CALIBRATION OF THE *VOYAGER* ULTRAVIOLET SPECTROMETERS AND THE COMPOSITION OF THE HELIOSPHERE NEUTRALS: REASSESSMENT

LOTFI BEN-JAFFEL^{1,3} AND J. B. HOLBERG²

¹ Sorbonne Universités, UPMC Univ Paris 6 & CNRS, UMR 7095, Institut d’Astrophysique de Paris, 98 bis bd Arago, F-75014 Paris, France; bjaffel@iap.fr

² University of Arizona, Lunar & Planetary Laboratory, Tucson, AZ, USA; holberg@vega.lpl.arizona.edu

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ABSTRACT

The data harvest from the *Voyagers*’ (*V1* and *V2*) Ultraviolet Spectrometers (UVS) covers encounters with the outer planets, measurements of the heliosphere sky-background, and stellar spectrophotometry. Because their period of operation overlaps with many ultraviolet missions, the calibration of *V1* and *V2* UVS with other spectrometers is invaluable. Here we revisit the UVS calibration to assess the intriguing sensitivity enhancements of 243% (*V1*) and 156% (*V2*) proposed recently. Using the Ly α airglow from Saturn, observed in situ by both *Voyagers*, and remotely by *International Ultraviolet Explorer* (*IUE*), we match the *Voyager* values to *IUE*, taking into account the shape of the Saturn Ly α line observed with the Goddard High Resolution Spectrograph on board the *Hubble Space Telescope*. For all known ranges of the interplanetary hydrogen density, we show that the *V1* and *V2* UVS sensitivities cannot be enhanced by the amounts thus far proposed. The same diagnostic holds for distinct channels covering the diffuse He I 58.4 nm emission. Our prescription is to keep the original calibration of the *Voyager* UVS with a maximum uncertainty of 30%, making both instruments some of the most stable EUV/FUV spectrographs in the history of space exploration. In that frame, we reassess the excess Ly α emission detected by *Voyager* UVS deep in the heliosphere, to show its consistency with a heliospheric but not galactic origin. Our finding confirms results obtained nearly two decades ago—namely, the UVS discovery of the distortion of the heliosphere and the corresponding obliquity of the local interstellar magnetic field ($\sim 40^\circ$ from upwind) in the solar system neighborhood—without requiring any revision of the *Voyager* UVS calibration.

Key words: instrumentation: spectrographs – interplanetary medium – ISM: atoms – radiative transfer – Sun: heliosphere – ultraviolet: general

1. INTRODUCTION

The far and extreme ultraviolet (FUV and EUV) wavelength windows contain most of the atomic and molecular lines and bands from neutrals and ion species. The access to neutral hydrogen and helium distributions in planetary atmospheres and the heliosphere are key ingredients, respectively, in understanding the formation and evolution of the atmospheric envelope of planets and in deriving the helium content in the local interstellar medium (LISM; Ben-Jaffel & Abbes 2015). The paradigm thus far assumed is that diffuse emissions from planetary airglow and sky background could be converted to species abundances as long as the radiative processes and the photon sources are constrained. However, this approach requires taking into account inherent problems regarding radiation transfer (RT) effects in moving and very extended, optically thick media, along with difficulties in accurately monitoring over time key parameters such as the solar wind, the solar Ly α flux, or the calibration of the instruments that measure the FUV and EUV airglow. While most problems could be addressed using sophisticated modeling and comparison to observations, the instrument calibration remains a difficult problem, particularly the absolute calibration and the inevitable degradation of the apparatus over the lifetime of a space mission.

The Ultraviolet Spectrometers (UVS) on board the *Voyager 1* and *2* spacecraft have been operating in space since late 1977.⁴ The UVS observe both diffuse and point-like sources,

which include planetary airglow, sky-background emissions, and key stellar targets. The two instruments, which cover the spectral range 50–170 nm, were independently calibrated in the laboratory and in-flight (Broadfoot et al. 1977, 1981). The corresponding calibration pipeline is well documented in Broadfoot et al. (1981) and Holberg & Watkins (1992).⁵ The *Voyager* UVS instruments have a unique ability to observe the spectra of hot stars from the Lyman limit at 91.2 nm to 170 nm, and in the case of a few hot white dwarfs, also below the Lyman limit. In comparing the *Voyager* absolute stellar fluxes with published fluxes obtained from sounding rockets and from the *International Ultraviolet Explorer* (*IUE*), it was noted that although the two *Voyagers* agreed with one another, the fluxes did not agree with published values in the sense that the *Voyager* fluxes were too high. This issue was studied carefully by Holberg et al. (1982) and the following conclusions were reached: (1) In the wavelength range longward of Ly α all observations agreed. (2) Between 91.2 and 115 nm all observations disagreed, sometimes by as much as a factor of three. For a number of reasons elaborated in Holberg et al. (1991), the decision was made to reduce *Voyager 2* fluxes by a factor of 1.6, based on a comparison with model atmosphere fluxes from the hot white dwarf HZ 43. The *Voyager* calibration was left unchanged at 58.4 nm and was linearly interpolated between 58.4 and 91.2 nm. *Voyager 1* fluxes were adjusted to agree with *Voyager 2*. These changes, made in 1982, still constitute current *Voyager* stellar UV and EUV calibration. The issue of *Voyager* calibration was revisited in Holberg et al. (1991), which provided additional compelling

³ Visiting Research Scientist, University of Arizona, Lunar & Planetary Laboratory, Tucson, AZ, USA.

⁴ The *V2* UVS was turned off in late 1998 to conserve spacecraft power.

⁵ http://vega.lpl.arizona.edu/Voyager_Ultraviolet_Spectrometer.pdf

evidence from very hot subdwarf stars that the calibration was essentially correct. Since that time, numerous results have been published comparing *Voyager* stellar observations with those from the *Far Ultraviolet Spectroscopic Explorer* and the Hopkins Ultraviolet Telescope, where agreement is at the 10% level (Kruk et al. 1997).

During *Voyager 1*'s encounter with Jupiter in 1979, the UVS endured excessive radiation-induced counting from >3 MeV electrons in the inner Jovian magnetosphere. The result was that post-Jupiter *V1* spectra showed a marked difference with respect to pre-Jupiter spectra. These changes manifest themselves in two ways: a reduced response across the detector, and a change in the channel-to-channel relative response. The explanation for these changes was a “gain-sag” in the microchannel plate caused by the excessive counts that effectively reduced detector gain. Since each individual channel had an independent readout and set of upper- and lower-level voltage discriminators, the channel-to-channel responses changed in response to the change in gain, giving the spectra an uncharacteristic noisy appearance. To remedy this situation, a careful study of pre- and post-Jupiter spectra was made to define a new fixed-pattern-noise (fpn) vector to correct the post-Jupiter spectra to their pre-Jupiter appearance and level (Holberg et al. 1982). This correction was applied to all subsequent *Voyager 1* spectra. Note that following the Jupiter encounter, some reports applied the correction on either the full UVS spectral range including the He 58.4 nm line (Sandel et al. 1982) or on wavelengths longer than 92 nm (Shemansky & Ajello 1983), which added to the confusion about the instrument calibration. Note also that *Voyager 2* avoided this problem by reducing detector voltages during the critical passage through the inner Jovian magnetosphere. These changes to *Voyager 1* were the only documented changes to the UVS instruments over the entire mission.

The calibration of the $\text{Ly}\alpha$ region (120–129 nm) requires some additional discussion. The adjustments to the UVS calibration discussed above were based on stellar spectra. However, in all cases the stellar profiles were relatively broad and nearly saturated features, which made comparisons of *Voyager* flux within this spectral range difficult. For instance, to estimate the reduced response across the *V1* detector after the Jupiter flyby, two independent analyses used reference to stellar spectra (respectively Alpha Virgo and Alpha Leo) recorded before and after the encounter to derive a $(32 \pm 7)\%$ degradation in the effective sensitivity of the *V1* UVS in the spectral windows 100–119 nm and 130–145 nm (Holberg et al. 1991; Hall 1992). The degradation was also applied to $\text{Ly}\alpha$ channels, but for a very short period of time around *V1*'s encounter with Saturn. Soon afterward, an independent study used the light scattered in the instrument to test whether changes in sensitivity could be detected. As shown in Hall (1992, see their page 171, Figure A.1), a signature of $\text{Ly}\alpha$ instrumental scattering is the formation of a faint, spectrally-extended emission feature around the base of the line core. By comparing channels corresponding to the line core (70–78) and adjacent channels covering the extended scattering feature before and after the encounter with Jupiter, Hall (1992) could show that the $\text{Ly}\alpha$ channels suffered (0.67 ± 0.07) less degradation than the adjacent channels used for the stellar calibration. According to Hall (1992), taken together, the two later-proposed corrections cancel each other, which led to the significant conclusion that the $\text{Ly}\alpha$ channel sensitivity

remained unchanged for *V1* before and after the Jupiter encounter. For consistency, Hall (1992) also proposed:

1. first, to use the *V2* UVS pre-flight laboratory calibration curve to generate a synthetic spectrum that is compared to a high-quality sky-background line, which should provide an absolute calibration for *V2* UVS;
2. second, to use the relative ratio between *V1* and *V2* UVS sensitivities obtained after the Jupiter encounter;
3. and finally, to derive the *V1* UVS sensitivity for the post-Jupiter encounter period.

The analysis reported in Hall's thesis led to $\text{Ly}\alpha$ absolute calibrations of 218 ± 33 R/counts s^{-1} (in channels 70–78; R is the rayleigh unit) for *V1* and 172 R/counts s^{-1} (in channels 72–80) for *V2*, with a ratio (0.79 ± 0.12) between the two instruments that was derived for the post-Jupiter period. It is significant that the calibration of Hall (1992) at $\text{Ly}\alpha$ is independent of any RT modeling of the sky background and of any solar $\text{Ly}\alpha$ flux assumed (see next section). The consistency between the pre-flight and post-flight calibrations, in addition to the intercalibration agreement between *V1* and *V2*, represents the strength of the calibration process proposed by Hall (1992).

Recently, Quémerais et al. (2013) used the radial distribution of the sky-background $\text{Ly}\alpha$ emission recorded by *V1* and *V2* along their trajectories in the heliosphere to derive a new, independent estimation of the UVS instruments' flux calibration. Those authors carefully emphasize that the proposed calibration was the first step in a complex approach aiming to intercalibrate most existing UV space missions, with the sky background as the common target to bring the different instruments into consistent, absolute calibrations over space and time. They made use of sophisticated three-dimensional kinetic models of the heliospheric H I distribution, including charge exchange with the local plasma, as well as 3D RT models to describe the transport of the solar $\text{Ly}\alpha$ photons inside a very extended and moving medium, which is bound by the Sun inside and the local interstellar cloud (LIC) outside (Quémerais et al. 2013). From the comparison between their model and UVS observations, Quémerais et al. conclude that there is a need to correct the *V1* UVS sensitivity by a large factor of 243% and the *V2* UVS by a factor of 156% with respect to the calibration thus far proposed by Hall (1992). The authors stress that the new calibration is based on a fit to the sky background observed by *V1* and *V2* UVS in the region 10–50 AU from the Sun. In contrast, the same RT models fail to fit the UVS data inside the 10 AU boundary for both *V1* and *V2* and beyond the outer 50 AU boundary for *V1* (Quémerais et al. 2013). While a low level of the $\text{Ly}\alpha$ solar flux presumably used by Hall (1992) is propounded to explain the new *V2* sensitivity, no further instrumental explanation is proposed for the enigmatic 243% jump derived for the *V1* UVS sensitivity (Quémerais et al. 2013). In addition, we cannot find in Hall's 1992 thesis any link between the derived UVS $\text{Ly}\alpha$ sensitivities and the solar flux level used by that author for his RT modeling, a problem that calls into question the jump in both the *V1* and *V2* calibrations.

First, it is important to stress that the *V1* and *V2* archive database also contains all the planetary airglow measurements obtained during the encounters of the two spacecraft with the outer planets. The enhanced new sensitivity of the UVS should strongly modify a planet's airglow emission levels, which calls for some caution before revising past studies. In addition, most

of the targets in the outer solar system have been observed by several instruments simultaneously with *VI* and *V2*, either during encounters or remotely (Shemansky et al. 1988; McGrath & Clarke 1992). More generally, what is actually missing is a comprehensive approach that incorporates the sky background glow, the planetary diffuse emissions, and simultaneous observations of different targets from multiple missions in order to derive *VI* and *V2* calibration that is coherent with most existing data. For all these reasons, the large differences between the old and new calibrations of UVS call for a reassessment.

In the following, we undertake such a comprehensive approach, insisting on its consistency rather than on the model’s sophistication. In Section 2, we compare airglow emission from Saturn simultaneously observed by *VI* and *V2* (in situ) and *IUE* (remote) in order to check the consistency of any proposed UVS calibration. First, we use Saturn and sky-background high-resolution Ly α line profiles observed by the Goddard High Resolution Spectrograph (GHRS) on board the *Hubble Space Telescope* (*HST*) in order to evaluate the imprint of the interplanetary hydrogen (IPH) absorption between Saturn and Earth. In that context, our goal is twofold: to assess the new UVS calibration, and to compare the consistency of our results with the IPH model used by Quémerais et al. (2013) to derive their calibration. In Section 3, we model the He 58.4 nm airglow of Jupiter based on the *Voyager* UVS with the goal of deriving the Jovian He abundance that we compare to the in situ abundance measured by the *Galileo* probe. In that way, we may obtain a further indication of the *VI* and *V2* sensitivity level based on distinct channels of the UVS detectors. With the original UVS calibration confirmed, we discuss in Section 4 the limitations of the global RT technique used in Quémerais et al. (2013), and propose a distinct approach based on the local RT technique, which proved to be efficient in several applications (Puyoo et al. 1997; Puyoo & Ben-Jaffel 1998; Ben-Jaffel et al. 2000). In that context, we recall how the inversion of the sky-background Ly α maps from the *Voyager* UVS helped derive the local abundance of heliospheric hydrogen at specific positions up to 40 AU from the Sun (Section 4.2), and how Fermi-glow interpretation of the sky-background excess Ly α emission, a feature detected by UVS deep in the heliosphere, was at the origin of the discovery of the distortion of the heliosphere (Ben-Jaffel et al. 2000). Because the Fermi glow is controversial (Quémerais 2006; Quémerais et al. 2013), we dedicate all of Section 4.3 to addressing the issue, emphasizing the importance of the fact that, despite their limited spectral resolutions, both *Voyager* UVS are stable enough to constrain key properties of the heliosphere without the need to modify their calibrations. In conclusion, we summarize all of our results and suggest a few experimental solutions for efficient exploration of the heliosphere in the future.

2. CALIBRATION OF VOYAGER UVS LY α CHANNELS: REASSESSMENT

In the following, we use airglow emission from Saturn observed simultaneously by *Voyager* and *IUE* to reassess the UVS calibration at Ly α . However, to properly achieve the calibration diagnostic, one must first determine Saturn’s Ly α emission line, a key parameter that was missing in past studies. In that context, we first analyze high-resolution Ly α line profiles of Saturn and the sky-background observed by the

GHRS on board the *HST* to determine that the line’s width is large enough to show the imprint of the IPH absorption between Saturn and Earth (Section 2.2). In the second step, we use the information on the Saturn Ly α linewidth and a local inversion RT technique to directly compare Saturn Ly α brightnesses from UVS to *IUE* for the different UVS calibrations thus far proposed (Section 2.3). We then show both the inadequacy of the newly proposed UVS calibration and the validity of the original instrument sensitivity derived after the Jupiter encounter.

2.1. Diffuse Sources in the Solar System: Cross-calibration of UV Instruments

Because the distance to the outer planets is large enough, the interplanetary medium that separates them from Earth is opaque enough in atomic hydrogen to leave an imprint on their Ly α brightness. Therefore, comparing remote and in situ observations of the planet offers key constraints both on the IPH opacity at Ly α and on the relative calibration between the observing instruments. More generally, abundances derived from planetary airglow emissions could be validated only if the same species could be measured either in the atmosphere or by independent techniques, such as solar and stellar occultations that are widely used on space missions (Broadfoot et al. 1981). In this respect, we consider here the H I abundance derived from the Saturn Ly α airglow measured by both *Voyager* and *IUE* instruments, the He abundance in Jupiter derived from the planet’s airglow measurements, and the *Galileo* probe measurement within the Jovian atmosphere. For reference, the *IUE* calibration has been assessed many times during the lifetime of the spacecraft, yielding firm conclusions as to the sensitivity of the instrument and its time variation, which should not exceed a few percent (Bohlin et al. 1990). Because our discussion will mainly focus on the *Voyager* UVS calibration within the context of the airglow observations of Jupiter and Saturn, all absolute fluxes used here are based on the standard calibration pipeline described in Holberg & Watkins (1992), taking into account the correction reported for the Ly α channels (Hall 1992).

First, it is important to recall that *IUE* was used for remote monitoring of the Saturn Ly α brightness over the period 1980–1990. Such long-term strategy has many benefits, particularly in showing the strong correlation between the Saturn Ly α airglow and the solar Ly α flux, along with intrinsic temporal and spatial variations observed across the planetary disk (McGrath & Clarke 1992; Shemansky et al. 2009). For instance, at the time of encounter of *Voyager 1* and *2* with Saturn in respectively 1980 and 1981, the Ly α dayglow of the planet was observed nearly simultaneously by *VI* UVS and *IUE* on day of the year (doy) 343 of 1980 and then by *V2* UVS and *IUE* on doy 240 of 1981 (e.g., Table 1). After the damage suffered by the *VI* spacecraft during its crossing of the Jovian magnetosphere, cross-correlation of *Voyager 1* UVS, *Voyager 2* UVS, and *IUE* observations of the Saturn Ly α emission has been used to assess the UVS calibration (Shemansky et al. 1984, 1988; Hall 1992). The simultaneous measurements were also exploited by Puyoo et al. (1997) and Puyoo & Ben-Jaffel (1998), leading to a self-consistent estimation of the IPH density. Generally, the moving IPH absorbs the planetary emission line at a spectral range that depends on the orientation of the line of sight to the planet in the heliosphere with respect to the upwind direction

Table 1Best-fit Saturn Ly α Line Profile From *HST*/GHRS: Sensitivity to IPH Models

Model	Model A	Model B	Model C
LISM proton density (cm ⁻³)	0.032	0.032	0.06
Temperature primary (K)	6100	6100	6020
Temperature secondary (K)	16500	16500	16300
Density primary at 90 AU (cm ⁻³)	0.088	0.058	0.035
Density secondary at 90 AU (cm ⁻³)	0.088	0.058	0.06
IPH velocity primary at 90 AU (km s ⁻¹)	28	28	28
IPH velocity secondary at 90 AU (km s ⁻¹)	18	18	18
Earth–Saturn layer primary opacity	0.361	0.24	0.14
Earth–Saturn layer secondary opacity	0.185	0.12	0.13
Model linewidth (Å)	0.108	0.107	0.108
Planet Ly α brightness (R)	1200	1000	970

Note. Best fit obtained for the Saturn Ly α line profile from *HST*/GHRS obtained after correction for the IPH absorption. IPH model A is based on Bzowski et al. (2008) but with a relatively higher density as reported in Puyoo & Ben-Jaffel (1998). Models B and C are based on Bzowski et al. (2008). It is interesting to note that the width of the derived Saturn Ly α line profile is insensitive to the adopted IPH model. In contrast, after correction for the model IPH absorption, the integrated emission line is sensitive to the model adopted, yet with a brightness level, for all models assumed, that is consistent with *IUE* observations obtained around the preceding solar minimum in 1985–1987 (McGrath & Clarke 1992).

($\sim \pm 26$ km s⁻¹). However, in all those studies, a key ingredient was missing: the exact shape of the Saturn Ly α line profile. Instead, it was approximated based on photometry or low-resolution observations and theoretical modeling of the excitation processes at the origin of the planetary emission line (McGrath & Clarke 1992; Ben-Jaffel et al. 1995; Puyoo et al. 1997). Within that framework, it is important to accurately derive the shape of the planetary emission line to check whether the width is large enough to show noticeable extinction by the IPH gas for the spectral range of the Doppler-shifted absorption (Wu & Judge 1979b).

2.2. *HST* Observation of Saturn and Sky-background Ly α Emission Line Profile

To constrain the Saturn Ly α emission line profile, we use the archive observations of the Saturn Ly α dayglow obtained with the GHRS on board the *HST* using the Echelle grating and the large 1.74×1.74 arcsec² aperture (*HST* program GO 5757). The *HST* program GO 5757 consisted of two distinct visits to the planet, one in 1994 October to obtain spatial scans across the planetary disk, and a second on 1996 December 24 but at fixed positions on the disk. Here, we decided to use the 1996 data set because the corresponding Doppler separation between the geocoronal emission line from Earth and the emission line from Saturn was the largest (~ 30 km s⁻¹). In total, we use three distinct exposures for the planet. An additional exposure for the sky background was also obtained ~ 2 arcmin away from the planet (Figure 2), far enough from the H I cloud that surrounds Saturn (Shemansky & Hall 1992). For the planet, each exposure was obtained as a time sequence of six or seven subexposures (for a total of roughly ~ 900 s). Here, the three separate pointings thus far used correspond respectively to latitude 30° south near disk center (*HST* data set z2jr1104t), latitude 30° south near sunlit limb (z2jr110et), and south pole (z2jr1109t) as sketched in Figure 1.

Figure 1. Sketch of the GHRS slit positions on the Saturn disk shown for the 1996 December 24 observations (*HST* program GO 5757). The three exposures provide the disk-averaged Ly α spectrum used in this study. The GHRS large science slit is shown with the right angular size (1.7×1.7 arcsec²). The image was obtained in the visible range with the Wide Field Planetary Camera (WFPC) very close in time to the GHRS Ly α observations, and is shown here only for reference.

We compared the line profile obtained at the south pole location (allowing for the possibility of auroral contamination) to the latitude 30° south near disk center and to the average of three line profiles. Because the individual spectra are noisy, we cannot find any noticeable difference (Figure 3). As documented by many observations of the Saturn aurora obtained with *HST* since 1994, a plausible explanation is that the south pole aurora could be very faint on 1996 December 24 (the observed system III longitude/latitude of the slit were $\sim 108^\circ/76^\circ$ S with a subsolar point latitude of 4° S), in addition to the fact that the latitudinal extent of the Saturn aurora may not fill the whole GHRS slit (Gérard et al. 2005). Furthermore, for both the south pole and sunlit observations, the GHRS slit is partially filled by the emission from the planetary disk, which may also explain the comparable level of signal obtained for the three pointings (see Figure 1). While the details of the individual line profiles are important for the study of Saturn’s upper atmosphere, our primary goal here is to find that the linewidth is comparable for the three targets.

2.2.1. Subtraction of Geocoronal and Sky-background Contaminations

Most UV observations are scheduled when *HST* is in the Earth’s shadow to reduce the contamination from geocoronal airglow. Because *HST* observations start with a high contamination from the Ly α geocoronal emission line at the Earth’s day–night terminator, we dismissed the first exposure of each visit, which leads to a final ~ 2700 s high-resolution line profile of the planetary emission and ~ 900 s exposure of the sky-background obtained near the orbital position of Saturn. For the observed diffuse light sources, the GHRS slit is filled, which reduces the final resolution of the Echelle mode to $\sim 18,000$. Here, it is important to stress that an observation of a lamp to calibrate the wavelengths was scheduled after each of the four *HST* visits, which helped calibrate the spectral line positions to better than ~ 2 km s⁻¹ (equivalent to ~ 0.008 Å) (Emerich et al. 1996).

In the initial plan of the *HST* program GO 5757, observations were scheduled to use Earth’s maximum orbital speed (~ 30.2 km s⁻¹), which allows for the largest Doppler shift (35.7 ± 2.0 km s⁻¹) between the geocoronal contamination and the planetary lines. At the time of observation in 1996 December, the line-of-sight pointing toward Saturn was $\sim 105^\circ$ away from upwind (around the crosswind region), which put

Figure 2. Sky-background Ly α emission observed with *HST*/GHRS Echelle mode using the large science slit on 1996 December 24. Spectra are binned by 4 to reduce the noise level and shown in the Earth reference frame. The line of sight was ~ 2 arcmin outside the limb of Saturn. The IPH emission line toward infinity clearly appears on the red wing of the strong geocoronal emission line from Earth. We assume Voigt profiles for the two lines that are convolved with the GHRS line-spread function (~ 0.007 nm). Using the Levenberg–Marquardt least-squares technique, our best fit to the IPH line (dashed) is Doppler-shifted by 35.7 ± 2.0 km s $^{-1}$ from the geocoronal line, and has a Voigt temperature of $(2.7 \pm 1.8) \times 10^4$ K and a brightness of 520 ± 100 R.

the interplanetary emission line at an average Doppler shift of 5.5 ± 2.0 km s $^{-1}$, as would be expected for that direction for an LIC speed of 26.4 km s $^{-1}$ (Wu & Judge 1979a; Katushkina & Izmodenov 2011). To achieve an accurate analysis of the spectral lines, a line-spread function (LSF) of the instrument is required. For the GHRS in the Echelle and large-slit mode, the LSF issue was carefully discussed by Clarke et al. (1998) in the frame of the sky-background observations and by Robinson et al. (1998) in the general case. With an accurate LSF on hand (Robinson et al. 1998), the Doppler separation (~ 36 km s $^{-1}$) between the geocoronal and IPH lines allows for extraction of both lines, which later should help in properly subtracting the variable geocoronal emission from the planetary one (e.g., Figure 2). For that purpose, we modeled the faint IPH line as a Voigt function that we convolved with the GHRS Echelle LSF and subtracted from the sky-background observation using the Levenberg–Marquardt least-squares technique (Vincent et al. 2011). In that way, we obtain a geocoronal emission line in the same instrument conditions as for the planetary line (e.g., Figure 2). Having the Earth’s geocoronal line and the IPH line separated makes it possible to scale each of them independently during the cleaning of the spectrum observed toward the disk of Saturn from its corresponding sky contamination.

It is now possible to properly clean the planetary emission spectrum first by scaling and subtracting the geocoronal emission line. However, it is important to remark that the intensity of the IPH emission line toward the disk of Saturn is different from the one measured toward infinity (far outside the planetary limb). In addition, for the sunlit limb and south pole pointing used here, the field of view may also contain a small contribution from the glow of the hydrogen cloud that surrounds the planet (Shemansky & Hall 1992; Shemansky

Figure 3. Saturn Ly α emission line observed with *HST*/GHRS Echelle mode using the large science slit on 1996 December 24. Spectra are binned by 2 to reduce the noise level. The Earth’s geocoronal emission (dashed line) was observed ~ 2 arcmin outside the limb of Saturn ~ 1.5 hr later, which corresponds to the following *HST* orbit. The average IPH emission line toward Saturn (dotted) has the same FWHM as the line shown in Figure 2 but with a reduced brightness of 280 ± 100 R (compared to 520 ± 100 R for the sky-background emission observed toward infinity). The resulting spectrum (thick histogram, brightness 900 ± 100 R) is the extracted Saturn emission line suffering an extinction by the IPH between the planet and Earth. For reference, we also show the emission line profiles obtained for the equatorial (solid thin line) and south pole (dashed–dotted line) targets, confirming the large width of the Saturn Ly α emission line.

et al. 2009). As noted in early studies, removing the total IPH emission results in oversubtracting from the planetary emission the sky-background emission that originates from behind the planet (McGrath & Clarke 1992). Using the Levenberg–Marquardt least-squares technique, our best fit shows that for the observations toward the three targets (equatorial, sunlit, south pole) on the Saturn disk, the corresponding sky-background emission line has $\sim (0.3, 0.67, 0.67)$ times the brightness of the same line (520 ± 100 R) observed ~ 2 arcmin away from the planet. The diagnostic was made on the red wing of the emission line of each of the individual targets, where the sky-background contamination is the most prominent (e.g., Figure 3). Independently of any attached statistical or systematic uncertainties, the sky-background emission toward Saturn is bound by two limiting values—the brightness of the same line toward infinity as an upper limit, and a very weak emission at the noise level of the observation as a lower limit (e.g., no sky-background emission). In the following, we will also use the two limiting values of the sky-background emission to bind the width of the Saturn Ly α emission line strongly, yet independently of the sky contamination observed and the related statistical uncertainties.

2.2.2. Sensitivity of the Saturn Ly α Line to the IPH Absorption

After the subtraction of the reduced IPH emission, the resulting emission line observed at Earth’s orbit should correspond to the intrinsic planet’s line that is partially absorbed by the IPH atoms that fill the space between the two positions (McGrath & Clarke 1992; Puyoo et al. 1997). The estimation of the IPH absorption is tricky because the gas

distribution depends strongly on both the outer and inner boundary conditions assumed. For Saturn airglow correction, the problem was carefully discussed in McGrath & Clarke (1992), yet the outer boundary effect was missing in their study. Because H I transport in the heliosphere is a complex problem, a few approximations were proposed to obtain practical diagnostic tools that could be implemented for the studies of the inner heliosphere. For instance, the so-called two-component hot model was proposed as a helpful approximation to study the impact of neutrals on the distribution of H II pickup ions measured in the inner heliosphere (Bzowski et al. 2008). The model reflects the main properties of the heliosphere’s neutral distribution, including the charge-exchange effect at the outer heliosphere (Baranov & Malama 1993; Bzowski et al. 2008; Izmodenov et al. 2013). In addition, the kinetic equation of neutral transport is solved separately for the primary and secondary populations, which correspond to the dominant species that compose the hydrogen in the inner heliosphere (Baranov & Malama 1993). At the outer boundary, which is postulated at the termination shock (TS) of the solar wind around ~ 90 AU, the velocity distribution is assumed to be Maxwellian for each of the two populations, which have properties that are related to the LISM bulk properties (H I density $n_{\text{H-LISM}}$, temperature T_{LISM} , proton density $n_{\text{p-LISM}}$) via the Baranov–Malama self-consistent model (Baranov & Malama 1993; Bzowski et al. 2008; Izmodenov et al. 2013).

The two-component hot model was applied to interpret production rates of H II pickup ions in the inner heliosphere, which helped estimate the H I density level around the TS around ~ 90 AU (Bzowski et al. 2008). Recently, a more sophisticated and proper handling of the 3D boundary conditions at the outer heliosphere used 3D MHD-kinetic and RT simulations to help build the heliosphere H I distribution and the corresponding photon scattering, which have been useful in analyzing the sky-background reflected light measured by different spacecraft (Katushkina & Izmodenov 2011; Fayock et al. 2013; Quémerais et al. 2013). However, despite their sophistication, those models were not very successful in describing the sky-background radiation observed in the inner heliosphere (inside 10 AU) or the outer heliosphere (beyond 50 AU) and gave no further indication of the origin of the discrepancy found (Quémerais et al. 2013). A distinct approach used the invariance principle (optics) to derive the distribution of H I neutral density by directly inverting maps of sky-background reflected light measured by both *Voyagers 1* and 2 locally along their path up to 35 AU from the Sun (Puyoo et al. 1997; Puyoo & Ben-Jaffel 1998). Interestingly, those authors were able to fit the H I distribution in the inner heliosphere using a Baranov–Malama kinetic model to derive a self-consistent solution that relates the intrinsic properties of the LISM (H I density, ionization rate, etc.) to the inner heliosphere distribution, yet the solution is not unique (Puyoo & Ben-Jaffel 1998).

In addition to missing the LISM magnetic field, which forces a pressure distortion on the whole heliosphere, most of the above-cited studies also miss the self-shielding effect of the solar radiation at Ly α by the IPH atoms that should strongly modify the strength of the radiation pressure force in the inner heliosphere, and consequently the H I distribution in the inner heliosphere (Wu & Judge 1979a). Recently, momentum transfer during photon scattering with H I atoms was properly estimated using a Monte Carlo scattering model, leading to the

important conclusion that the calculated fall-off in radiation pressure with distance from the Sun may differ significantly from the $1/r^2$ dependence typically assumed in the past (Fayock et al. 2015). Given the present conditions, it is difficult to come up with a self-consistent model for the IPH that would fit most observations of sky-background radiation from the inner to the outer heliosphere (Ben-Jaffel & Abbes 2015). For those reasons, we consider typical models thus far reported in the literature to describe the IPH in the 1–10 AU region, but we will not discuss the general problem of the composition and distribution of the IPH as those are beyond the scope of the calibration study conducted here. Therefore, in the inner boundary, we assume a total ionization rate $\beta \sim 7.5 \times 10^{-7} \text{ s}^{-1}$ and a ratio of the force of radiation pressure to that of gravity that depends on the H I opacity radially (see Section 2.3 for more detail).

In order to test the sensitivity of our results to the IPH properties in the outer heliosphere, we consider three two-component models that are consistent with the Baranov–Malama model in the outer heliosphere boundary (A, B, and C) as defined in Table 1. Model A is based on the H I distribution derived for the inner heliosphere up to 35 AU by Puyoo & Ben-Jaffel (1998), a distribution that can be characterized by its relatively high local H I density at 10 AU. Model B and Model C correspond to the two-component hot models assumed in Bzowski et al. (2008). For Model A, because the LISM proton density derived in Puyoo & Ben-Jaffel (1998) ($\sim 0.04 \text{ cm}^{-3}$) is close to Model B, we assume the same model but with a larger IPH density. While the assumption might seem arbitrary, it is worthwhile because it shows the effect of a strong extinction by the IPH (Puyoo & Ben-Jaffel 1998). All IPH models are calculated for a direction of ecliptic coordinates $\lambda \sim 1^\circ$ and $\zeta \sim -2.4^\circ$ of Saturn on 1996 December 24, which corresponds to a line of sight that is $\sim 105^\circ$ away from upwind. For that direction, the hydrogen layer between Saturn (~ 9.47 AU) and Earth (~ 0.99 AU) has a total opacity indicated in Table 1 for each model.

Here, it is important to stress that the three models are considered for the calibration purposes only because no unique correction exists for the IPH extinction (Shemansky et al. 1984; McGrath & Clarke 1992). Indeed, our purpose is not to derive the exact Saturn Ly α line profile, but rather to verify that the width of the line is large enough to reflect the Doppler-shifted absorption produced by the H I atoms flowing between Saturn and Earth (Puyoo et al. 1997). In the first step, to estimate the sensitivity of the linewidth to the sky-background emission subtracted, we derive the best fit obtained for reference Model A, also showing the impact of subtracting the two limiting maximal and minimal values of the sky-background emission measured toward Saturn (Figure 4). In doing that, we test the sensitivity of the derived linewidth to a systematic error that would be much larger than the statistical uncertainty ($\sigma_B = 100$ R) attached to the *HST*/GHRS data. For reference, it is helpful to recall that the minimal linewidth required to see a substantial IPH imprint is related to the Doppler shift that corresponds to the line of sight assumed. In the case of the *HST* 1996 observations, the minimal linewidth should be $\sim 5 \times 10^{-3} \text{ nm}$. It is interesting to see that the width of the Saturn Ly α line is bound between $(9.2 \pm 1) \times 10^{-3} \text{ nm}$ (when subtracting 9/10th of the maximum value measured to infinity, which corresponds to $\sim 4.7 \times \sigma_B$) and $(11.5 \pm 1) \times 10^{-3} \text{ nm}$ (1/10th of the maximum value measured to infinity, which corresponds

Figure 4. Saturn Ly α emission line (histogram binned by 4) observed with *HST*/GHRS Echelle mode on 1996 December 24 and shown for three distinct corrections of the sky-background emission toward the planet. The best fit (solid) is compared to two limiting corrections corresponding to the maximum (dots) and minimum (dot-dashed) sky-background emission subtracted. The shaded area corresponds to the spectral range of the contamination from the geocoronal emission line. We assume a Gaussian profile for the planetary Ly α line that is convolved with the GHRS line-spread function (~ 0.007 nm). The IPH absorption by hot Model A is applied and the resulting line profile (dashed line) is compared to the observation (solid histogram). The intrinsic Ly α emission line of Saturn without any contamination (solid line) has a FWHM that is strictly bound between 0.009 ± 0.001 nm and 0.011 ± 0.001 nm corresponding to the two unrealistic extrema of the sky-background emission subtracted (see text). Only the fit to the middle curve (solid) is shown for clarity.

to $\sim 0.5 \times \sigma_B$). The derived Saturn Ly α linewidth $(10 \pm 1) \times 10^{-3}$ nm is larger than the value previously used in Puyoo et al. (1997) and is, in all cases, large enough to bear the imprint of the IPH absorption.

In a second step, to test the sensitivity of our results to the IPH absorption assumed, we show in Figure 5 the best fit to the Saturn Ly α line profiles before and after absorption by each of the three IPH models for the conditions of observation by *HST*/GHRS (12/1996). First, for the weak-opacity Models B and C, we remark that despite the large statistical uncertainties of the data, a slight difference exists between the planetary emission lines obtained before and after the IPH model absorption. Second, it is interesting to note that the width of the line profiles derived is insensitive to the IPH model assumed ($\sim 0.01 \pm 0.001$ nm, e.g., Table 1). In contrast, the line brightness varies with the assumed model. As shown in Table 1, for the minimum of solar activity at which the *HST*/GHRS time of observations were scheduled, we obtain a planetary emission between 970 ± 100 R and 1200 ± 100 R for the three IPH models assumed, a brightness level that is consistent with *IUE* observations obtained around the preceding solar minimum in 1985–1987 (McGrath & Clarke 1992).

Our new analysis of the *HST*/GHRS observations of the Saturn Ly α emission shows that the line profile is larger than previously assumed (e.g., Figures 4 and 5), a finding that confirms that the IPH atoms strongly absorb the planetary emission as predicted by previous studies at all possible Doppler shifts of the IPH line (McGrath & Clarke 1992; Puyoo et al. 1997). It is also interesting to note that the width of the planetary emission line is larger than predicted by resonant scattering of thermal hydrogen in the upper atmosphere of Saturn (Ben-Jaffel et al. 1995), a finding that requires further

investigations to uncover any potential link with the hydrogen plume reported in *Cassini*/UVIS observations (Shemansky et al. 2009), and more generally with the controversial problem of the heating of the thermosphere of Saturn (Smith et al. 2007; Shemansky et al. 2009; O’Donoghue et al. 2014). Interestingly, the line broadening observed for the Saturn Ly α line brings to mind a similar process observed by *IUE* and *HST*/GHRS in the bulge region in the upper atmosphere of Jupiter (Ben-Jaffel et al. 1993; Emerich et al. 1996). It is outside the scope of this paper to evaluate the impact of the new *HST*/GHRS line profile reported here on the thermal structure of Saturn, a study that we leave for the near future.

2.3. Saturn Ly α Emission: A Lever to Assess the Calibration of Voyager UV Spectrometers

Given the important new result regarding the width of the Saturn Ly α emission line, which is large enough to bear the absorption by the moving IPH embedded between the planet and Earth’s orbit, we can proceed using that line profile as a lever to test for the different *Voyager* UVS calibrations. In Table 2, we list the brightness of planetary Ly α emission simultaneously observed by *IUE* (remotely) and *Voyager* VI and V2 (in situ), respectively, in 1980 November and 1981 August, both for the traditional UVS calibration (Hall 1992; Holberg & Watkins 1992) (hereafter VOY92) and the new calibration proposed by (Quémerais et al. 2013) (hereafter ISSI13).

In the following, we use the same inversion technique using the invariance principle as described in Puyoo et al. (1997) and Puyoo & Ben-Jaffel (1998) to derive the IPH number density required in order to match *IUE* and *Voyager* UVS observations of the Saturn Ly α brightness. First, it is important to stress that in deriving their results for the inner heliosphere (1–10 AU), Puyoo et al. (1997) assumed a parametric hot model with a temperature $T_\infty = 8000$ K and $V_\infty = 20$ km s $^{-1}$ for the IPH layer separating Earth (*IUE*) from Saturn (VI and V2). However, as described in the previous section, sophisticated kinetic modeling of the heliospheric hydrogen clearly shows that a two-component hot model is more suitable for capturing the impact of the charge-exchange process that operates near the heliopause to produce, at minimum, the secondary hot H I population (Baranov & Malama 1993; Puyoo & Ben-Jaffel 1998; Bzowski et al. 2008; Izmodenov et al. 2013). In that context, the question is how the relative weight of the secondary population density (compared to the primary population) affects the boundary conditions at the 10 AU position and the results thus far reported in Puyoo et al. (1997), particularly the opacity between Earth and Saturn. The issue was noted yet not fully explored in Puyoo & Ben-Jaffel (1998). In addition, most studies of the IPH distribution near the Sun neglected the effect of self-shielding by atomic H I, a process that may strongly absorb the solar Ly α line and consequently modify the strength of the radiation pressure force versus distance along the Earth–Saturn line of sight (Wu & Judge 1979b). For reference, Puyoo et al. (1997) also derived in a self-consistent way the rate of ionization by solar wind particles, showing that the parameter is well described by theoretical models related to the daily measurements of the solar wind parameters (Bzowski et al. 2013). Finally, it is important to stress that Puyoo et al. (1997) and Puyoo & Ben-Jaffel (1998) discussed the sensitivity of their results to the *Voyager* UVS calibration but only within the attached 20%

Figure 5. Saturn Ly α emission line (binned by 4) observed with *HST*/GHRS Echelle mode on 1996 December 24. The shaded area corresponds to the spectral range of the contamination from the geocoronal emission line. We assume a Gaussian profile for the planetary Ly α line that is convolved with the GHRS line-spread function (~ 0.007 nm). The IPH absorption (two-component hot model) is applied and the resulting line profile is compared to the observation (dashed line). The resulting intrinsic Ly α emission line of Saturn without any contamination (solid) has a FWHM ~ 0.01 nm for all IPH models defined in Table 1. We use the Levenberg–Marquardt technique to solve the least-squares problem (Vincent et al. 2011). (a) Model A; (b) Model B; (c) Model C. All derived brightnesses are comparable to *IUE* observations made during the minimum solar activity of 1985–1987 (e.g., Table 1) (McGrath & Clarke 1992).

Table 2
Saturn and Sky-background Ly α Observations

UV Instrument	Observation Date	I_P (R) ^a	I_{sky}^{∞} (R) ^b	$(I_P - I_{\text{sky}}^{\infty})$ (R)	Sun–Earth–Saturn Angle ^c	Observer–Planet Distance (AU)	Solar Flux ^d	Calibration Method
VI UVS	1980 Nov 12	3300 ± 200	950	2350	44° L	0.001	5.2	VOY92
VI UVS	1980 Nov 12	1360 ± 80	390	970	44° L	0.001	5.2	ISSI13
V2 UVS	1981 Aug 26	3000 ± 200	1000	2000	35° T	0.001	5.8	VOY92
V2 UVS	1981 Aug 26	1920 ± 130	640	1280	35° T	0.001	5.8	ISSI13
<i>IUE</i>	1980 Nov 17	...	...	1200 ± 100	48° L	9.51	5.3	BOH90 ^e
<i>IUE</i>	1981 Aug 10	...	...	1100 ± 100	49° T	9.59	5.6	BOH90

Notes.

^a $I_P = I_{\text{Sat}} + I_{\text{sky}}^{\text{Sat}}$ where I_{Sat} is the intrinsic emission from the planet and $I_{\text{sky}}^{\text{Sat}}$ is the sky-background emission toward Saturn with the planetary disk occulting the region behind. For *Voyager* in situ observations, $I_{\text{sky}}^{\text{Sat}}$ vanishes (for more details, see Puyoo et al. 1997).

^b I_{sky}^{∞} is the sky-background emission measured toward infinity by the quoted instrument at the indicated date and position.

^c This angle allows one to estimate the right solar flux taking into account the rotation period of the Sun of ~ 25 days. L is for Saturn leading the Sun and T is for Saturn trailing the Sun (see JPL Horizon ephemerides for more details).

^d Unit is 10^{11} photons $\text{cm}^{-2} \text{s}^{-1}$.

^e The *IUE* calibration used by McGrath & Clarke (1992) is the most updated sensitivity reported in Bohlin et al. (1990). Note that for *IUE* the sky-background emission is derived from the same observation using a portion of the slit outside the planetary disk, which highlights that only the difference between the planetary and sky emissions is reported (e.g., see McGrath & Clarke 1992 for more details).

uncertainty known at that time. With that in mind, it would help to know how sensitive the inversion technique and the derived IPH density are to all the uncertainties listed above.

At this point, it is essential to recall that the IPH models used here are parametric models intended only to fit the opacity produced by the density distribution embedded between Earth and Saturn. First, as described in the previous section, the two-component model is a suitable approximation for describing the nature of the inner heliosphere’s atomic hydrogen, which is mainly composed of two populations—namely, the primary interstellar medium species, and the secondary species that suffered a first charge-exchange with the plasma background in the outer heliosheath (e.g., Baranov & Malama 1993; Izmodenov et al. 2013; Zank 2015). Second, in considering three IPH models with distinct LISM properties, we test the sensitivity of our results to the outer heliosphere’s boundary condition. To ease the implementation of the fitting process, we make use of three existing models thus far published in the literature: the two-component models 1 and 2 defined in Bzowski et al. (2008) and the two-component model defined in Izmodenov et al. (2013). All parameters of the three models are defined in Table 3. For each of these models, considered separately, we operate the fitting process by keeping the velocity, temperature, and the ratio of the primary to the secondary population densities unchanged, but varying the primary species density versus the ionization rate β in order to match the two sides of Equation (4) of Puyoo et al. (1997):

$$I_{\text{IUE}}^{\text{Sat}} - I_{\text{IUE}}^{\text{Sky}} = T \cdot I_{\text{UVS}}^{\text{Sat}} - T \cdot I_{\text{UVS}}^{\text{Sky}} - I_{\text{screen}} \quad (1)$$

where I_{screen} is the sky-background emission blocked by the disk of Saturn and T is the transmission function that depends on the photon frequency and on the opacity of the Earth–Saturn layer (for more details, see Puyoo et al. 1997). We repeat the same fitting process for each of the three distinct models (1–3) in order to test the sensitivity of our approach to different ratios of the primary to secondary population densities.

Because matching the brightness from each of the *IUE* observations to that of each respective *Voyager* UVS depends only on the opacity of the Earth–Saturn layer, we determined that we would display our fitting results using the pair $(\beta, n_{10 \text{ au}})$, where $n_{10 \text{ au}}$ is the total hydrogen density at 10 AU. As we show below, our results are insensitive to the assumptions made on the conditions in the outer heliosphere, particularly to the relative weight of the secondary and primary populations (or equivalently, the LISM proton density) assumed for each of the three main models considered—results that, in turn, make our conclusion about the UVS calibration free of any modeling. The extrapolation of the derived densities at 10 AU to the outer heliosphere region is beyond the scope of the present study.

To evaluate the ratio of radiation pressure to gravity at any radial distance r from the Sun, we use $\mu(r) = 3.473 \times F_{\odot} \exp^{-\tau(r)} - 0.412$, where $\tau(r)$ is the opacity between the Sun and the position r (Emerich et al. 2005; Bzowski et al. 2013). If we include the VOY92 and ISSI13 calibrations, we have a total of 12 cases for matching remote (Earth) to in situ (Saturn) Ly α observations: namely, *IUE* and *V1* (model 1), *IUE* and *V1* (model 2), *IUE* and *V1* (model 3), *IUE* and *V2* (model 1), *IUE* and *V2* (model 2), and *IUE* and *V2* (model 3) for either VOY92 or ISSI13 calibration. For each of these 12 cases, the exercise consists in finding the best density level at 10 AU for a set of values of ionization rate (β) that allows matching of the Ly α brightnesses from the *IUE*

and *Voyager* UVS. As IPH models here are parametric models used only to describe the IPH distribution inside the Earth–Saturn layer, the same fitting process thus entails finding the $(\beta, n_{10 \text{ AU}})$ relation for each of 12 cases, keeping in mind that each of the three IPH models considered is related to the outer heliosphere’s physical parameters via the ratio $n_{\text{sec}}/n_{\text{prim}}$ assumed at 90 AU and the two components’ temperatures and bulk velocities (e.g., Table 3).

In order to properly achieve the comparison between *IUE* and UVS observations, we should also evaluate the solar flux and the sky-background emission level around Saturn for each date of observation. For the solar flux, we use the solar irradiance database provided by the Colorado group at <http://lasp.colorado.edu/lisird/lya/>. Using the JPL Horizon ephemerides, we could derive the right level of solar flux that corresponds to each date of observation taking into account the effect of solar rotation for the hemisphere that faces the planet (see Table 2). For the sky-background emission around Saturn, we used *V1* and *V2* UVS scans obtained during the two spacecraft encounters with the planet (Yelle et al. 1986; Ben-Jaffel et al. 1995). By matching the two sides of Equation (1), we first attempt to evaluate the sensitivity of the derived IPH density to the assumed parametric model 1 to model 3. As shown in Figure 6 (top curves), the best-fit density distributions obtained for the cases *IUE* and *V1* (model 1), *IUE* and *V1* (model 2), and *IUE* and *V1* (model 3) are comparable for the VOY92 calibration. We also obtain a similar conclusion using *IUE* and *V2* (model 1), *IUE* and *V2* (model 2), and *IUE* and *V2* (model 3) for the ISSI13 calibration (curves at bottom of Figure 6). Obviously, our best fits are not sensitive to the assumed parametric IPH model, a result that is not surprising because the difference between the UVS brightnesses of *IUE* and *Voyager* is related to the IPH absorption integrated over the whole line, which is mainly sensitive to the number of H I atoms present between Earth and Saturn, a quantity that is governed by the total density of all absorbing species and the ionization rate.

In the following, we discuss our results using model 1 (or equivalently model 2 or model 3) as a reference. Using Table 2, it is interesting to note that for the new ISSI13 calibration (correction by a factor 243%), the brightness of Saturn in the *V1* encounter drops below the value measured remotely by *IUE* for the same period. As shown in Section 2.2.2, for most existing IPH models, the Saturn–Earth layer is opaque enough to reduce the brightness level measured at Earth compared to the level measured at the planet’s position. In that context, one would expect a lower brightness level at Earth, a result that contradicts the ISSI13 brightness levels shown in Table 2. Even in the unrealistic, extreme condition of empty space between Saturn and Earth with no absorption by the IPH atoms, the brightness level observed by *IUE* is not compatible with the ISSI13 calibration unless we modify the *IUE* calibration itself. The latter assumption is unrealistic because it would require a strong jump (243%–156%) in the *IUE* sensitivity between 1980 and 1981 in order to be marginally consistent respectively with *V1* and *V2* observations of Saturn. Furthermore, the *IUE* calibration has been assessed many times in the past with changes that never exceed a few percent (Bohlin et al. 1990). The indisputable facts above prove that the new sensitivity enhancement of the Ly α channels proposed by Quémerais et al. (2013) for *V1* UVS is absolutely unacceptable.

Table 3
Matching Saturn Ly α Observations from *IUE* and *Voyager* UVS: IPH Model Solutions

Model	$n_{\text{sec}}/n_{\text{prim}}$ (at 90 AU)	T_{prim} (K)	T_{sec} (K)	V_{prim} (km s $^{-1}$)	V_{sec} (km s $^{-1}$)	Earth–Saturn Layer Opacity (Primary)	Earth–Saturn Layer Opacity (Secondary)	$I_{\text{screen}}^{\text{a}}$ (R)	Total H I Density $^{\text{b}}$ $n_{10 \text{ AU}}$ (cm $^{-3}$)
<i>IUE</i> and <i>VI</i> (model 1, VOY92)	1.73	6020	16300	28.5	18.7	0.68	0.61	348	0.152
<i>IUE</i> and <i>VI</i> (model 2, VOY92)	1.00	6100	16500	28.2	18.5	0.88	0.45	340	0.155
<i>IUE</i> and <i>VI</i> (model 3, VOY92)	1.45	6840	18126	28.0	16.6	0.73	0.54	342	0.154
<i>IUE</i> and <i>V2</i> (model 1, VOY92)	1.73	6020	16300	28.5	18.7	0.64	0.56	351	0.147
<i>IUE</i> and <i>V2</i> (model 2, VOY92)	1.00	6100	16500	28.2	18.5	0.92	0.47	356	0.156
<i>IUE</i> and <i>V2</i> (model 3, VOY92)	1.45	6840	18126	28.0	16.6	0.72	0.54	355	0.150
<i>IUE</i> and <i>VI</i> (model 1, ISSI13)	1.73	6020	16300	28.5	18.7	...	...	...	...
<i>IUE</i> and <i>VI</i> (model 2, ISSI13)	1.00	6100	16500	28.2	18.5	...	...	...	...
<i>IUE</i> and <i>VI</i> (model 3, ISSI13)	1.45	6840	18126	28.0	16.6	...	...	...	...
<i>IUE</i> and <i>V2</i> (model 1, ISSI13)	1.73	6020	16300	28.5	18.7	6.8×10^{-2}	8.2×10^{-2}	197	0.022
<i>IUE</i> and <i>V2</i> (model 2, ISSI13)	1.00	6100	16500	28.2	18.5	0.1	6.7×10^{-2}	199	0.023
<i>IUE</i> and <i>V2</i> (model 3, ISSI13)	1.45	6840	18126	28.0	16.6	7.9×10^{-2}	7.7×10^{-2}	198	0.022

Notes. Derived IPH opacity (for each of the primary and secondary populations) and corresponding total H I density required for matching Saturn Ly α brightness from *IUE* to *VI* and *IUE* to *V2* using Equation (1) for the different cases considered: VOY92 and ISSI13 calibrations and three distinct parametric two-component models (defined by the primary population temperature T_{prim} and velocity V_{prim} , the secondary population temperature T_{sec} and velocity V_{sec} , and the ratio of the secondary to the primary component densities $n_{\text{sec}}/n_{\text{prim}}$). The derived IPH total density (last column) corresponds to the sum of the primary and secondary population densities evaluated as a mean value over the range $\beta = (5\text{--}6) \times 10^{-7} \text{ s}^{-1}$ as shown in Figure 6. Our study shows that the total H I density is not sensitive to using model 1, model 2, or model 3, which is consistent with the local inversion technique used. For the ISSI13 calibration (243%), it is impossible to match Saturn Ly α measurements from *IUE* and *VI*. For *V2*, a marginal solution exists at the limit of the noise level. For the standard VOY92 calibration, a common solution exists for both *VI* and *V2* independently of the IPH model assumed.

^a I_{screen} is the sky-background Ly α emission that is blocked by the disk of Saturn and oversubtracted in the *IUE* measurement $I_P - I_{\text{sky}}^{\infty}$ (Puyoo et al. 1997).

^b Total H I density is the best fit ($n_{\text{prim}} + n_{\text{sec}}$) at 10 AU.

Figure 6. Best fit for the pairs $(\beta, n_{10 \text{ AU}})$ of the parametric two-component hot models using Equation (1) to match *IUE* (1AU) to the *VI* and *V2* (~ 9.5 AU) observations of the $\text{Ly}\alpha$ emission of Saturn, respectively in 1980 and 1981. VOY92 refers to the *Voyager* reference calibration and ISSI13 corresponds to the new calibration recently proposed by Quémerais et al. (2013). For the VOY92 case we show the following curves: dashed–triple-dots: (*VI*, model 1), solid: (*VI*, model 2), square: (*VI*, model 3), $\times$: (*V2*, model 1), dashed: (*V2*, model 2), dotted: (*V2*, model 3). For the ISSI13 *V2* calibration, we show triangles: (*V2*, model 1), dashed–dotted: (*V2*, model 2), stars: (*V2*, model 2). For the VOY92 calibration case, the best solution is obtained with an IPH density at the position of Saturn $n_{10 \text{ AU}} = 0.15 \pm 0.02 \text{ cm}^{-3}$ (for an angle of $\sim 73^\circ$ from upwind). For the ISSI13 *V2* calibration, a marginal solution exists with a density at 10 AU $n_{10 \text{ AU}} = 0.022 \pm 0.004 \text{ cm}^{-3}$, at the limit of the noise level. In contrast, no solution exists for the ISSI13 *VI* calibration. The shaded areas show the range $(5-6) \times 10^{-7} \text{ s}^{-1}$ of the ionization rate at 1 AU, β , that best corresponds to the period of observation (Bzowski et al. 2013).

For the *V2* ISSI13 calibration (correction by a factor 156%), the comparison of the *IUE* to *V2* $\text{Ly}\alpha$ observations of Saturn leads to a solution that is shown in Figure 6 (triangles (model 1), dashed–dotted (model 2), and stars (model 3)). For the same ionization rate in the range $(5-6) \times 10^{-7} \text{ s}^{-1}$, the best two-component hot model solution has an IPH local density $n_{10 \text{ AU}} = 0.022 \pm 0.004 \text{ cm}^{-3}$ in the region around 10 AU at an angle $\sim 64^\circ$ from upwind. This solution is marginal because the difference between the corrected *V2* $\text{Ly}\alpha$ brightness ($\sim 1175 \text{ R}$ corresponding to the right-hand side of Equation (1)) and the *IUE* value ($\sim 1100 \text{ R}$) is at the noise level of the measurements. The corresponding IPH density is very weak as if the Earth–Saturn layer is mostly empty. In addition, despite the similar conditions of solar wind and radiation parameters that prevail for the period 1980–1981 (less than 10% variation), the non-existence of solution for the *IUE/VI* observations in 1980 when using the ISSI13 calibration casts doubt on the derived solution for 1981.

In contrast, for the *VI* and *V2* reference calibration (VOY92), the comparison of $\text{Ly}\alpha$ observations of Saturn from *IUE* to those from both *VI* and *V2* leads to a solution for the IPH density that is depicted in Figure 6. For the ionization rate in the range $(5-6) \times 10^{-7} \text{ s}^{-1}$ that prevails around the period 1980–1981 (Bzowski et al. 2013), the best model solution has an IPH local density $n_{10 \text{ AU}} = 0.15 \pm 0.02 \text{ cm}^{-3}$ in the region around ~ 10 AU at an angle $\sim 73^\circ$ from upwind, which is consistent with results previously obtained by Puyoo & Ben-Jaffel (1998). For reference, we obtained similar results (not shown) when using hot models with the appropriate boundary conditions as proposed in Izmodenov et al. (2013). Matching *IUE* to UVS observations leads to a total H I density at 10 AU that is independent of any assumption made on the outer heliosphere boundary. All our results are summarized in Table 3.

Here, it is important to stress that the degeneracy noted in the derived IPH density at 10 AU for the different IPH models used with distinct LISM ionization rate makes its extrapolation to the outer regions difficult because the exact relative weight of the primary and secondary populations remains unconstrained. Other observational constraints should be used in the future in order to accurately derive the external LISM hydrogen density from observations in the inner heliosphere. For reference, using the Baranov–Malama model, Puyoo & Ben-Jaffel (1998) could fit the H I distribution measured in the inner heliosphere using a LISM H I density $n_{\text{H-LISM}} \sim 0.24 \pm 0.05 \text{ cm}^{-3}$ for a LISM proton density of $n_{\text{p-LISM}} \sim 0.043 \text{ cm}^{-3}$. The solution is not unique, yet it is consistent with high H I density required in the outer heliosphere from independent 3D MHD-kinetic and RT modeling of UVS observations (Katushkina et al. 2016).

In conclusion, using the results of Puyoo et al. (1997) and Puyoo & Ben-Jaffel (1998) and the reassessment provided above, we can see that the flux levels observed by *IUE* and *VI* and *V2* when using the VOY92 calibration are consistent with each other and with the IPH model that is assumed locally in the Earth–Saturn layer. With the uncertainty of 30% on the different parameters, our solution and those reported in Puyoo et al. (1997) and Puyoo & Ben-Jaffel (1998) are also consistent with the IPH model used in Quémerais et al. (2013). All of these simple facts show that the new sensitivity enhancement of the $\text{Ly}\alpha$ channels proposed by Quémerais et al. (2013) for *VI* and *V2* UVS is definitely unacceptable.

3. JUPITER AIRGLOW: CALIBRATION OF UVS He 58.4 nm CHANNELS

We follow the same paradigm using airglow from planetary atmospheres to infer their main species abundance. The technique was recently applied to the He abundance of Jupiter and Saturn using *VI* and *V2* UVS observations of He 58.4 nm dayglow made respectively in 1980 and 1981 (Ben-Jaffel & Abbes 2015). Here, we implement the technique as a lever to test the *Voyager* UVS calibration at the He 58.4 nm channels using the He 58.4 nm dayglow observed for Jupiter by *Voyager 1* ($6.5 \pm 1.1 \text{ R}$) and *Voyager 2* ($5.7 \pm 1.2 \text{ R}$) (Vervack et al. 1995; Ben-Jaffel & Abbes 2015). For that purpose, we compare the Jovian He abundance derived from the *Voyager* UVS airglow to the one measured in situ by the *Galileo* probe (von Zahn & Hunten 1996). As shown in Table 3 of Ben-Jaffel & Abbes (2015), the He mixing ratio $\text{He}/\text{H}_2 = 0.16 \pm 0.03$ derived from *Voyager* UVS nicely matches with the *Galileo* probe measurement of $\text{He}/\text{H}_2 = 0.156 \pm 0.006$ (von Zahn & Hunten 1996). The coincidence between the two results confirms that the *VI* and *V2* UVS calibration used is correct (Holberg et al. 1991). The uncertainty that appears in the derived He abundances shows that a 30% uncertainty on the UVS sensitivities is also possible at the He 58.4 nm channels. To summarize, for the very distinct $\text{Ly}\alpha$ and He 58.4 nm channels, the *Voyager* UVS calibrations do not require any substantial revision beyond the attached 30%.

4. WHY THE SKY-BACKGROUND MODELING DOES NOT WORK FOR CALIBRATION: A FEW HINTS

With the conclusions derived above, a legitimate question immediately presents itself: why is it that sophisticated models of sky-background $\text{Ly}\alpha$ emission do not provide the correct calibration?

4.1. Global RT Approach: An Open Issue

For instance, the sky background is the target most observed by several space missions over the last four decades. Because *Pioneer* and *Voyager* UV instruments cover extended regions of the heliosphere over large time spans, the two databases have been extensively used, yet with a constant failure to correctly reproduce the brightness level over time and space unless the instrument calibration is revised up or down (Gangopadhyah et al. 2006; Quémerais et al. 2013). Here, it is crucial to realize that the problem is quite complex because it addresses a very extended, optically thick, moving medium illuminated by a time-variable radiation source, the Sun. Generally, the entire medium is included with appropriate boundary conditions, and the scattering is described either by using the Monte Carlo method or by making approximations of the number of photons diffusing (Keller et al. 1981; Hall 1992; Scherer et al. 1999; Quémerais 2000; Pryor et al. 2008; Katushkina & Izmodenov 2011; Fayock et al. 2013). Hereafter, we call the modeling concept described above the global RT technique. In most applications of the global RT technique, kinetic descriptions of H I and 2D/3D RT models are generally applied to an axisymmetric heliosphere without the distorting effect of the helio-latitudinal variation of the solar wind parameters or of an oblique local interstellar magnetic field (LIMF). The presence of such a magnetic field is actually well established, with clear signatures predicted by models and confirmed by observations and in situ measurements of plasma and field distributions in the outer heliosphere (Ratkiewicz et al. 1998; Ben-Jaffel et al. 2000, 2013; Lallement et al. 2005; Stone et al. 2005, 2008; Schwadron et al. 2009; Heerikhuisen & Pogorelov 2011; McComas et al. 2012; Zirnstein et al. 2016). However, with the smoothing effect of the charge exchange between neutrals and ions (Izmodenov et al. 2005; Wood et al. 2014), the impact of the LIMF on the distribution of neutrals and consequently on the sky-background Ly α radiation field is not too trivial to evaluate.

4.2. Local RT Approach: A First Application

In contrast to the global RT technique, another distinct approach is to consider the differential aspect of the RT equation, a technique that allows direct inversion of data obtained at locations that are close in space. This is indeed the case for maps of sky background Ly α obtained by *Voyager* UVS along their trajectory out to ~ 35 AU from the Sun (Puyoo et al. 1997; Puyoo & Ben-Jaffel 1998). Hereafter, the differential concept is called the local RT model. The implementation of this technique is fully based on the invariance principle to relate different maps of the sky-background radiation field to recover the physical properties of the gas layer embedded between two UVS measurements (Ambartsumian 1958, p. 555; Puyoo et al. 1997). The only limitation of this technique is the requirement of accessing the radiation field that must be observed on both sides of a layer, information that is only available through 1996 (the date at which the scan platform of UVS was stopped). This limitation explains why Puyoo & Ben-Jaffel (1998) inverted the *Voyager* UVS sky maps to derive the H I neutral density distribution up to ~ 35 AU from the Sun (position of VI in 1996). Interestingly, Puyoo & Ben-Jaffel (1998) extrapolated the *Voyager*-based H I density measurements to infinity using the interface model of Baranov & Malama (1993) to find a LIC density of

$\sim 0.24 \pm 0.05 \text{ cm}^{-3}$ that is consistent with most recent findings about the outer heliosphere and the H I number density in the LIC (Katushkina et al. 2016), including the IPH distribution used in the ISSI13 calibration, yet without requiring any revision of the *Voyager* UVS calibration.

4.3. Local RT Approach and the Fermi Glow: Another Application

In the following, we discuss the application of the local RT technique to the inversion of the sky-background excess Ly α emission, a feature detected by UVS deep in the heliosphere (Quémerais et al. 1995). For reference, two explanations are competing to account for the observed excess: the heliospheric origin (Fermi glow as reported in Ben-Jaffel et al. 2000) and the galactic origin (Lallement et al. 2011). Because the Fermi glow model is controversial (Quémerais 2006; Quémerais et al. 2013), we dedicate Section 4.3.1 to addressing all theoretical and instrumental issues, and confirm the interpretation reported in Ben-Jaffel et al. (2000). With that result in hand, we compare the heliospheric and galactic interpretations of the origin of the Ly α excess, emphasizing the importance of the UVS calibration that should not be decided arbitrarily (Section 4.3.2).

4.3.1. Fermi Glow: Reassessment

In 1993, the *Voyager* UVS team began a campaign scanning the sky background over great circles that intersect the upwind and antisolar directions (Quémerais et al. 1995). The main goal of that campaign was to discover any asymmetry in the sky-background radiation field that may be caused by the hydrogen wall near the heliopause (Baranov & Malama 1993). An excess, showing a maximum in brightness close to the upwind direction, was indeed derived by Quémerais et al. (1995), yet their global RT model of solar photon scattering in a sophisticated H I model (accounting for the hydrogen wall) failed to properly reproduce the observations (Quémerais et al. 1995, 2013). In contrast, Ben-Jaffel et al. (2000) proposed an alternative interpretation related to the Fermi scattering of Ly α photons across the hydrogen wall, while Lallement et al. (2011) proposed a galactic origin for the observed excess. In Ben-Jaffel et al. (2000), the idea is principally based on the spatial distribution of the hydrogen atoms produced by charge exchanges with ions slowing down when approaching the stagnation interface (Baranov & Malama 1993). The model could fit the observed Ly α distribution, showing that the nose of the heliosphere deviates $\sim 12^\circ$ from the upwind direction, a deviation that was associated with the presence of an oblique LIMF. Interestingly, the orientation $\sim 40^\circ$ of the LIMF thus far derived by Ben-Jaffel et al. (2000) nicely fits the orientation $\sim 39^\circ$ – 42° obtained by many independent studies that use *Voyager* plasma observations of the TS, *IBEX* ribbon, and/or the interpretation of the *Solar and Heliospheric Observatory* (SOHO)/SWAN hydrogen deflection plane (Schwadron et al. 2009; Pogorelov et al. 2010; Heerikhuisen & Pogorelov 2011; Ben-Jaffel & Ratkiewicz 2012; Ben-Jaffel et al. 2013; Zirnstein et al. 2016). In addition, the derived $\sim 12^\circ$ deflection of the heliosphere's nose is consistent with the $\sim 9^\circ$ asymmetry estimated from the 2–3 kHz heliospheric radiation (Fuselier & Cairns 2013), and with the constraint on the heliotail deflection from observations of *HST* Ly α absorption toward nearby stars (Wood et al. 2014).

Contrary to many misinterpretations of the model (Quémerais 2006; Quémerais et al. 2013), the information on the LIMF orientation in Ben-Jaffel et al. (2000) was deduced from the Ly α excess of the *Voyager* UVS and not from the *HST*/GHRS spectrum; the latter was only used to support the idea of that kind of scattering across a differential velocity field. In addition, Ben-Jaffel et al. (2000) admittedly rejected the classical optically thick model of the Fermi process and clearly provided the expression that better applies to moderate opacities that occur in the heliosphere (Binette et al. 1998; Ben-Jaffel et al. 2000). For that reason, we do not see the logic in attaching the optically thick version of the Fermi process to Ben-Jaffel et al. (2000) when the latter clearly rejected it (e.g., their page 927 and Equation (1)).

One possible way to explain how the Fermi process, as applied by Ben-Jaffel et al. (2000), worked well in fitting the sky Ly α excess and deriving the correct information about the LIMF orientation is that the model was applied as a local RT technique. Indeed, what matters is that the proposed process quantitatively describes the scattering events of photons on atoms that are not symmetrically distributed in space, which helps attach the observed asymmetry of the Ly α excess to the asymmetries of the density and velocity field and, consequently, to the obliquity of the LIMF. Looking back to the *Voyager* UVS observations, it was possible to recover the LIMF orientation from the *Voyager* UVS excess by invoking any local RT model of photon scattering on the asymmetric hydrogen distribution as caused by the LIMF orientation and the charge-exchange process near the interface. For that reason, Ratkiewicz et al. (2008) could recover the same orientation of the LISM magnetic field of $\sim 40^\circ$ using the tilt of the peak of the plasma distribution away from the upwind direction as a direct measure of the peak of the density of neutrals that are at the origin of the Ly α excess observed by *Voyager* UVS. In addition, the same study provided the first 3D direction of the LIMF that is now fully confirmed by *Voyager* plasma and *IBEX* observations (Ben-Jaffel & Ratkiewicz 2012; Ben-Jaffel et al. 2013). Hereafter, we make reference to the heliospheric origin for both the Fermi glow interpretation (which is related to the velocity field asymmetry; Ben-Jaffel et al. 2000) and to the density asymmetry interpretation as reported in Ratkiewicz et al. (2008).

Apart from the model concept, two additional arguments have been commonly used to question the existence of the Fermi feature in the *HST*/GHRS spectrum reported in Ben-Jaffel et al. (2000). The first claim was that the feature was spectrally coincident with the D Ly α line of the Earth's geocorona (Quémerais et al. 2013). On the caption of their Figure 2, Ben-Jaffel et al. (2000) clearly state that the GHRS Echelle mode with the large science aperture could not resolve both the Fermi and the telluric D Ly α lines, and that the latter was properly subtracted using brightness levels estimated from independent sky observation obtained with the same instrument toward Mars and in the same conditions of solar flux and *HST* observing geometry (Krasnopolsky et al. 1998). For reference, the observations were scheduled on 1997 January 20 for Mars and on both 1994 April 4 and 1995 March 25 for the IPH observations reported in Ben-Jaffel et al. (2000). In addition, far-UV observations are usually scheduled during Earth's nighttime of the *HST* orbit, so the observing geometry with respect to Earth remains unchanged. According to the website lasp.colorado.edu/lisird/lya/, the solar Ly α irradiance was

$\sim 3.6 \times 10^{11}$ photons $\text{cm}^{-2} \text{s}^{-1}$ for the 1997 Mars observation, $\sim 3.8 \times 10^{11}$ photons $\text{cm}^{-2} \text{s}^{-1}$ for the 1994 IPH, and $\sim 3.9 \times 10^{11}$ photons $\text{cm}^{-2} \text{s}^{-1}$ for the 1995 IPH. This means that no noticeable difference exists between the solar Ly α fluxes for those three dates (solar minimum activity). To the best of our knowledge, no one questions the D Ly α detection of Mars ($\sim 20 \pm 6$ R as reported in Krasnopolsky et al. 1998), which was obtained with the same instrument and in the same conditions of solar flux and observing geometry as for the IPH observations. For reference, the extra emission feature reported in Ben-Jaffel et al. (2000) has a brightness of $\sim 38 \pm 6$ R. After subtraction of the telluric D line ($\sim 21 \pm 6$ R), we obtain a Fermi line brightness of $\sim 17 \pm 6$ R ($\sim 3\sigma$ detection).

The second argument against the Fermi process is based on the non-detection of the Fermi feature in subsequent observations made with the Space Telescope Imaging Spectrometer (STIS) on board the *HST* in the upwind direction (Quémerais et al. 2013). Here, it is necessary to recall that Ben-Jaffel et al. (2000) were cautious, clearly stressing that the interpretation of the GHRS data in terms of the Fermi line cannot be conclusive until high-resolution detection of the extra emission is obtained. Generally, a non-detection means that either the spectral feature does not exist or the instrument does not have the capability. We argue that the STIS Echelle 140H grating has no capability to detect faint emissions. In the following, we propose two main reasons to explain the non-detection of faint emissions by *HST*/STIS. First, the STIS 140H Echelle grating does not have the sensitivity to detect faint emissions. Indeed, using the *HST*/STIS exposure time calculator for that mode, it is not difficult to find that an extended source of ~ 20 R ($\sim 7.0 \times 10^{-16}$ erg $\text{cm}^{-2} \text{s}^{-1} \text{arcsec}^{-2}$) produces a count rate that represents less than 1% of the background count rate (sky and dark current). This means that, even using an extended slit to gather more light, the signal will be dominated by noise, and the detection of such a faint source will be impossible with the STIS/E140H grating. In contrast, the GHRS has proven in the past its unique capability in counting events rapidly at a rate of 20,000 counts per second per diode, compared to a local count rate of $\sim 50 \text{s}^{-1} \text{pixel}^{-1}$ for STIS (*HST*/STIS handbook, 2006). This underscores the fact that GHRS helped detect faint emissions, particularly the telluric deuterium Ly α emission line (Krasnopolsky et al. 1998). In contrast, the same emission line has never been detected with STIS. The first author participated in many campaigns to study the Ly α line profile of the sky background in the upwind direction obtained with *HST*/STIS since 2001, and the D Ly α line was detected in none of them (Vincent et al. 2011, 2014). All those facts, taken together, explain why the *HST*/STIS E140H mode is not capable of detecting the Fermi line or any faint emission line.

4.3.2. Heliospheric or Galactic Origin? The Answer of the UVS Calibration

There are two competing explanations for the sky-background Ly α excess observed by UVS: the heliosphere origin (our model) and the galactic origin (Lallement et al. 2011). To support the galactic origin, Lallement et al. (2011) proposed a potential correlation between the UVS Ly α distribution and H α emission from the H II region over the sky. The approach is interesting because if the observed emission has a galactic origin, then the correlation should be strong at any time and any place in space, particularly if using two distinct spacecraft

(*VI* and *V2* in the present case). The problem is that when looking back at Figure 4 in Lallement et al. (2011), it is easy to verify that the reported correlation between two $\text{Ly}\alpha$ scans (out of four available) and the $\text{H}\alpha$ distribution over the sky is poor. In addition to the problem of spatial distribution, the issue of the brightness level of the $\text{Ly}\alpha$ excess received little attention. Indeed, Lallement et al. (2011) used UVS calibrations of 70 R/count s^{-1} and 80 R/count s^{-1} respectively for *VI* and *V2* to obtain a $\text{Ly}\alpha$ excess of 3–4 R, a brightness that corresponds to a signal level in the range 0.02–0.05 count s^{-1} . In contrast, Quémerais et al. (1995) derived a brightness of 10–15 R based on a signal level of ~ 0.1 count s^{-1} and using a UVS calibration that is distinct from Lallement et al. (2011) and from Quémerais et al. (2013). For reference, using the ISSI13 calibration, the observed excess $\text{Ly}\alpha$ emission reported in Quémerais et al. (1995) is three times the values reported in Lallement et al. (2011), while if the VOY92 calibration is used the emission (~ 17 – 22 R) is at least four times that value. This means that the $\text{Ly}\alpha$ excess brightness exceeds the estimation made by Blum & Kundt (1989) and the upper theoretical limit of ~ 10 R derived by Thomas & Blamont (1976) for our galaxy based on the same $\text{H}\alpha$ distribution invoked by Lallement et al. (2011) for their proposed correlation.

In contrast, the Fermi glow brightness $\sim 17 \pm 6$ R observed by *HST*/GHRS is consistent with the UVS $\text{Ly}\alpha$ excess of ~ 17 – 22 R derived with the original calibration (e.g., Section 4.3.1). In addition, a heliospheric origin of the UVS $\text{Ly}\alpha$ excess (Ben-Jaffel et al. 2000; Ratkiewicz et al. 2008) leads to properties of the orientation of the LISM magnetic field that are now accurately confirmed by measurements of *SOHO*/SWAN, *Voyager* plasma, *Voyager* radio emission, *IBEX* ribbon, and *HST* $\text{Ly}\alpha$ absorption (Lallement et al. 2005; Schwadron et al. 2009; Heerikhuisen & Pogorelov 2011; Ben-Jaffel & Ratkiewicz 2012; McComas et al. 2012; Ben-Jaffel et al. 2013; Fuselier & Cairns 2013; Wood et al. 2014; Zank 2015; Zirnstein et al. 2016). Furthermore, recent sophisticated 3D MHD-kinetic and RT modeling of the observations of the outer heliosphere obtained by UVS during the period 1993–2003 led to the important result that a high hydrogen density is required to fit the data (Katushkina et al. 2016), a finding that is consistent with the high density derived by Puyoo et al. (1997) and Puyoo & Ben-Jaffel (1998) with the original UVS calibration, and confirmed here for the inner heliosphere (< 10 AU).

All arguments discussed above question the galactic origin of the UVS $\text{Ly}\alpha$ excess, and support its heliospheric origin, making the *Voyager* UVS the first instruments to have detected the distortion of the heliosphere, and consequently the presence of an ambient oblique interstellar magnetic field in the vicinity of our solar system (Ben-Jaffel et al. 2000).

5. CONCLUSIONS: A FIRST STEP

During the last two decades, the harvest from *Voyager 1* and 2 UVS covered EUV and FUV observations of the outer planets and their satellites, in situ measurements ($\text{Ly}\alpha$, Lyman- β , He 58.4 nm) of the heliospheric sky-background, and stellar spectrophotometry. Recently, Quémerais et al. (2013) used sophisticated modeling of the sky-background emission in the outer heliosphere to revise the calibration of the UVS instruments by no less than a factor of 243% for *VI* and 156% for *V2* compared to the calibration after the encounter with Jupiter (Hall 1992). A reassessment was required because

a strong modification of the UVS calibration has a much broader impact on many other topics than just the heliosphere problem.

Here, we use simultaneous *Voyager* UVS (encounters) and *IUE* (remote) observations of the dayglow of Saturn to reevaluate the *VI* and *V2* UVS calibration. For that purpose, we first use *HST*/GHRS archive high-resolution observations of the Saturn $\text{Ly}\alpha$ line profile to derive that the planetary emission linewidth ~ 0.01 nm is large enough to show an absorption signature due to the moving IPH atoms between Saturn and Earth for all possible ranges of the Doppler-shifted absorption. With the Saturn $\text{Ly}\alpha$ line profile in hand, we have compared the brightness of Saturn found by *VI* and *V2* to the brightness observed simultaneously by *IUE* at Earth's orbit using both the old and new calibrations of the *Voyager* instruments. As shown in Tables 2 and 3, with the recent ISSI13 calibration of *VI* UVS, the brightness of Saturn in 1980 is below levels measured by *IUE* at the Earth's orbit, which is wholly in contradiction with the IPH model used by Quémerais et al. (2013) to derive their calibration. Even if it were possible for the interplanetary medium to be empty, the lower intensities derived for *VI* are not consistent with the brightness of emissions observed at Earth unless the *IUE* calibration itself is revised. Because the *IUE* sensitivity is well established (Bohlin et al. 1990), matching UVS ISSI13 with *IUE* observations would require a strong change in the *IUE* sensitivity over one year between 1980 (*VI*) and 1981 (*V2*), which has never been reported in any other *IUE* observations. Such strong variations on short timescales are thus unrealistic, thereby casting doubt on the ISSI13 revision of the *VI* and *V2* UVS calibration. In addition, for the ISSI13 calibration of *V2* UVS, the difference between the *V2* and *IUE* measurements is less than the uncertainty related to the UVS measurements, which led to a marginal solution at the limit of the noise level with a low hydrogen density at 10 AU, almost a factor of 2 below the hydrogen density assumed in the model used to derive the ISSI13 calibration (e.g., Table 3). Finally, the comparison of our RT modeling of the He I 58.4 nm airglow of Jupiter measured by *VI* and *V2* to the *Galileo* probe measurement in situ of the helium abundance in the Jovian atmosphere leads to the same diagnostic on the validity of the original UVS calibration but at distinct channels covering the diffuse He I 58.4 nm emission.

With the strong evidence reported here for the stability of their calibration, the *Voyager* UVS almost certainly become two of the most stable EUV/FUV spectrographs in the history of space exploration. The final uncertainty of 30% derived here on the UVS sensitivity includes the nominal in-flight uncertainty of 20% thus far reported by the UVS team (Holberg et al. 1982), in addition to the potential variability of the planetary airglow used in the calibration process, particularly during the comparison with the *IUE* observations (Puyoo et al. 1997). For reference, we show the final *VI* and *V2* UVS sensitivity curves for extended sources in Figure 7.

One possible way to explain the inadequacy of the ISSI13 calibration is related to the technique used to solve the complex RT problem in the heliosphere. While a differential local approach to the modeling of the sky $\text{Ly}\alpha$ background appears as a self-consistent inversion technique to derive the composition of the interplanetary medium without requiring any revision of the instruments' calibration, global models (like the one used in ISSI13) that include the whole heliosphere and

Figure 7. Reference Sensitivity Curves for V1 (Solid) and V2 (Dashed) UVS.

its complex interaction with the LIC seem to fail to capture the key feature of the physics of the problem, which causes unrealistic modification of the sensitivity of *Voyager* UVS instruments. With this in mind, we reconsider the local RT inversion of maps of UVS sky-background Ly α to confirm the high H I density level reported two decades ago by Puyoo et al. (1997) and Puyoo & Ben-Jaffel (1998) for the inner heliosphere, a finding that is now supported by sophisticated 3D RT interpretation of UVS measurements obtained in the outer heliosphere (Katushkina et al. 2016). In addition, we provide evidence that the interpretation of the excess Ly α emission, a feature detected since 1995 by *Voyager* UVS deep in the heliosphere, is not consistent with a galactic origin as reported in Lallement et al. (2011). In contrast, our theoretical and experimental reassessment of the Fermi glow and, more generally, of the heliospheric interpretation of the same Ly α excess, confirms our finding on the distortion of the heliosphere and the corresponding obliquity of the LIMF ($\sim 40^\circ$ from upwind) (Ben-Jaffel et al. 2000), without requiring any revision of the *Voyager* UVS calibration. The above arguments make both *Voyager* UVS the first instruments to have detected (two decades ago) the distortion of the heliosphere, and consequently, the presence of the oblique interstellar magnetic field in the neighborhood of our solar system (Ben-Jaffel et al. 2000; Ben-Jaffel & Ratkiewicz 2012).

To build on the rich heritage from both *Voyager* UVS and past space missions, our study points to the need in the future for fine Doppler-shift measurements and detection of faint emissions (probably including polarimetry) in different locations of the heliosphere so that direct inversion techniques can be applied in order to directly access the microphysical processes that drive the instant shape and composition of the heliosphere that is forced by the magnetized plasmas from solar wind and the local interstellar medium. Future deep space missions should thus include robust UV capabilities that make use of sensitive, high-resolution technology that will make it possible to attain the highest throughput for extended light sources (Ben-Jaffel et al. 2005; Harris et al. 2005).

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