discussed in the literature, the IPM absorption is Doppler shifted with a spectral position and strength that depend on the heliospheric position of the target with respect to the interstellar medium (ISM) flow. For example, during the HST/GHRS observation in 1996 (Table 2), the IPM absorption was near the Saturn line center, thus necessitating a model of the IPM extinction in order to deduce the undisturbed Ly α brightness from the one measured by HST/GHRS (e.g., Table 2). As we show below, the new data set obtained by HST/STIS in 2017 does not require such modeling and deduction to obtain the undisturbed Ly α brightness.

In addition to the IPM extinction, degeneracy in theoretical modeling of the airglow and uncertainty related to instrument calibration (see Appendices A–C) and solar flux variability have made the technique questionable and should therefore be carefully addressed (Ben-Jaffel & Holberg 2016; Strobel et al. 2019). For instance, long-term monitoring of the Ly α airglow of Saturn with many space missions has clearly shown that the bright Ly α emission exhibits a strong correlation with the solar cycle, supporting resonant backscattering of the solar and IPM Ly α emission lines as the dominant sources (McGrath & Clarke 1992; Ben-Jaffel et al. 1995). However, contradictory conclusions resulted from the existing data analysis owing to intercalibration issues between instruments (Ben-Jaffel et al. 1995; Koskinen et al. 2020). Using Voyager UVS observations, Ben-Jaffel et al. (1995) stressed the importance of the IPM Ly α emission reflected by the upper atmosphere of Saturn and concluded that there is a need for an enhanced H content of the upper atmosphere ($[H] \sim 9 \times 10^{16} \text{ cm}^{-2}$) in order to fit the disk Ly α brightness ~ 3.3 KR observed by Voyager 1 UVS during solar maximum activity in 1980. In contrast, Koskinen et al. (2020) estimated that the reflected IPM Ly α emission is negligible, and their prediction for the H content ($[H] \sim 3 \times 10^{16} \text{ cm}^{-2}$) is enough to reproduce Saturn’s brightness observed by Cassini/UVIS in 2007 during solar minimum activity. Following Quémerais et al. (2013), they concluded that the Voyager 1 and 2 UVS calibration should then be strongly corrected.

It is important to stress that while all studies described above are derived on the basis of the Ly α line integrated brightness, they are missing the key spectral information of the line profile. Besides calibration issues related to each instrument, the broad Ly α line profile observations by HST/GHRS in 1996 question the conclusions obtained only on the basis of integrated brightness (Ben-Jaffel & Holberg 2016). In addition, we note that past conclusions regarding UVIS and UVS calibration are not adequate because of the absence of a reference instrument observing the genuine Saturn Ly α brightness in the same conditions. The 2017 HST/Cassini campaign reported here addresses that issue.

In the following, we describe the new data sets obtained (Section 2). In Section 3, starting from existing official pipelines, we reassess the calibration of UVIS and STIS around the Ly α spectral band. Independently of any theoretical modeling, we also cross-correlate the calibration of UVIS and STIS with the IUE spectrometer, HST/GHRS, and Voyager 1 and 2 UV spectrometers, all of which observed Saturn Ly α

airglow over the 1980–2017 period. In Section 4, we use an adding–doubling radiative transfer (RT) model to analyze Saturn high-resolution Ly α line profiles observed by HST/STIS and the disk brightness distribution observed by several UV instruments. Finally, we discuss our finding within the global context of Saturn’s complex upper atmosphere, focusing on new modeling efforts that will be required in the future.

2. Observations

On 2017 August 26, HST/STIS performed high-resolution ($\Delta\lambda \sim 0.006 \text{ nm}$) spectro-imaging of Saturn’s dayglow using the echelle E140H grating with the long $52'' \times 0.5$ slit (HST/GO 14931) simultaneously with Cassini/UVIS low-resolution ($\Delta\lambda \sim 0.48 \text{ nm}$) measurement of the nightside brightness. This was the first step of the HST/Cassini campaign that was intended to disentangle the IPM source contribution to the planetary Ly α emission. In the second step on 2017 September 2, HST/STIS obtained another high-resolution spectral imaging of the planetary dayglow with a different geometry of observation simultaneously with a Cassini/UVIS scan of the planetary limb. On both dates, HST/STIS also performed near-UV (NUV) imaging of Saturn using an NUV filter (F25srf2) that helped accurately capture the geometry of observation of the oblate shape of the planet. This important step allowed accurate definition the light-scattering conditions at the different locations observed over the planetary disk. Details about all observations obtained during the campaign for both STIS and UVIS are listed in Table 1.

Here, it is important to stress that using HST/STIS E140H echelle grating is crucial to achieve the high-resolution measurement required by the RT analysis of the planetary Ly α line profile. When associated with a narrow and short slit, the STIS echelle mode works well, and it has been used in the past to investigate auroral emissions from other planets (Chaufray et al. 2010). However, when associated with the long planetary slit, the echelle mode is allowed for observations but not fully supported in the Space Telescope Science Institute (STScI) CALSTIS calibration pipeline. Indeed, when using this mode for extended sources, it is difficult to handle overlap between echelle orders at different positions along the long-slit spatial direction, thereby making the extraction of the target signal very difficult. However, as shown in Vincent et al. (2011) and Vincent et al. (2014), there is no issue for cold planetary atmospheres or sky background far-UV (FUV) emission where only the Ly α line is dominant. In addition, even if a few Earth geocorona airglow lines are present, they are several orders of magnitude fainter than the Ly α signal (Vincent et al. 2014). In that frame, as long as we avoid the very bright auroral region, the E140H long-slit echelle mode works well for the Saturn Ly α study. In practice, we have verified that no interorder contamination is affecting our data, which is consistent with long-slit mapping of the Saturn disk outside the polar region. If any faint auroral contamination appears, it must be below the 1σ statistical noise.

In that frame, we calibrated the HST/STIS E140H long-slit echelle data using the procedure described in detail in Appendix B (see also Vincent et al. 2011, 2014). In summary, for each exposure, starting from the flat-field file provided by STScI, the pipeline consists in correcting the geometry distortion of the spectral image, subtracting the so-called detector FUV glow that is monitored by STScI over time, and using a new technique for removing the contamination from

Table 1
HST/STIS^a and Cassini/UVIS Observations Obtained during the HST/Cassini 2017 Campaign

Instrument/Grating	Mode	Data Set	Obs. Date	Obs. Time	Expo. Time (s)	Description
HST/E140H	52 × 0.5	ODFBA1010	2017-8-26	02:40:24	1861.148	Saturn disk
HST/E140H	52 × 0.5	ODFBA1020	2017-8-26	03:57:17	2941.195	Saturn disk
HST/E140H	52 × 0.5	ODFBA1030	2017-8-26	05:33:21	2898.193	Saturn disk
HST/G140M	52 × 0.1	ODFBA1040	2017-8-26	07:07:59	597.001	Saturn disk
HST/MIRFUV	F25SRF2	ODFBA1D8Q	2017-8-26	07:41:33	907.200	NUV disk
HST/E140H	52 × 0.5	ODFB1A010	2017-8-26	08:47:54	2483.184	Sky Back.
HST/E140H	52 × 0.5	ODFBA2010	2017-9-01	23:57:21	1861.190	Saturn disk
HST/E140H	52 × 0.5	ODFBA2020	2017-9-02	01:13:42	2941.199	Saturn disk
HST/E140H	52 × 0.5	ODFBA2030	2017-9-02	02:49:47	2898.19	Saturn disk
HST/G140M	52 × 0.1	ODFBA2040	2017-9-02	04:24:25	547.014	Saturn disk
HST/MIRFUV	F25SRF2	ODFBB2DIQ	2017-9-02	05:00:02	784.200	NUV disk
HST/E140H	52 × 0.5	ODFB2A010	2017-9-02	06:43:37	2483.193	Sky Back.
Cassini/UVIS	LR	290SA-EQUAMAP001_VIMS	2017-08-26	10:39:36	12,240	Saturn Night
Cassini/UVIS	LR	290SW-IPHSURVEY	2017-8-27	13:55:33	28712.5	Sky Back.
Cassini/UVIS	LR	291SW-IPHSURVEY	2017-8-31	03:02:33	25575	Sky Back.
Cassini/UVIS	LR	291SA-LIMBINT001_PRIME	2017-9-02	02:08:33	20,160	Saturn limb
Cassini/UVIS	LR	FUV1999-231	1999-8-19	01:30:40	64,800	Sky Back
Cassini/UVIS	LR	FUV2007-246	2007-9-03	01:12:28	12,880	Saturn Disk
Cassini/UVIS	LR	FUV2013-133	2013-5-13	00:11:59	28,800	Saturn Disk
Cassini/UVIS	LR	FUV2013-154	2013-6-03	15:42:03	20,880	Saturn Disk
Cassini/UVIS	LR	FUV2014-095	2014-4-05	14:25:03	15,600	Saturn Disk
Cassini/UVIS	LR	FUV2014-100	2014-4-10	14:00:19	38,400	Saturn Night
Cassini/UVIS	LR	FUV2017-016	2017-1-16	10:12:33	2880	Saturn Disk
Cassini/UVIS	LR	FUV2017-018	2017-1-18	00:05:46	4800	Saturn Night

Note. We also use other archive data of different UV instruments that we describe in Section 3.

^a HST data accessible via <https://doi.org/10.17909/caj-3r46/>.

Earth’s geocorona and the sky background Ly α emissions (see Appendix B for more details). To obtain the sky background emission line, we have performed an STIS/E140H spectral imaging of the sky far from the planetary disk during one HST orbit (e.g., Table 1). For reference, the flux calibration is performed using the standard STIS/E140H calibration for extended targets⁸ (e.g., Appendix B).

Remarkably, during the HST/Cassini campaign in 2017 August/September, the spectral position of the IPM absorption ($\sim 10^4$ K) was strongly blueshifted (~ 23 km s $^{-1}$) relative to the Saturn reference frame. Thus, an important consequence is that the red-side half of the Saturn Ly α line profile remains unaffected by the IPM absorption. In the worst-case scenario of a dense IPM, this absorption of the red wing should not exceed $\sim 3\%$. This means that the HST/STIS observation provides the genuine undisturbed half line of the planetary emission (or at

least a minimum value) that can be directly compared to UVIS in situ observations.

To improve the signal-to-noise ratio (S/N) for each date of observation, we merged all available HST exposures (e.g., Table 1) and binned by 50 pixels ($\sim 1''.45$) along the slit spatial direction.

For HST observations, in order to define the light-scattering geometry over the planetary disk that is required for any RT modeling, we first fit the oblate shape of the planet using the NUV image and derive the scattering angles (incident solar angle and emission angle) over the planetary disk, particularly along the projection of the STIS long slit over the planetary disk (e.g., Figure 1). For Cassini/UVIS observations, the scattering geometry is provided by the Cube Generator, which uses SPICE, a NASA/JPL toolkit software.⁹

The resulting Ly α brightness levels for 2017 August 26 and 2017 September 2 are comparable after correcting for the solar

⁸ <https://hst-docs.stsci.edu/stisdhb/chapter-5-stis-data-analysis/5-4-working-with-spectral-images>

⁹ <https://naif.jpl.nasa.gov/naif/toolkit.html>

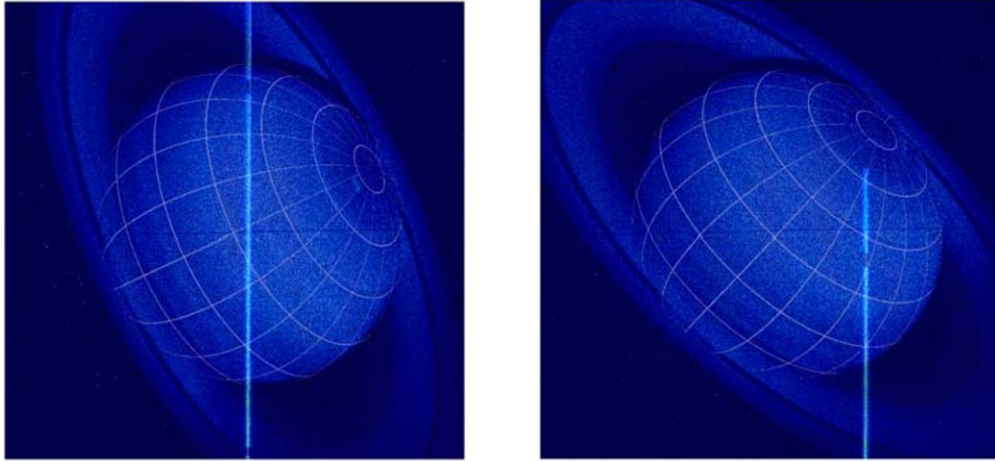


Figure 1. NUV image of Saturn showing the geometry of the HST/STIS observations. The STIS $52'' \times 0.''5$ long slit is shown, particularly the fiducial bars that block light from two regions along the slit and appear as gaps. For 2017 August 26 the slit center was at central meridian longitude (CML), whereas for 2017 September 2 the slit was shifted from CML to avoid the auroral region. At both dates, only the north pole is visible. Left: sketch for the 2017 August 26 observations. Right: same as the left panel, but for the 2017 September 2 observations.

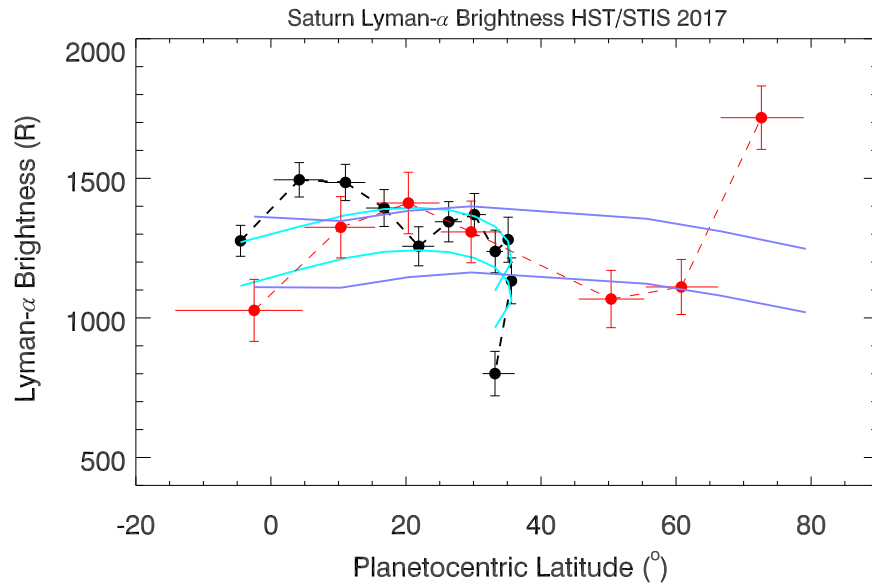


Figure 2. Saturn dayside Ly α total brightness vs. planetocentric latitude, observed by HST/STIS during the HST/Cassini 2017 campaign. All brightnesses are scaled to the 2017 September 2 solar flux condition. Data are averaged over 50 pixels along the HST/STIS long slit (1 pixel $\sim 0.''029$ along the spatial direction). We show 2017 August 26 brightness (black), 2017 September 2 brightness (red), and RT model brightness for $2\times$ and $3\times$ the reference H I content (aqua for August 26 RT model and blue for September 2). We provide the reference H I content vs. latitude in Section 4.

flux difference between the two dates (e.g., Figure 2). First, we remark that the 2017 September 2 data set is much closer to a latitudinal distribution (along meridian; e.g., Figure 1). In contrast, the 2017 August 26 observations better show the effect of the incident/emission scattering angles. A dip in the brightness distribution of August 26 appears around latitude $\sim 20^\circ$ N but cannot be confirmed because of the noise level. For reference, the solar flux on 2017 September 2 is close to a minimum of solar activity and will be used in the following as our reference level. The change is remarkable in the line profile versus latitude (and also scattering geometry) that we show in detail using the 2017 September 2 observations, which cover an extended latitudinal range from the equator up to the north pole (e.g., Figure 3). The STIS Ly α brightnesses will be used as our reference for the cross-correlation with past UV instruments that we investigate in the following section.

3. Cross-calibration of UV Instruments (1980–2017)

For reference, we describe the STIS E140H long-slit mode calibration steps in Appendix B and those of UVIS in Appendix C.

In the following, we cross-calibrate STIS, UVIS, IUE, Voyager 1 and 2 UVS, and HST/GHRS instruments, using Ly α archive observations of Saturn obtained between 1980 and 2017 that cover nearly four consecutive solar cycles. To achieve our goal, we only assume that the Saturn Ly α brightness is resonance backscattering of solar and interplanetary light sources by its upper atmosphere. Indeed, as discussed in the introduction, there is strong evidence that this should be the case (McGrath & Clarke 1992; Ben-Jaffel et al. 1995), yet we have no idea how it is achieved, and we make no specific assumption about the atmospheric composition. To implement the comparison while avoiding theoretical model uncertainty

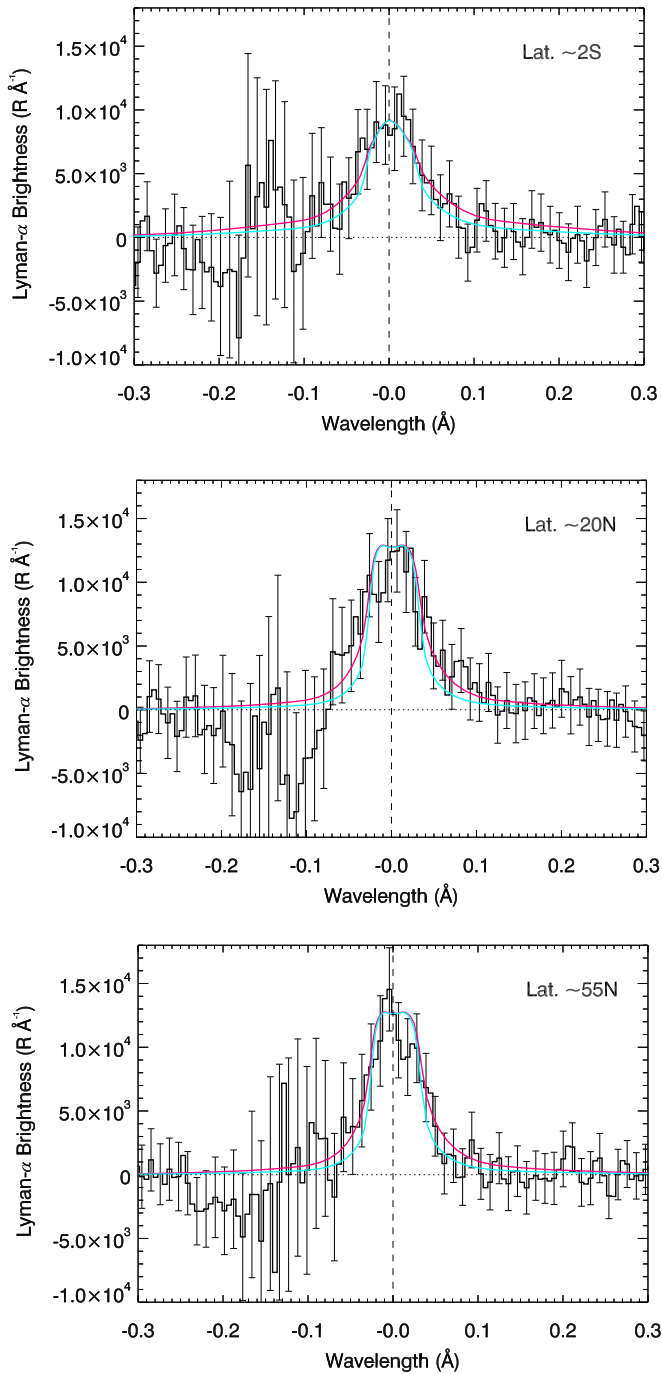


Figure 3. Saturn Ly α line profiles observed by HST/STIS (E140H echelle grating and the long slit $52'' \times 0.5''$). Only the red-side half of lines is used in the brightness diagnostic. Line profiles are shown at specific latitudes indicated in each panel (averaged over the latitude range highlighted in Figure 2). We show RT line profile models using a reference photochemistry model (aqua) and a best fit (red) corresponding to 2–3 times enhanced H I column atmospheric models. Only the red-side half of the line is used in our analysis. Top: line profile in the latitude range $[-13^\circ, 5^\circ]$ when the region was near the planetary limb, a position that explains the line broadening that the RT model reproduces well for a H I column $2\times$ the reference model. Middle: line profile in the latitude range $[16^\circ, 25^\circ]$. For this position, the RT model requires a H I column $3\times$ the reference model. Bottom: line profile in the latitude range $[50^\circ, 60^\circ]$. For this position, the RT model requires a H I column $2\times$ the reference model.

when possible, we use four key parameters to describe the scattering processes that produce the Ly α emission of the planet: phase angle between incident light and observer line

of sight, incident angle of the incoming light source, emission angle of the emitted light measured from the local normal to the surface, and the planetocentric latitude location. As shown below (Figure 7), we found no apparent dependency of the Ly α brightness of Saturn on the planetary longitude (Yelle et al. 1986). Finally, we must point out that, when needed, we do include a slight correction ($\sim 10\%$) for the change of the atmospheric reflectivity between minimum and maximum solar activity corresponding to the change in the atmospheric composition (Figure 8). This correction is included for consistency but has no incidence on the conclusion on the calibration correction derived for the different instruments. Because measurements for our reference HST instruments were made during solar minimum activity, if one does not include the evolution of the atmospheric reflectivity versus solar activity, the derived calibration correction factor should be considered as a minimum value. In that frame, our cross-calibration correction factors (minimum) are model-free, particularly for the comparison between STIS and UVIS.

One key input also required to achieve the cross-calibration is an accurate estimation of the solar flux at the Saturn orbit for each date of observation. Usually, the flux at the solar Ly α line center is taken as a reference in the literature. For consistency, we use the LISIRD Colorado database that provides the solar Ly α line profile at 1 au, a combination of measurements from multiple instruments and models to estimate the full disk integrated solar Ly α line profile over time (Machol et al. 2019). In addition, we take into account the change in the solar disk irradiance due to the solar rotation between the date of Saturn observation and the LISIRD daily prediction/measurement. In a second step, we propagate the 1 au line profile to the orbital position of Saturn (Table 2), taking into account the absorption by the interplanetary hydrogen (IPH) between the Sun and the planet (Wu & Judge 1979). The IPH absorption depends on the Saturn orbital position in the heliosphere that we describe by the angle between the Sun and Saturn, the interstellar upwind directions, and the distance from the Sun (e.g., Table 2). As shown in Figure 4, the imprint of the IPH absorption is not negligible, showing an asymmetric line profile $F(x)$ (where x is wavelength relative to the line center), which affects the flux level near the line center. Recall that the flux of interest for RT calculations of the planetary brightness is the mean $(F(x) + F(-x))/2$ (e.g., Figure 4, magenta curve). For example, for the 2017 August 26 observations, the average flux around the line center ($\pm 0.15\text{Å}$ from line center) is $\sim 12\%$ smaller when the IPH absorption is included.

For the different observations included here, the line-center average fluxes are shown in Table 2 and will be used for scaling the Saturn Ly α brightness obtained at different dates between 1980 and 2017.

Fortunately, during the lifetime of the Cassini mission, a rich database was collected between 2006 and 2017, sampling extended scattering properties over time. Therefore, starting from the scattering properties obtained during the HST/STIS observations (Section 2), we used the OPUS powerful engine¹⁰ to search in the PDS archive for UVIS observations obtained in the same scattering properties (within $\sim 1^\circ$ angular error bar) as for each of the two HST/STIS data sets separately (2017 August 26 and 2017 September 2).

¹⁰ <https://opus.pds-rings.seti.org/>

Table 2
Summary of Saturn Ly α Brightness, Solar Flux Variation, and Intercalibration Factors during the Period 1980–2017

UV Instrument	Date (day/yr)	Orbital Position (au)	Angle/Upwind (deg)	Flux (@Sat) (avg $\pm$ $-0.15\text{\AA}$) $\times 10^9$ photons $\text{cm}^{-2} \text{s}^{-1}$	Calibration Correction/Reference Instrument
IUE	322/80	9.51	73.	5.78	1.07/STIS
V1	317/80	9.52	73.	6.093	0.8/STIS
V2	238/81	9.6	65.	6.612	0.95/STIS
GHRS	359/96	9.47	105.	3.662	0.97/STIS
UVIS	246/07	9.234	110	3.95	1.78/GHRS
UVIS	133/13	9.83	39	4.056	1.73/STIS
UVIS	154/13	9.83	41	3.973	1.75/STIS
UVIS	95/14	9.9	43	4.892	1.75/STIS
UVIS	238/17	10.06	7.0	3.053	1.7–1.8/Night/STIS
STIS	238/17	10.06	7.0	3.053	1
STIS	245/17	10.06	7.0	3.463	1

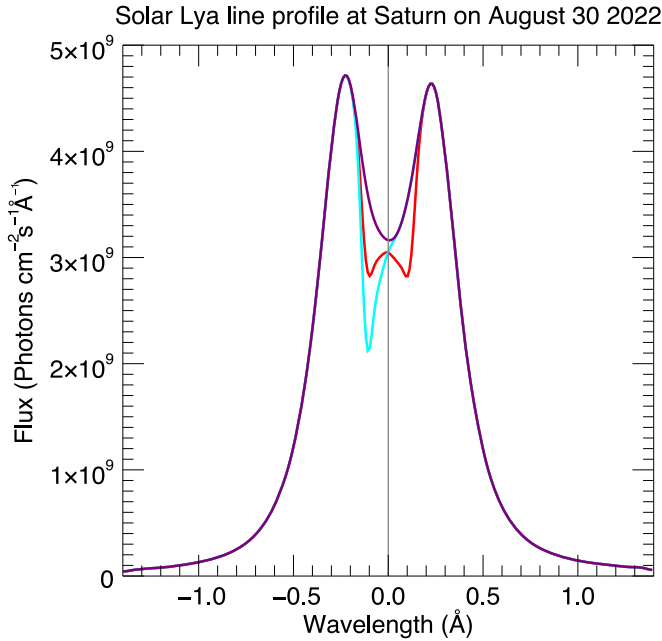


Figure 4. LISIRD Ly α line profile at Saturn orbital position on 2017 August 30 corresponding to STIS observation on 2017 August 26 (scaled down by the square of the Saturn orbital distance (10.06 au), and taking into account the Sun rotation). We also show the same line profile without the imprint of the interplanetary atomic hydrogen absorption between the Sun and Saturn (magenta). The same line profile is shown but now including the IPH absorption that produces an asymmetric line profile (aqua). Finally, we provide the line profile as seen in the rest frame of the atmosphere ($F(x)+F(-x)/2$) that must be used for RT modeling or for scaling solar fluxes between different dates (red).

We also required that UVIS data be in nonbinned mode (1024 spectral pixels and 64 spatial pixels along the slit; Esposito et al. 2004) to avoid the effect of unexpected “evil” pixels. We could find two data sets obtained on 2013 May 13 and 2013 June 3 that fulfill those conditions. In both cases, using either August or September STIS data sets, we could match STIS and UVIS brightness levels only if UVIS brightnesses are scaled up by an average factor ~ 1.75 (e.g.,

Figure 5), after correcting for the solar flux ratio between the different dates (e.g., Table 2). This scaling is equivalent to reducing the UVIS sensitivity by the same factor.

In the following step, we compare STIS and Voyager V1 and V2 observations, after correction for the solar flux ratio between the different dates (Table 2). We find that while V1 brightnesses need to be scaled down by a factor ~ 0.8 , V2 UVS calibration is compatible with STIS (a correction factor ~ 0.95 on V2).

For GHRS observations, we found a UVIS data set obtained on 2007 September 3 that has comparable scattering properties and comparable solar flux (Tables 1 and 2). Again, after correcting for the solar flux ratio between the two dates, an extra correction ~ 1.78 on the UVIS brightness is required to match the 1996 GHRS measurement (e.g., Table 2).

To compare Voyager V1 to UVIS, we also used OPUS/PDS to find a UVIS data set obtained on 2014 April 5 that has similar scattering conditions and comparable maximum solar activity conditions. After correcting for the solar flux ratio between the dates, we could fit V1 and UVIS distributions using correction factors for the calibration comparable to those derived from the cross-calibration between STIS and V1 (~ 0.8) and separately from STIS and UVIS (1.74) (e.g., Table 2).

From the comparison above, a remarkable similarity appears between the latitudinal brightness measured by V1 in 1980 and the one measured by UVIS 33 yr later (Figure 6). In addition, the same trend is also observed by STIS on 2017 September 2 (e.g., Figure 6). The similarity obtained between the three distinct instrument measurements on different dates and different solar activity, after updating their calibration (Table 2), confirms that the observed latitudinal distribution is a permanent latitudinal pattern (bulge) of the Saturn Ly α disk brightness. The bulge is characterized by a brightness excess $\sim 30\%$ in the latitudinal range $\sim 5^\circ$ – 35° N that is at least 12σ above the brightness in the surrounding regions at the equator and $\sim 60^\circ$ N. In addition, as shown in Figure 7, the distribution has no apparent dependency on the atmospheric longitude, a property of the Saturn Ly α disk brightness that confirms an earlier finding from Voyager UVS observations (e.g., Figure 6 in Yelle et al. 1986).

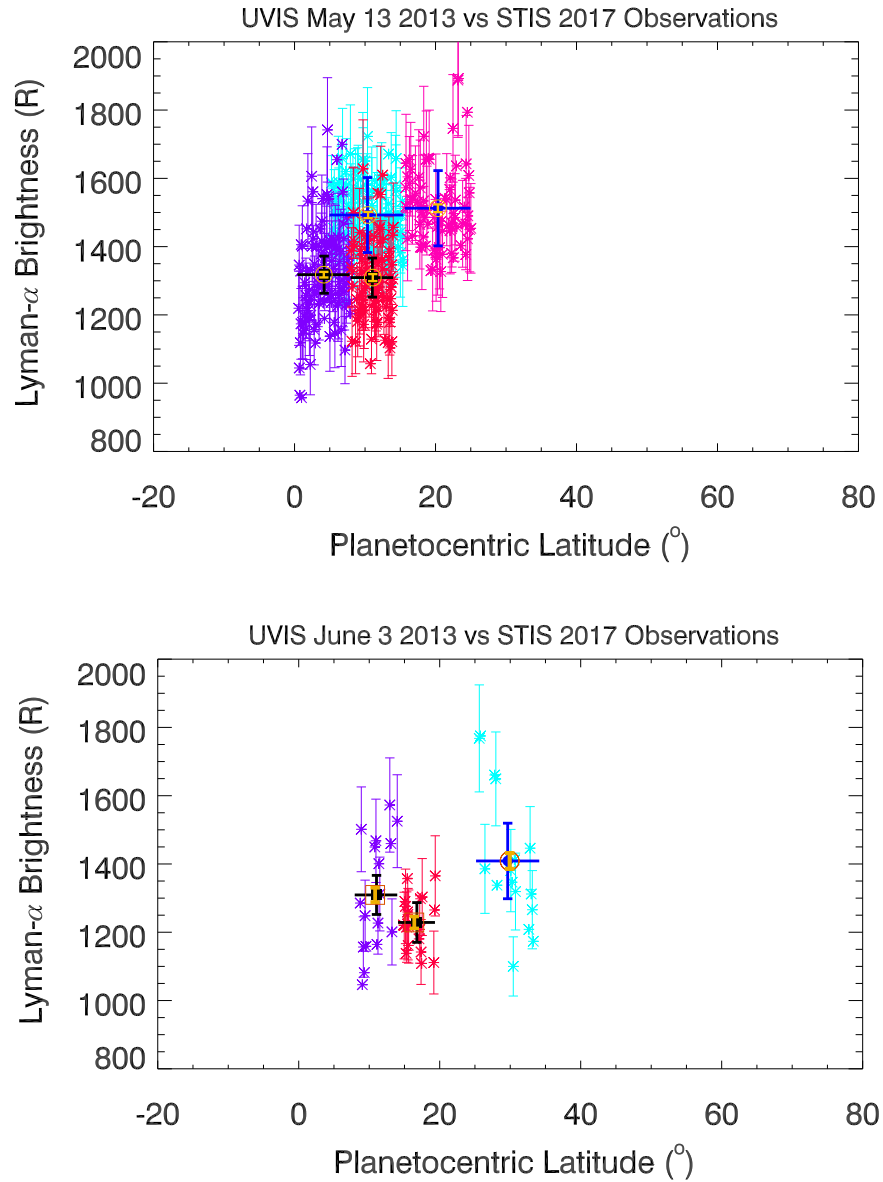


Figure 5. Comparison between UVIS (scaled by a factor listed below) and STIS observations of Saturn Ly α brightness. Clouds of UVIS data points (colored) that fit the same range of scattering properties as the STIS data points (averaged over the same latitude range shown by the STIS horizontal error bars). For each date of HST observations (black for August 26 and blue for September 2 shown in Figure 2), we could find at most two STIS data points for which UVIS data share the same scattering properties. Averages of UVIS data points are shown with attached error bars (gold). Top: UVIS 2013 May 13 data points and related errors scaled (Table 1): purple and red for 2017 August 26 scattering conditions, and aqua and pink for 2017 September 2 scattering conditions. Scaling factors are listed in Table 2, leading to an average correction factor of 1.73 ± 0.05 on UVIS brightness in order to match STIS brightness. Bottom: same as the top panel, but for UVIS 2013 June 3 (Table 1). The average correction factor is 1.75 ± 0.06 .

To further test our diagnostic about the UVIS calibration, we now use a quite different approach based on the night-to-day (N/D) ratio of the Saturn brightness. This ratio is independent of the instrument calibration. Because both Saturn and IPH Ly α emissions are directly proportional to the solar source flux, the N/D ratio should be weakly dependent on the solar flux. In making this assumption, we implicitly require that the atmospheric reflectivity is evolving in the same way for the incident IPH and solar light sources at both low (STIS) and strong (V1) solar activity. For V1 (1980), we derived a ratio $N/D \sim 350 R/3300 R \sim 0.106$ between nightside and dayside brightnesses (Broadfoot et al. 1981).

To check the validity of our assumption about the invariability of the N/D ratio, we searched the UVIS archive around maximum (similar to V1 conditions) and minimum

(similar to HST/STIS 2017 observations) solar activity conditions. We found quasi-simultaneous night (2014 April 10) and day (2014 April 5) observations of the Saturn disk close to the maximum solar activity at the same planetary latitudinal range with a ratio $N/D \sim 0.1065$ (Tables 1 and 2). We also found quasi-simultaneous night (2017 January 18) and day (2017 January 16) observations of the Saturn disk close to minimum solar activity at the same planetary latitudinal range with a ratio $N/D \sim 0.1145$, which is within 10% of the V1 value derived above. In the following, we use both values.

Thus, starting from $N/D \sim 0.106$ to 0.114 measured by Voyager 1 in 1980 or UVIS in 2014 and 2017, we use the nightside measurement $\sim 77.8 R$ made by UVIS on 2017 August 26 (e.g., Table 1) to derive a dayside brightness in the range ~ 730.5 – $679.5 R$. When compared to the daytime

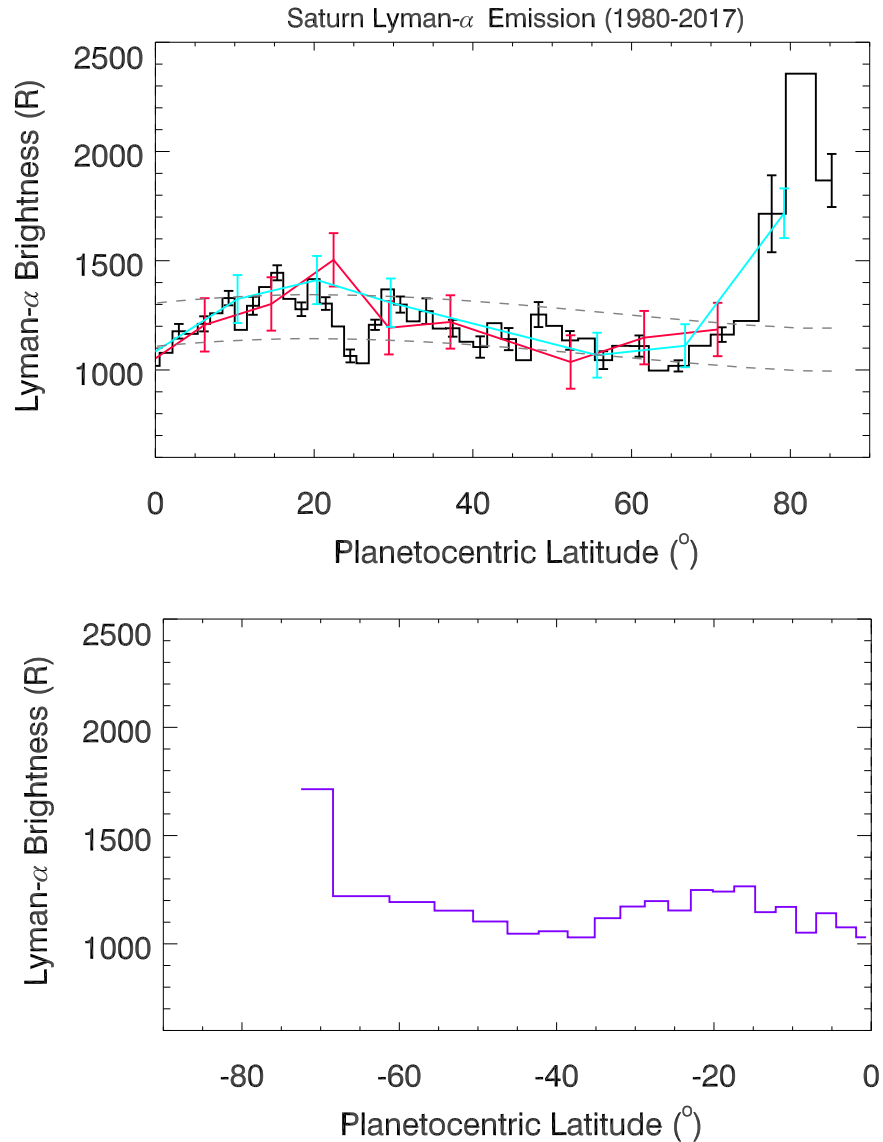


Figure 6. Saturn latitudinal Ly α brightness distribution. Top: north summer hemisphere. Aqua: STIS 2017 September 2. Red: Voyager 1 UVS 1980 November 12 scaled by the solar flux ratio (~ 1.76) between the two dates and corrected for its calibration (~ 0.8). Black: UVIS 2014 April 5 scaled by the corresponding solar flux ratio between the two dates (~ 1.41) and corrected for its calibration (~ 1.74). The remarkable similarity obtained between the three distributions/instruments supports the existence of a permanent latitudinal brightness pattern that appears as a Ly α brightness excess ($\sim 30\%$) in the 5° – 35° N latitude range compared to equatorial and $\sim 60^\circ$ N latitudes. The brightness peak around $\sim 80^\circ$ N is not caused by any RT effect and is probably related to the auroral emission. Dashed: RT model brightness for $2\times$ and $3\times$ the reference H I content. Bottom: for the south summer hemisphere, we show UVIS 2007 September 5 scaled by the corresponding solar flux ratio between the two dates (~ 0.86) and corrected for its calibration (~ 1.78). The Ly α brightness distribution shows no clear latitudinal offset (O’Donoghue et al. 2019) compared to the northern hemisphere but is $\sim 13\%$ less pronounced. Unfortunately, we found no disk Ly α distribution from other instruments for the same south hemisphere and season.

measurement $\sim 1230 R$ obtained by STIS on 2017 August 26 around the same latitudinal range (0° – 20° N), a correction factor in the range ~ 1.68 – 1.80 on the UVIS brightness is required to make the two measurements compatible. This compares rather well with the correction derived on the UVIS calibration at other dates (e.g., Table 2 and Figure 6).

As a final test of the UVIS calibration, we compare the interplanetary emission observed by UVIS on 1999 August 19 (when Cassini was near Earth’s orbit) to the sky background observed by HST/GHRS on 1994 June 4. Both instruments observed the sky background toward the so-called cross-wind direction ($\sim 90^\circ$ from the ISM upwind direction). After correction for the solar flux ratio between the two dates, we

derive that a correction of ~ 1.6 is required on UVIS calibration in order to fit the GHRS IPH observation (Clarke et al. 1998).

For consistency, we also compare the interplanetary emission observed by GHRS on 1994 April 7 to the sky background observed by STIS on 2017 August 26. Both instruments observed the sky background toward the so-called upwind direction during solar minimum activity conditions (the ISM upwind direction). After correction for the solar flux ratio between the two dates, we found no real difference (only a few percent) between the two measurements ($\sim 960 R$; Clarke et al. 1998; see also Appendix B for more details about the IPH line observed by STIS), which is a further indication of the consistency between the two instruments’ calibration.

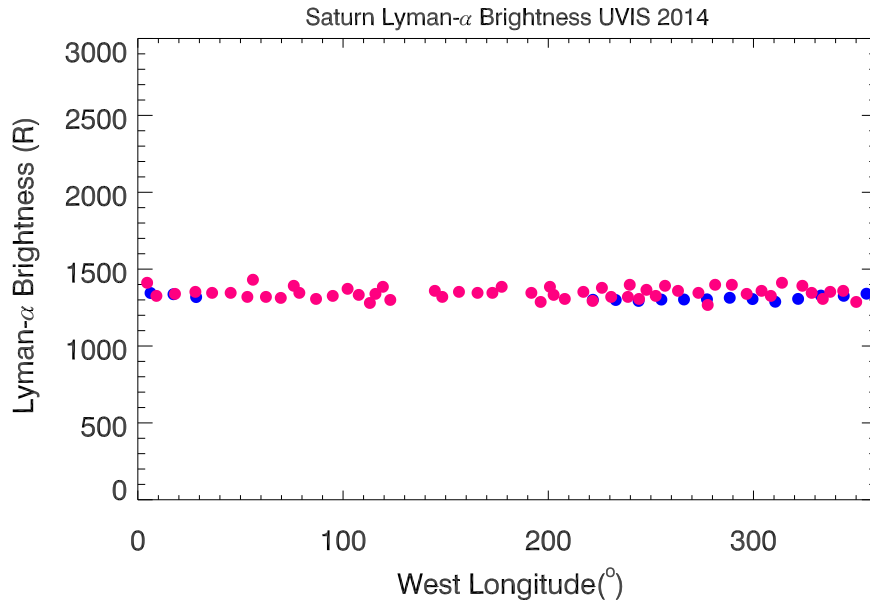


Figure 7. Saturn Ly α brightness distribution (blue) vs. west longitude as observed by UVIS on 2014 April 5 (Table 1). For the covered longitude range, the distribution is fairly flat, much like the distribution derived from Voyager UVS observation in 1980 (red), which strongly supports that the nonauroral Ly α emission shows no apparent variation with longitude.

The conclusion on the correction ~ 1.75 required for the UVIS calibration when compared to HST spectrometers (GHRS and STIS) is robust because it is confirmed by different data sets obtained on distinct dates in both similar and distinct solar activity. The attached error on the average correction factor for the UVIS calibration derived above is relatively small (statistical error less than 5%), yet we increase it to $\sim 10\%$ to account for potential systematic effects related to the assumptions made (line formation, reflectivity, etc.). Our finding harmonizes four decades of NASA space missions that observed the Saturn Ly α airglow over several solar cycles, with the discovery of a permanent latitudinal excess on its disk brightness that did not change between 1980 and 2017.

In the following, we use RT and atmospheric models to compare our brightness model to STIS/HST and archive data of different instruments, focusing on key properties of Saturn’s disk brightness inferred in this section (latitudinal profile, line profiles, etc.).

4. Model Comparison to Observations

To analyze the HST/STIS Ly α data, we use 1D adding-doubling RT model that handles the scattering of photons with the constituents of Saturn’s upper atmosphere that we describe with a photochemistry model. The RT model accounts for partial redistribution of photons during scattering with H, Rayleigh scattering of photons with H $_2$, and photoabsorption by hydrocarbon and water molecules (Ben-Jaffel & Vidal-Madjar 1988; Ben-Jaffel et al. 2007). At the top of the atmosphere, Ly α solar flux and sky background Ly α emission at the orbital position of Saturn are required. For both the solar Ly α line (from Sun to Saturn) and the Saturn Ly α line (from Saturn to Earth), we include the imprint of the IPH absorption on the line profile (e.g., Section 3). For the Ly α sky background emission, we use in situ observations obtained by Cassini UVIS on 2017 August 27 and 31 (e.g., Table 1).

In addition, we use a 1D photochemical model to describe the composition of Saturn’s upper atmosphere as a function of

altitude at specific latitudes during various time frames relevant to the Ly α emission observations. The model utilizes the Caltech/JPL KINETICS code (Allen et al. 1981; Yung et al. 1984) to solve the continuity equations for the chemical production, loss, and vertical transport of species. We develop several different models to test the sensitivity of the H abundance to different assumptions: (1) fixed-season 1D models at specific latitudes relevant to UVIS occultations described in Koskinen et al. (2015, 2016), (2) a time-variable seasonal model (e.g., similar to Moses & Greathouse 2005) for 19 latitudes that considers neutral photochemistry only (adopting the neutral reaction list from Moses et al. 2018), and (3) a time-variable seasonal model of the same 19 latitudes that considers coupled ion–neutral photochemistry (see Moses et al. 2022, for details of the ion–neutral chemistry model). The background atmospheric temperature structure for the latitudes considered in the seasonal model is derived from CIRS and UVIS occultation retrievals from observations late in the Cassini mission (Brown et al. 2020, 2022). In all models, the eddy diffusion coefficient profile is constrained by the methane retrievals from UVIS occultations (e.g., Koskinen et al. 2015; Brown et al. 2022) in the upper stratosphere and by ethane retrievals from CIRS data in the lower stratosphere (e.g., Fletcher et al. 2020). These models provide the vertical profiles of temperature and density of the constituents that contribute to the formation of the Ly α emission from the thermosphere of the planet—namely, H and H $_2$ for photon scattering and CH $_4$, H $_2$ O, etc., for photoabsorption (e.g., Figure 8). To investigate the impact of a change in the gas mean mass, we also consider a few models with different He abundances (e.g., Figure 8).

Ideally, one would solve the RT of the Ly α emission line using an oblate spheroid model for Saturn that takes into account the latitudinal variation of the altitude profile of the temperature and species densities as derived from the occultation observations. However, because the thickness of the H layer is very small compared to the radius of the planet, one could approximate the problem by taking several 1D plane-parallel RT calculations at specific latitudes and build the final

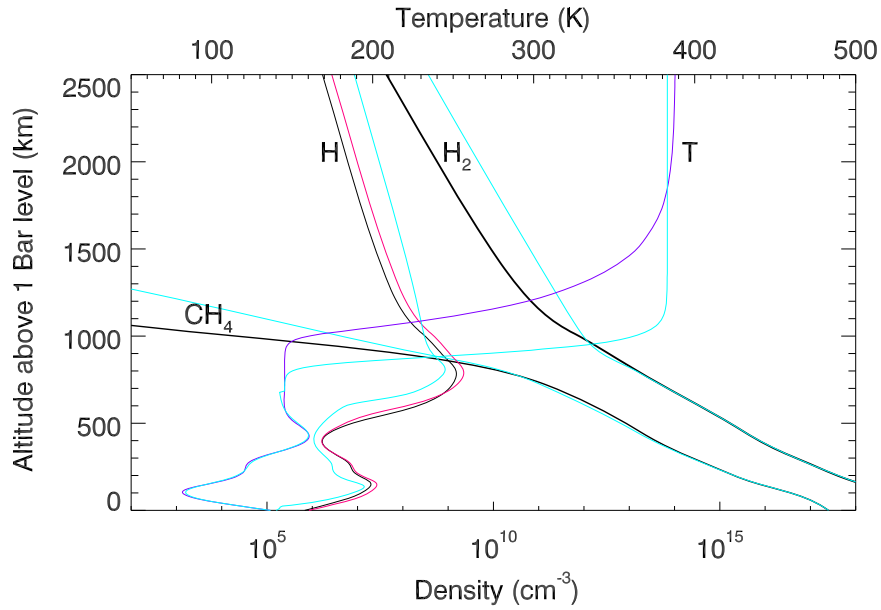


Figure 8. Example results from the photochemistry models of Saturn derived for 2° N planetocentric latitude. The 1D fixed-season models (red and black) adopt the thermal structure derived from a 2015 UVIS stellar occultation described in Koskinen et al. (2016), with an assumed deep helium abundance of 9.18%. The H atom abundance is sensitive to solar activity, and results are presented for solar minimum (black) and maximum (red) conditions. The increase of the solar flux from minimum to maximum activity enhances the H I abundance, which increases the Ly α albedo of the planet by $\sim 10\%$. However, there is a degeneracy between temperatures and the assumed deep He abundance in the UVIS retrievals, as described more fully in Koskinen & Guerlet (2018). For our time-variable seasonal model at 2° N at summer-solstice conditions (aqua), we adopt a thermal structure for this occultation (Brown et al. 2022) that assumes an updated 11% deep helium abundance, such that the resulting lower-thermospheric temperatures must be increased in the “gap” region between the CIRS and UVIS data to account for the larger mean molecular weight of the gas and to maintain the H₂ density at higher altitudes consistent with the UVIS retrievals. The resulting temperature profile is steeper than that derived from Koskinen et al. (2016) in our fixed-season models, and the thermosphere extends deeper, which explains its much larger abundance of H I above the homopause level (above ~ 1000 km).

brightness by interpolating between those single models. Yet this approximation has two limitations: first, it breaks down near the planetary limb because a single line of sight could cross different layers with distinct altitude scaling properties (gravity, temperature, etc.) versus latitudes; and second, fast latitude variation of the atmospheric parameters could be missed even if the H layer is thin.

Because our approach is driven by observations, we will investigate the relevance of any of those assumptions to our study case. For the nightside, we take the same dayside model because the chemical loss timescale for H is many years through the upper atmosphere, and although the production timescale is shorter at some altitudes—down to 90 hr at the μ bar level—that is longer than a Saturn day. In addition, diurnally varying ions (of which H₃⁺ is most important) do not significantly affect the local H abundance over the course of a day, although we find that ion chemistry itself increases the overall H abundance.

Practically, to compare the RT model results to the Ly α data, we generate several photochemistry models (fixed season) in the latitude range covered by the HST observations, namely at planetocentric latitudes (12° S, 6° S, 2° N, 23° N, 32° N, 51° N, and 70° N). For each latitude, we calculate photochemistry models using solar X-ray and UV spectra for both minimum and maximum solar activity conditions (Woods & Rottman 2002). For the time of the HST/Cassini joint observations, the solar cycle was close to minimum activity. For the latitudes listed above, the corresponding total H column is $[H] = (3.78, 3.82, 4.43, 4.23, 3.81, 4.63) \times 10^{16} \text{ cm}^{-2}$. Depending on the hydrocarbon homopause altitude, the H I content that contributes to the Ly α photon scattering is usually smaller.

For each atmospheric model, we ran the RT model and verified that Rayleigh scattering by H₂ has a negligible contribution. This result can be explained by the relatively small optical thickness of the H₂ layer available for Rayleigh scattering above the homopause level.

Because resonant scattering by atomic H appears as the dominant process for the Saturn Ly α line formation, it seems reasonable to investigate the possibility of a different atomic H column from that predicted by photochemistry models. Such thermal or nonthermal H content enhancement could result from many sources/processes such as auroral H production and global transport, precipitation of water or heavy H-bearing species from the ring system or Enceladus, high-resolution ultraviolet cross sections and solar flux (e.g., Kim et al. 2014; Chadney et al. 2022) not considered in our current models, high eddy diffusion coefficients extending into the thermosphere, seasonal modulation versus latitudes, and variation of the species scale height and the temperature vertical profile as discussed below. To facilitate the comparison with the HST/STIS observations (e.g., Figures 2 and 3), we thus conducted a simple sensitivity analysis versus the total H column using a factor $1\times$, $2\times$, and $3\times$ the reference value at each specific latitude.

Interestingly, models corresponding to the reference atmospheric model (for solar minimum activity in 2017) cannot reproduce the observed brightness or the line profiles at all latitudes (e.g., Figures 2 and 3). However, models with 2 to 3 times the reference H content provide a rather good fit to both brightness and line profiles (e.g., Figures 2 and 3). Our result confirms the finding of earlier studies of the need for enhanced H I content to explain the Saturn Ly α airglow (Ben-Jaffel et al. 1995). For instance, doubling H I content is required to fit the

high-resolution line profiles at latitudes around $\sim 2^\circ$ S, 55° N, and 66° N. In contrast, in the range 5° – 35° N, three times the H I content is required to fit the corresponding line profiles (e.g., Figure 3). Thus, a planet-wide enhancement of the H content is clearly required in order to fit the HST/STIS observations over the northern hemisphere up to 60° N. Based on the RT modeling used here, the rather small H I column variation and exospheric temperature modulation with latitude in the considered photochemistry models are quite far from producing a modulation of $\sim 30\%$ contrast in the $\text{Ly}\alpha$ brightness as observed by V1, UVIS, and STIS (e.g., Figure 6).

The challenge is then to find the potential sources of atomic H that could enhance the column in the range required by the STIS and UVIS observations, particularly at the latitude range $\sim 5^\circ$ – 35° N. There are seemingly few options to enhance the H content in the thermosphere: either an external source that produces atomic H I or a substantial increase of the H I scale height in the region above the homopause level (Ben-Jaffel et al. 2007). During the grand finale orbits of Cassini, substantial influxes of water $((0.4\text{--}13.7) \times 10^8 \text{ cm}^{-2} \text{ s}^{-1})$, methane $((7\text{--}25.7) \times 10^8 \text{ cm}^{-2} \text{ s}^{-1})$, and other heavy species have been reported around the equatorial region, showing the complexity of the coupling between the rings and the Saturn ionosphere/upper atmosphere (Waite et al. 2018; Yelle et al. 2018; Serigano et al. 2020). Such species modify the atmospheric structure and composition at specific latitudes (Yelle et al. 2018; Moses et al. 2022) and, according to the photochemistry model used here, enhance the H content. Independently, we also have a good indication of water precipitation from Enceladus into the upper atmosphere of Saturn, with an average downward flux of $\sim 1.5 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ planet-wide (Moses et al. 2000; Moore et al. 2015). To test both scenarios, we added a downward flux of water and methane on top of a few of our reference atmospheric models. Interestingly, influx of water from Enceladus in the range $\sim 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ has negligible impact on the H content and $\text{Ly}\alpha$ brightness. However, the influx of water $(\sim 3.7 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1})$ and methane $(\sim 1.7 \times 10^9 \text{ cm}^{-2} \text{ s}^{-1})$ in the range detected during the Cassini grand finale (Waite et al. 2018; Serigano et al. 2022) enhances the H content by a factor as much as ~ 1.75 compared to the reference model, which is close to the factor (2) required by the RT analysis at the equator and midlatitudes (50° – 60° N) but still falls short of the value ($3\times$) required in the 5° – 35° N band. The problem is that the H enhancement required by the fit to the HST data is planet-wide, while heavy-species influxes were confined to specific latitudes (O'Donoghue et al. 2019). In addition, recent photochemistry modeling of species influx on Saturn's atmosphere clearly shows that substantial influxes of H_2O above $\sim 10^7 \text{ cm}^{-2} \text{ s}^{-1}$ are not supported by occultation observations, which tend to support the supposition that the measurements recorded by the Ion Neutral Mass Spectrometer were likely caused by small dust particles hitting the spacecraft and/or instrument during atmospheric passage and vaporizing (Moses et al. 2022). Considered in that way, it is difficult to link the H I enhancement required to fit the $\text{Ly}\alpha$ observation to H_2O influx from the rings.

A second possibility for enhancing the H I content is to increase its scale height in the region above the homopause where most of the $\text{Ly}\alpha$ photons are backscattered. For reference, the structure and composition of the thermosphere

are based on connecting two regions—namely, the region at pressures larger than a few $\times 10^{-3}$ mbar that is probed by the CIRS limb scans, and the region at pressures below a few $\times 10^{-5}$ mbar that is best probed by UVIS occultation observations (Guerlet et al. 2011; Koskinen et al. 2015). In between, there is a gap where the temperature gradient is poorly constrained (Koskinen et al. 2015; Brown et al. 2020). If one adds the uncertainty on the gas mean mass and scale height that are sensitive to the He abundance, the resultant species local scale height and abundance could also be affected.

In the following, we test the scenario of a change in the thermal structure of the gap region, taking into account ion chemistry and seasonal effects (over several Saturn years) that might also enhance the H content versus latitude depending on Saturn's season. As expected, the addition of ion chemistry does indeed result in more H, especially in the northern (summer) hemisphere. In addition, we observe much more H I in the seasonal model above the homopause because the whole atmospheric scale height (mean molecular weight) increased owing to a larger deep helium mixing ratio (11%) used compared to the fixed-season model (9.8%). For instance, the temperature profile starts increasing deeper in the atmosphere, providing hotter H I in the gap region (yet with the same final exospheric temperature; e.g., Figure 8). The net effect is that the new H I distributions reflect enough $\text{Ly}\alpha$ photons to fit the $\text{Ly}\alpha$ line profile near the equator and 55° N latitudes but still cannot reproduce the excess in the $\text{Ly}\alpha$ brightness observed in the 5° – 30° N latitude range (e.g., Figure 9). However, the solution to the temperature profile in the gap region as used in the seasonal model is not unique. One can, in theory, adjust the temperature profile to improve the H atom abundance in order to enhance the $\text{Ly}\alpha$ brightness, as long as the overall H_2 density still remains consistent with the UVIS occultation and the gas scale height is also consistent with the He abundance assumed deep in the atmosphere.

As discussed above, the $\text{Ly}\alpha$ observations could be used to help break the degeneracy attached to the retrieval of the temperature vertical profile in the gap region between a few microbars and $\sim 0.01 \mu\text{bar}$. To achieve that goal, it is likely that using a global approach that associates distinct data sets is required. For instance, using occultation data together with He 584A airglow helped retrieve the deep atmosphere He mixing ratio for Jupiter ($\sim 16\% \pm 3\%$) and Saturn ($\sim 15\% \pm 2.5\%$) using specific temperature profiles based on occultation observations. For Jupiter the derived He mole fraction (0.136) is consistent with the Galileo probe in situ value (0.137), while for Saturn the derived He mole fraction ($\sim 0.13 \pm 0.02$) is larger than previously reported, making the stratosphere warmer by ~ 149 K (Ben-Jaffel & Abbes 2015). Similarly, CIRS limb scans and UVIS occultation measurement have been combined to investigate the thermal structure of the thermosphere and the deep atmosphere helium mixing ratio ($\sim 11\%$) of Saturn (Koskinen & Guerlet 2018). More than likely, the next step is to consider an iteration between the CIRS limb scans, UVIS occultation data, and $\text{Ly}\alpha$ observation that should better constrain the temperature vertical profile, a task that is beyond the scope of this preliminary investigation.

Besides the impact of the vertical temperature profile, our first test of a seasonal model indicates a potential role of ion chemistry and seasonal effect with a substantial enhancement in the H content above the homopause level (altitude ~ 1000 km). It is probable that sophisticated, time-consuming

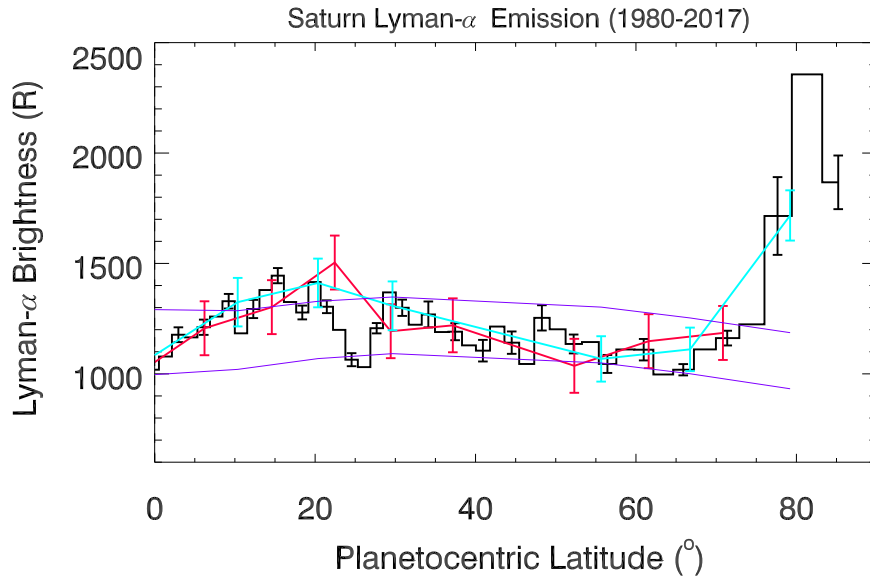


Figure 9. Saturn Ly α brightness in the north hemisphere (summer). Same as in Figure 6, except for the purple curves that represent the seasonal and ion chemistry model brightness for $1\times$ and $2\times$ the H I content. With the later model, we fit rather well the brightness levels near the equator and in the latitude range 50° – 65° N. However, for the 5° – 35° N latitude range, a larger H I content is required that could be produced by a steeper temperature gradient in the gap region between a few microbars and ~ 10 nbar or by a thin layer ($\sim 10^{12}$ cm $^{-2}$) of superthermal H I population in the region above ~ 1 nbar.

simulations that include solar-cycle variations, aurorally produced H, enhanced ring-vapor inflow, and thermospheric circulation would be required to understand definitely the latitudinal distribution of H atoms in Saturn’s thermosphere.

We also consider the impact of the presence of an arbitrary nonthermal H population that could be produced above pressure level ~ 1 nbar. The existence of this layer is justified by conditions (electromagnetic coupling with the rings, heavy-species influx from the rings and Enceladus, etc.) that favor the formation of hot atoms in the outermost region around the exosphere with a transition between a dense atmosphere and the collisionless region above it. For instance, the hot H column is negligible compared to the total H column of the atmosphere, yet the presence of hot atoms could affect the formation of the Ly α emission reflected by the atmosphere (Ben-Jaffel et al. 2007). The source of hot H atoms is defined by the strength of their nonthermal velocity. We are able to fit the Ly α brightness by invoking a latitudinal distribution of superthermal H I with a turbulent velocity ~ 18 km s $^{-1}$ (such as that produced from photodissociation of water; Crovisier 1989); however, the origin of this population is arbitrary, and it is difficult to imagine that thermospheric winds would produce such a great level of turbulence (Sommeria et al. 1995). In addition, it is unclear how such a population could survive thermalization by collision with the ambient gas. Kinetic ionospheric modeling is required to investigate some of these issues, a task that is also beyond the scope of this study.

At latitudes above $\sim 60^\circ$, the influence of the auroral activity could be suspected at the origin of the brightness/width excess observed by HST/STIS. Indeed, the efficiency of the excitation of H/H $_2$ species by impact of energetic particles that produce Ly α photons should decrease with latitudes from the main auroral north and south ovals ($\sim \pm 80^\circ$) down to latitudes $\sim \pm 50^\circ$, respectively (Ben-Jaffel et al. 1995b, their Figure 2). We inspected the STIS spectrum for any weak auroral emission features but found no indication, probably because the detector thermal glow is the dominant source of contamination. The investigation of this potential process is beyond the scope

of our study but should be addressed by future modeling of the auroral region based on the new HST/STIS observations obtained on 2017 September 2.

5. Discussion and Conclusions

We report HST/STIS echelle high-resolution observations of the Saturn Ly α emission line obtained during a joint Cassini/HST campaign that occurred 2 weeks before the end of mission final plunge in 2017. From the STIS observations, we derive brightness and line profiles versus latitude that we use to compare to previous UV instruments (IUE, Voyager 1 and 2 UVS, HST/GHRS, UVIS) independently of any theoretical modeling. In this study, we searched the PDS UVIS archive to find UVIS brightness measurements that are obtained with light-scattering conditions as close as possible to the ones observed by IUE, Voyager 1 and 2, HST/GHRS, and HST/STIS over the last four solar cycles (since 1980).

As shown in Table 2, our finding is that the Voyager 1 UVS sensitivity should be corrected by $\sim 20\%$ upward at the Ly α channels, the Voyager 2 UVS sensitivity should remain unchanged, and the Cassini/UVIS should be revised 75% downward if we take the HST instrument calibration as a reference. In addition, we found no need to correct the calibration of IUE and HST/GHRS compared to HST/STIS, as the required correction is less than 5% (e.g., Table 2). With the revised calibrations, all detectors provide the right Ly α brightness level of Saturn at different epochs despite the evolving solar cycle.

The resulting corrections of the UVS brightness ($\sim 20\%$ downward for V1 and $\sim 4\%$ for V2) are within the 30% uncertainty attached to the instruments’ calibration (Ben-Jaffel & Holberg 2016). In addition, Puyoo et al. (1997) discussed such a possibility of change in the UVS calibration and provided its impact on the far undisturbed ISM H density that should be revised from ~ 0.25 down to ~ 0.22 cm $^{-3}$ before any filtration in the outer heliosphere. In both cases, the derived ISM H density is consistent with the most recent RT

investigation of the sky Ly α brightness distribution in the deep heliosphere as measured by Voyager 1 UVS (Katushkina et al. 2016).

This comparison also allowed the discovery of a permanent feature of the Saturn disk Ly α brightness that appears at all longitudes as a brightness excess of $\sim 30\%$ extending over the latitude range $\sim 5^\circ$ – 35° N compared to the regions at equator and $\sim 60^\circ$ N. This feature is confirmed by three distinct instruments between 1980 and 2017 in the north summer hemisphere of the planet. In contrast, in the southern summer hemisphere, the Ly α brightness shows less modulation. Interestingly, the Saturn latitudinal Ly α distribution was reported 6 yr after the Voyager observation in 1980 and described as a distribution that shows no significant variation (Yelle et al. 1986). Finding the same feature observed by three different instruments was the key step in uncovering the Saturn bulge in the present study.

From the STIS observations, we derive brightness and line profile distributions versus latitude that we analyzed with an RT model combined with a latitude-dependent photochemistry model, itself constrained by Cassini/UVIS occultation observations. Our first finding is that the sophisticated photochemistry model does not produce enough atomic hydrogen to explain the Ly α brightness and line profile at all latitudes (planet-wide). By scaling the H distribution predicted by the photochemistry model, our finding is that 2–3 times the thermal H is required to reproduce the Ly α emission observed by HST/STIS at all latitudes, which calls into question the photochemistry model assumptions.

In an effort to explain the discrepancy, we considered the potential enhancement of the H content via planet-wide water influx from Enceladus on top of the atmospheric model (Moses et al. 2000; Moore et al. 2015). Based on the photochemistry model used here, such H enhancement is negligible and has no impact on the Ly α brightness. In the second step, we considered the possibility of H enhancement by influx of water and other species from the rings of the planet (Serigano et al. 2022). The same photochemistry model shows that the corresponding H content is important (factor ~ 1.75), yet such a large influx of water above $1.0 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$ seems inconsistent with UVIS occultation observations (Moses et al. 2022).

For latitudes above $\sim 50^\circ$, auroral processes could potentially explain the bright and wide emission lines observed, but this requires confirmation by quantitative RT and auroral photochemistry modeling.

However, for latitudes below $\sim 50^\circ$ but different from those visited during the grand finale, we still need a global H enhancement. In addition to ion chemistry that is efficient to enhance the H content, here we propose two additional potential scenarios that need confirmation in the future:

1. The first scenario is related to increasing the species scale height in the region between a few microbars and ~ 10 nbar, a gap that is poorly constrained by ultraviolet occultations or infrared remote-sensing observations. A tentative comparison with a photochemistry model using solar-cycle average solar flux values, ion chemistry, a deep atmosphere He mixing ratio of 11%, seasonal variations in geometry, and Gaussian-shaped H₂O influx as a function of latitude does provide the H I content required by the present Ly α analysis at several latitudes. More sophisticated simulations that include auroral

production, ring-vapor inflow, thermospheric dynamics, a thermal structure that is consistent with the still-unconstrained He deep atmosphere mixing ratio, and ionospheric processes are needed to better understand Saturn's atomic H distribution.

2. The second scenario is related to the production of superthermal H I population at high altitudes following the influx of materials from the rings or from Enceladus, or from turbulence produced from thermospheric winds. We have tested the potential effect of a thin hot H I layer that effectively enhances the planetary Ly α emission. However, it is not clear how this population is produced or how it could survive in the upper thermosphere.

Finally, our findings seem to confirm the main trend so far observed for exoplanets: their diversity. For instance, the Ly α bulge of Saturn is related to the influx of materials from the planet's rings, showing no significant longitudinal variation. In contrast, the Ly α bulge of Jupiter shows strong variation with the system III longitude of the planet, making the planetary magnetic anomaly the primary suspect at the origin of the process (Dessler et al. 1981). More generally, the H I content and the thermal structure of the extended atmosphere of most known exoplanets remain uncertain, with a degeneracy that existing models have difficulty resolving (Shaikhislamov et al. 2018; Ben-Jaffel et al. 2022). Our findings for the upper atmosphere of Saturn show the dramatic impact of material influx from a ring system on the intrinsic composition/structure of the upper atmosphere of a giant exoplanet. In that frame, improving our understanding of the Saturn upper atmosphere (seasonal effects, thermospheric structure, etc.) is required in order to build the right diagnostic tools to properly interpret transit observation of a planetary system where a ring system is suspected.

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Some of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST) at the Space Telescope Science Institute. The specific observations analyzed can be accessed via <https://doi.org/10.17909/cafi-3r46/>.

Appendix A

First, we note that the calibration issue concerns the Ly α channels and not wavelengths shorter or longer than Ly α . Indeed, outside the Ly α channels, most instruments agree on the flux levels measured for stellar targets like Adhara (ε CMa),

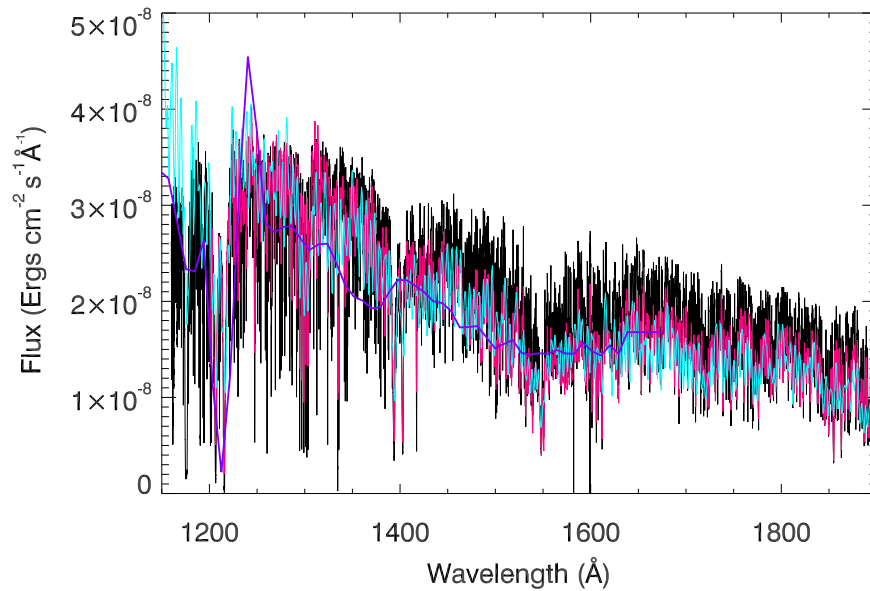


Figure 10. Comparison of the FUV spectrum of Adhara (ϵ Cma) observed by four NASA instruments: HST/STIS E140M (black), Voyager 2 UVS (purple), Cassini/UVIS (turquoise), and IUE (magenta). The flux levels recorded by the four instruments are consistent within $\sim 20\%$, yet nothing could be identified on the $\text{Ly}\alpha$ channels that would require a specific investigation (see main text).

a reference star that was used by (Koskinen et al. 2020) to show the consistency between IUE and UVIS. Here, we show the information that was missing: the signal observed by Voyager 2 UVS, for which the $\text{Ly}\alpha$ calibration was revised by a factor as large as 156% by Quémerais et al. (2013), is also consistent with the other instruments (Figure 10).

For reference, $\text{Ly}\alpha$ channels suffer significantly more impact from photons than the other channels do during an instrument's life, which influences the detector's local sensitivity over time. The use of a star like Adhara as a calibration lamp for the $\text{Ly}\alpha$ channels is not consistent with the fact that the stellar flux is nearly vanishing at those channels owing to the absorption by the ISM hydrogen, despite the relatively smaller ISM H content along that line of sight. If any signal appears at those channels, it is the result of the line-spread function of the low-resolution grating used and light scattering inside the instrument. At high resolution, HST/STIS observations of Adhara show almost no stellar photons at the $\text{Ly}\alpha$ channels (HST data sets: ocb6j0020 and ocb6j1020 for STIS/E140H and ocb6j0010, ocb6j1010, and ocb6j2010 for STIS/E140M).

For those reasons, we believe that our technique, which is based on the Saturn $\text{Ly}\alpha$ brightness as a template lamp and uses HST/STIS as a reference instrument, is the most straightforward way to cross-calibrate past FUV instruments despite the different epochs.

Appendix B

STIS pipeline: for each STIS echelle spectral image obtained (three for each HST visit of Saturn):

1. We read a flat-field-corrected image as provided by the STScI pipeline.
2. We obtain MAMA detector glow measured by STScI over very long exposures during the same period (2017).¹¹

3. We remove the scaled 2017 glow image from the Saturn image. The scaling is applied based on the scattered light level measured in the fiducial bar spectral position (which blocks the source light and is only filled by photons scattered inside the detector).
4. We apply geometry distortion correction to the result of step 3 (e.g., Figure 11; McGrath et al. 1998).
5. We use time-tag events to split the original exposure into two subexposures of equal exposure time. This is a new technique to derive the shape of Earth's genuine geocoronal emission line at exactly the same spectral position on the MAMA detector. By subtracting one subexposure from the other, this technique affords the unique opportunity of removing any signal that is not varying over the exposure time (such as the interplanetary $\text{Ly}\alpha$ signal or the planetary emission) and only keeping the varying geocoronal emission line with a lower brightness level, yet with the exact emission-line shape at exactly the same detector position.
6. We scale the genuine geocoronal line shape obtained in step 5 and remove it from the initial observation to obtain the following results:
 - 6a. When using the sky background observation, the genuine geocoronal line derived from the same exposure allows one to properly derive the interplanetary emission line (between Earth and infinity), showing, for the first time, the self-absorption of the line by Earth's geocorona atomic hydrogen (Figure 12). This effect is generally neglected and only rarely discussed in the literature. This step allows for reconstruction of the IPH emission line along that line of sight, which aids in its subtraction from the planetary signal.
 - 6b. When using the Saturn observation (planet + sky background), our new technique allows one to properly derive the planetary emission after subtracting the genuine $\text{Ly}\alpha$ and interplanetary lines (between Earth and Saturn) using a least-squares fitting based on

¹¹ <https://stars.stsci.edu/>

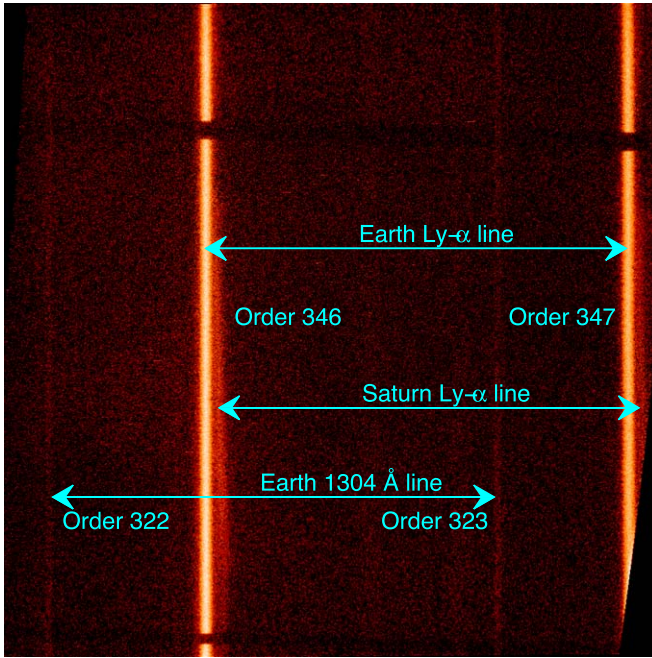


Figure 11. HST/STIS spectral image of Saturn Ly α obtained on 2017 August 26. Corrected for geometry distortion, the image shows the Saturn and Earth emission lines for the two echelle orders. Here, only order 346 is used.

scaling the two line profiles obtained in the previous step. Usually, the IPH emission between Earth and Saturn is ~ 0.55 times the emission of the total IPH line, a fraction that seems weakly sensitive to the heliospheric angular position of Saturn (e.g., Table 2; see also Ben-Jaffel & Holberg 2016).

7. We apply step 4 particularly to the sky background observation obtained during each HST visit in order to derive a detector flat-field correction along the STIS long slit, thereby ensuring that the sky signal should not vary spatially along the slit. We apply the same technique also to derive a flat field along the UVIS slit.
8. We fulfill flux calibration using the STScI official procedure described in the STIS data handbook (Section 5.4),¹² which we briefly describe in the following for the E140H grating when used with the STIS long slit $52'' \times 0''.5$. Following the STIS data handbook, we define the surface brightness for an extended source as

$$B_i = \frac{10^8 N_\lambda h c}{S_\lambda A_{\text{HST}} \lambda f_{\text{TDS}} f_T W m_s \text{disp}},$$

where N_λ is the count rate (ratio of total counts to the exposure time), $h = 6.626 \cdot 10^{-27}$ erg s $^{-1}$ is Planck's constant, $c = 2.8879 \cdot 10^{10}$ cm s $^{-1}$ is the speed of light, and S_λ is the integrated system throughput as provided by the PHOTAB file 15o1440ro_pht.fits (as defined in the STIS data file headers and that can be downloaded from the HST archive). In the expression above, $A_{\text{HST}} = 45,238.93416$ cm 2 is the area of the unobstructed HST mirror, λ is the wavelength (Å), $f_{\text{TDS}} = 0.9$ is the correction for time-dependent sensitivity of E140H, $f_T = 0.98$ is the correction for temperature-dependent sensitivity for the same grating, $m_s \sim 0''.029$ pixel is

the plate scale in the spatial direction, $W = 0''.5$ is the slit width, and $\text{disp} \sim 0.0054$ Å pixel $^{-1}$ is the echelle grating dispersion.

We have applied the above expression to the geometric corrected image derived in the previous step using order 346. Because of the geometric distortion, the echelle order 347 also contains the Ly α line but is not used here because the spectral image is affected at the detector edge.

For consistency, we have tested the same procedure on the E140M observations that we obtained during the same HST visits and that are fully supported by the STScI STIS pipeline calibration. Using the input parameters that are appropriate to that mode, we do obtain the same results as provided by the $_x2d$.fits files produced by the CALSTIS pipeline.

The procedure is further tested using echelle archive observations of stars (e.g., G191B2B) obtained with slit mode $0''.2 \times 0''.2$ that is fully calibrated by the STScI STIS pipeline to obtain consistent results.

9. To improve S/N, exposures obtained during the same HST visit are merged assuming that the planetary signal is not changing over a time period corresponding to 4.5 hr (three HST orbits). We checked the individual exposures and noticed no time-varying signal from the planet (within statistical noise attached to each exposure).
10. We fit the oblate shape of the planet at the time of observation using an optical image of Saturn recorded during the same HST visit. This allows for allocating planetocentric latitudes/longitudes, incident solar light-scattering angles with respect to local normals, and corresponding emission angles with respect to the line of sight to the observer (HST).
11. Doppler shifts due to the planetary spin are corrected for depending on the exact latitude/longitude position on the planetary disk as derived in the previous step.
12. Despite the improved S/N obtained at steps 8–9, we found it necessary to bin spectra (Doppler shifted) each 50 pixels over the STIS slit. This corresponds to an average over a spatial region $1''.2 \times 0''.5$ over the planetary disk.
13. Error bars include statistical noise from photon counting, detector glow subtraction, Earth geocorona emission signal and interplanetary emission line at specific spectral ranges, and flat-field corrections either provided by the STScI archives or derived in this study (step 6).
14. We do include the error due to the statistical uncertainty related to the position of the Ly α line center. Indeed, the final Ly α brightness depends on where the line center is placed in the observed spectrum.

Appendix C

In the following, we discuss a few aspects of the UVIS calibration pipeline that may be useful in handling properly the software:

1. Cube Generator (CG) is the official pipeline to calibrate UVIS raw data.¹³ It is available as a package that can be

¹² <https://hst-docs.stsci.edu/stisdb/chapter-5-stis-data-analysis/5-4-working-with-spectral-images>

¹³ https://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/Cassini/CASSINIUVIS/UVIS-16/Cube%20Generator%20Software/

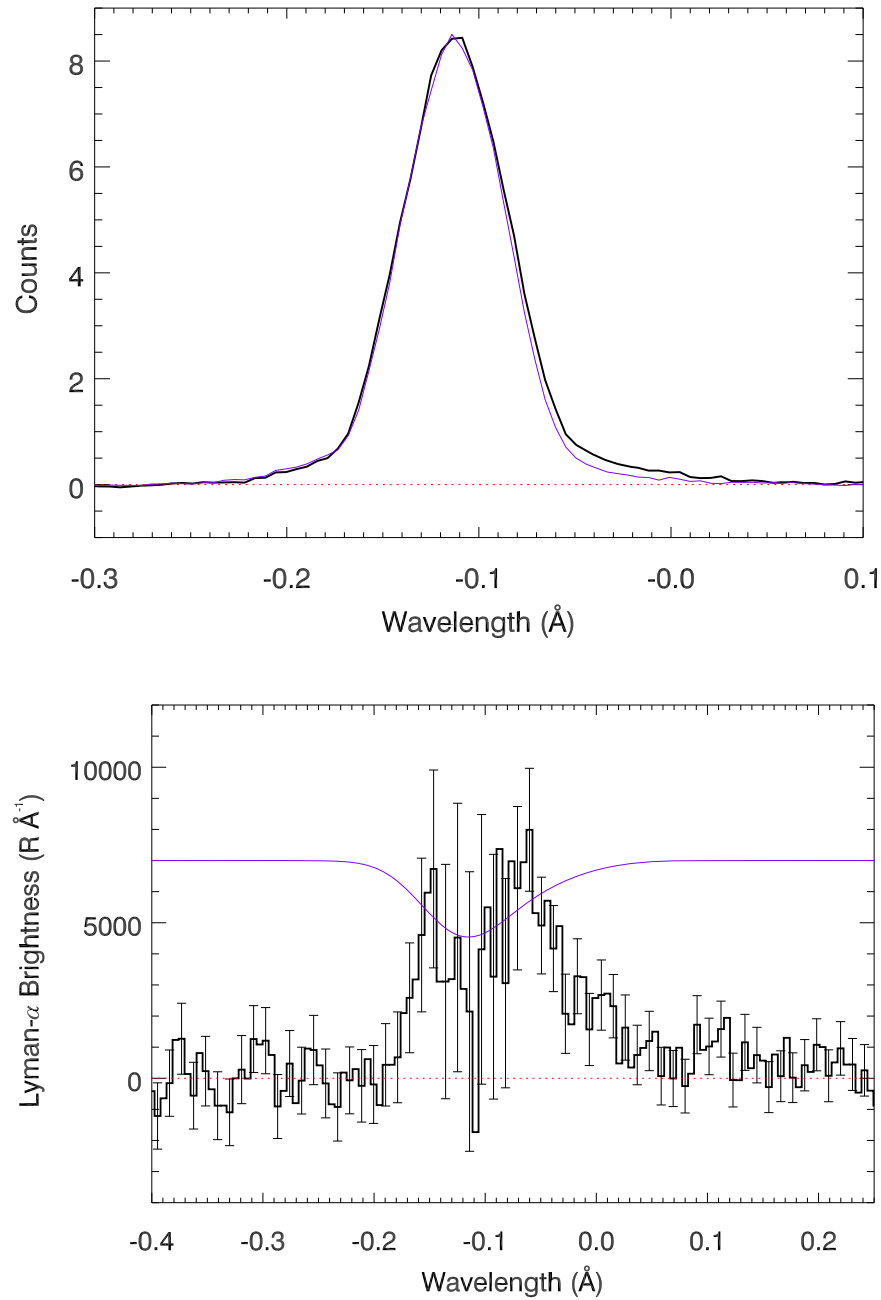


Figure 12. Top: sky background Ly α line profile (black) observed on 2017 August 26 compared to the genuine geocoronal emission Ly α profile (purple) obtained by the new technique described in step 4 (heliospheric reference frame). The IPH Ly α emission appears as the difference between the two lines (red wing). Bottom: the IPH Ly α line emission (black). We also show the self-absorption line profile by the geocoronal H I atoms that we scaled for clarity. This effect is usually neglected in the literature. The final IPH Ly α emission is $1060 R \pm 130 R$.

installed using the IDL software. A Python version exists and can be accessed at <https://github.com/Cassini-UVIS/pyuvis>. One of the main problems related to the UVIS calibration is how to handle the response of the so-called “evil” pixels that behave in a way that is not fully understood. The UVIS team made great efforts to characterize their spatial distribution and time variation that led them to include additional time-dependent flat-field correction to compensate for the deficient response of those pixels (UVIS Users Guide; Esposito et al. 2018).

For this project, we investigated the spatial and time evolution of evil pixels using sky background observations obtained between 1999 and 2017.

It appears from the different data sets that “evil” pixels modify the signal; some are repeatable, but others are not (such as those during 2008). Finding every single “evil” pixel over time is not trivial because of the additional statistical noise that makes the diagnostic difficult.

This means that CG and the extra flat fields collected from stellar observations are not enough to capture the sporadic behavior of each “evil” pixel. As long as we are interested in the integrated emission, we use long-exposure IPH nonbinned (1024 spectral pixels) observations where we merge the signal over the Ly α spectral band (including “evil” pixels), requiring that the final

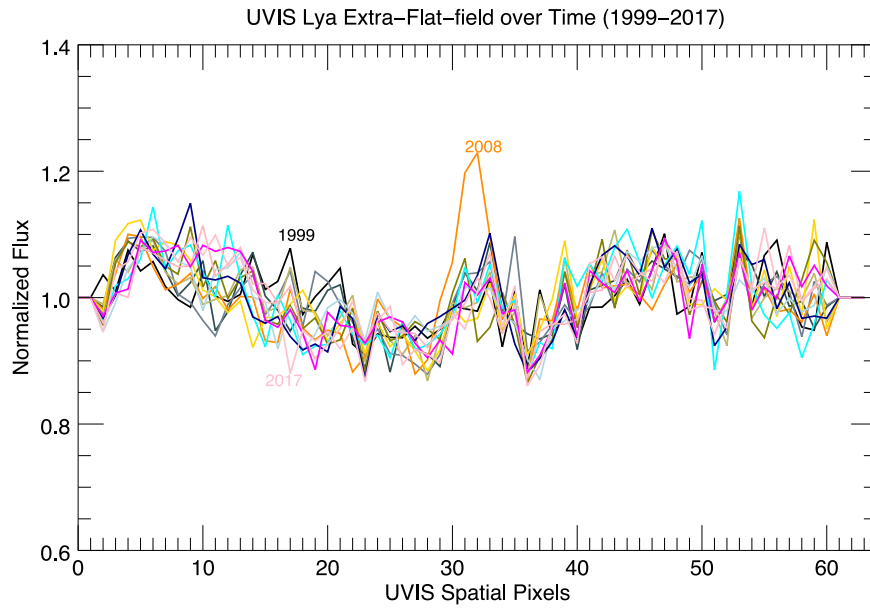


Figure 13. Pixel-to-pixel flat-field correction due to “evil” pixels affecting the $\text{Ly}\alpha$ spectral band over time (1999–2017).

signal should not change over the spatial extent of the slit, beyond a linear trend across the limited spatial extent of the slit. This helps derive a pixel-to-pixel flat-field “evil” correction at the $\text{Ly}\alpha$ spectral band along the slit (spatial direction: 64 pixels) that we incorporate into the Cube Generator software. In addition, we now propagate within Cube Generator the corresponding error bars that are not negligible. Working on the $\text{Ly}\alpha$ integrated signal helped us to obtain a decent S/N, which allowed for separation between statistical photon noise and sporadic “evil” pixel time evolution.

We could find IPH low-resolution data from 1999 to 2017, which allowed comparing the derived extra flat fields over time. First, we confirm that CG provides a nice flat field outside the $\text{Ly}\alpha$ window (using the scattered light during each exposure). However, within the $\text{Ly}\alpha$ window, there are changes as shown in Figure 13.

As we can see, there is the same average trend for the spatial correction over time, except during 2008. We found that during 2008 a peak appeared around UVIS spatial pixels 29–34 for all observations available for that period (a priori, it should not be star contamination because we tested exposures obtained from different regions of the sky).

But apart from that exception, we have the same trend that can be used to correct for the spatial distribution of the planetary $\text{Ly}\alpha$ brightness, which is related to the composition of the atmosphere.

One can also use UVIS high-resolution observations of the sky background to derive an equivalent flat field, but we see no real difference because the IPH line is not resolved in any of the UVIS modes, in addition to limited time coverage in the high-resolution mode.

2. Here, we assess the time evolution of the $\text{Ly}\alpha$ sensitivity as implemented in Cube Generator. In the spectral range outside $\text{Ly}\alpha$, the UVIS team used repeated stellar observations to monitor the time evolution of the instrument sensitivity. The work done is described in detail in the UVIS Users Guide (Esposito et al. 2018). However, there are no known independent methods to perform a similar analysis at $\text{Ly}\alpha$ (Greg Holsclaw, private communication). To address that issue, we use the IPH data set shown in Figure 13 to extract the calibration matrix provided by the Cube Generator software over the time period between 1999 and 2017. Taking the UVIS 1999 sensitivity as a reference, we could derive the time evolution of the instrument $\text{Ly}\alpha$ response. As shown in Figure 14, the $\text{Ly}\alpha$ sensitivity implemented in CG declines by $\sim 30\%$ between 1999 and 2010 and remains unchanged up to the end of the Cassini mission. To avoid confusion, we stress that the calibration correction (~ 1.7) provided in our study is independent and should be applied on top of the sensitivity function implemented in the UVIS official pipeline.
3. By default, the UVIS calibration software removes a detector background of 4×10^{-4} counts s^{-1} pixel $^{-1}$. Besides that noise level, we process the emission line by subtracting an average background from the adjacent red wing (pixels 95:110) and blue wing (pixels 150:165) of the line profile, and we finally get the total brightness summing over pixels 114–145 that cover the whole line. We tested other spectral windows for both the adjacent background and the emission line and found no significant impact on our final results. This treatment is confirmed by our RT modeling, which shows no significant contribution from flat intrinsic emissions such as by Rayleigh scattering at $\text{Ly}\alpha$ (e.g., Section 4).

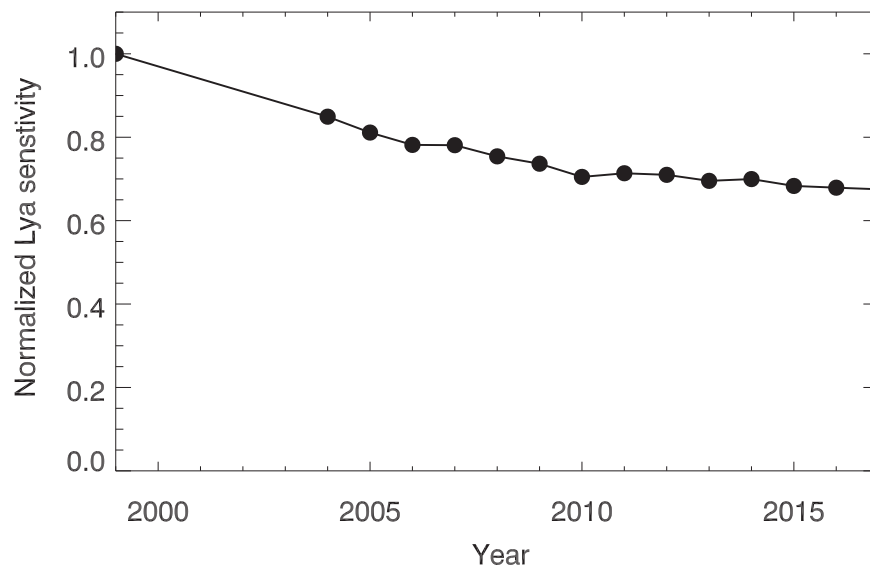


Figure 14. Yearly evolution of the UVIS Ly α relative sensitivity as implemented in Cube Generator, the UVIS official calibration pipeline. We show the sensitivity averaged over the Ly α spectral band relative to the 1999 sensitivity that we use as a reference (1999–2017).

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