Supporting Evidence for a Galactic Ly\(\alpha\) Background from Cassini UVIS Data

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Abstract

Cassini UVIS interplanetary hydrogen Ly\(\alpha\) measurements from 2003 to 2004, obtained from a heliospheric downwind to sidewind location on approach to Saturn and during the first Saturn orbit, are presented and fit by a heliospheric hot density model with solar illumination. Adding the recently proposed 43 \(\pm\) 3 Rayleigh (R) isotropic galactic hydrogen Ly\(\alpha\) signal derived from New Horizons data improves our model’s ability to fit the observed Cassini “27 day” signal modulations from both upwind and downwind directions. Our modeling of the UVIS data favors a galactic Ly\(\alpha\) background of \(\sim 40–100R\) over a model with no significant galactic background.

Unified Astronomy Thesaurus concepts: Interstellar medium wind (848)

1. Introduction

Several authors have previously considered the possibility of a galactic Ly\(\alpha\) background, but the consensus was that it should be a small signal compared to Ly\(\alpha\) emission from solar Ly\(\alpha\) photons scattered by interstellar wind hydrogen flowing through the solar system from “upwind” (e.g., Thomas & Blamont 1976; Lallement et al. 2011). Hall et al. (1993, their Figure 2) found an expected leveling beyond 30 au from the Sun in the Ly\(\alpha\) data from Voyager 1, which was traveling upwind and viewing upwind, and mentioned that one possibility is an unexpectedly large galactic background. Gangopadhyay & Judge (1996, their Figure 4) fit the Pioneer 10 Ly\(\alpha\) data obtained from about 5 to 62 au from the Sun viewing downwind while traveling downwind with a 1/r dependence on radial distance from the Sun. Our visual inspection of the data in that figure in the final range covered (~50–62 au) shows no decline from a constant ~20R signal, suggesting a significant constant galactic component. Lallement et al. (2011) identified a localized source of several R of galactic hydrogen Ly\(\alpha\) emission in Voyager data correlated with enhanced H\(\alpha\) emission in the direction of Scorpius–Ophiuchus. Recent work on the topic by Katushkina et al. (2016, 2017) considered a more significant galactic source of Ly\(\alpha\) in the upwind direction to explain Voyager data. Most recently, Gladstone et al. (2018, 2021) have found that the radial falloff in New Horizons Ly\(\alpha\) data at increasing solar distances is consistent with a surprisingly large and isotropic galactic Ly\(\alpha\) source, estimated at 43 \(\pm\) 3 R. As New Horizons and Voyager are both located far upwind, an obvious follow-up question is to check for evidence for a galactic Ly\(\alpha\) source from a downwind-located spacecraft to see if there is such a source, and to what extent the source is isotropic.

The Cassini spacecraft spent considerable time in locations both downwind and upwind in the heliosphere during its cruise to Saturn (1997–2004) and its Saturn orbital mission (2004–2017). This paper will look at Cassini Ultraviolet Imaging Spectrograph (UVIS; Esposito et al. 2004) cruise phase data from 2003 to 2004 and some early Saturn orbital phase data from 2004, when Cassini was in the heliospheric downwind hemisphere and moving sidewind. These cruise data were described and presented by Pryor et al. (2008), who compared the time-varying UVIS brightness with a model incorporating the varying solar source, and found good agreement between data and model when the Cassini UVIS was looking upwind. This paper will examine both the upwind-looking and downwind-looking UVIS data and see how adding a large galactic signal affects the model fits. Because the downwind-looking signal from a downwind-located spacecraft is lower than the upwind-looking signal we expect the downwind-looking data to be more sensitive to a possible isotropic galactic signal. In particular, the “27 day” modulations seen in the Ly\(\alpha\) signal are entirely due to solar illumination changes (resulting from rotation of solar active regions with enhanced Ly\(\alpha\) emission in roughly 27 days, as seen at Earth), and will not be present in the galactic signal. Modeling the observed modulations allows us to test for a galactic signal.

2. Data Sets

The Cassini UVIS far-ultraviolet (FUV) channel (111.5–191.2 nm) routinely obtained interplanetary Ly\(\alpha\) data during its long cruise to Saturn and during its orbital mission at Saturn. The Ly\(\alpha\) line was spectrally unresolved, with a three-position slit mechanism providing 0.275, 0.48, and 2.49 nm spectral resolution for extended sources like interplanetary hydrogen Ly\(\alpha\). Data presented here were obtained with 0.48 and 2.49 nm spectral resolution through the “low-resolution” and “occultation” slits. Selected cruise phase data included here are from 2003 and 2004, when the spacecraft was generally downwind of the Sun, moving sidewind, and nearing Saturn (Figure 1). Saturn orbital insertion (SOI) was on 2004 day 182 (June 30). Some additional orbital phase data from 2004 are included, up to decimal year 2004.9. Data from near SOI and from near the next Saturn periapole on 2004 day 302 (October 28) were excluded from this study as Ly\(\alpha\) signal from the Saturn system may be present. Upwind data were selected for this study where UVIS was pointing within 30° of the ecliptic...
plane and within 90° of ecliptic longitude 255°. Downwind data were selected where UVIS was pointing within 30° of the ecliptic plane and within 75° of ecliptic longitude 75°.

3. Model

We used a standard heliospheric hot model (Thomas 1978; Ajello et al. 1987; Pryor et al. 1992, 2013, 2020) to describe the interstellar wind hydrogen passing through the solar system and illuminated by sunlight. We assumed an inflow of interstellar wind neutral hydrogen from the upwind direction with thermodynamic parameters inside the termination shock of density $n = 0.085$ cm$^{-3}$, velocity $v = 20$ km s$^{-1}$, and temperature $T = 10,000$ K (for discussions of $v$ and $T$ see, e.g., Costa et al. 1999; Clarke et al. 1998). We note that $T = 10,000$ K for hydrogen is larger than the standard value of $T = 7500$ K (McComas et al. 2015) used for interstellar wind helium due to outer heliospheric heating effects preferentially affecting hydrogen and creating a somewhat non-Maxwellian distribution. The time-dependent Ly$\alpha$ line-integrated flux is taken from the Laboratory for Atmospheric and Space Physics (LASP) solar database (Woods et al. 2000), with a correction to the estimated line-center flux (Emerich et al. 2005; Lemaire et al. 2015). The major loss process for slow hydrogen near the Sun is charge exchange with solar-wind protons. Solar-wind proton density and velocity data are taken from the National Space Science Data Center (NSSDC) database (King & Papitashvili 2005). The solar-wind charge-exchange lifetime latitudinal variation is estimated using a solar-wind asymmetry factor $A = 0.4$, with the $A$ parameter defined by the expression that the hydrogen lifetime $t$ against charge exchange with solar-wind protons at a given heliographic latitude is

$$t(\text{latitude}) = t(\text{latitude} = 0)/(1 - A \sin^2(\text{latitude})),$$

which leads to a larger lifetime away from the ecliptic plane for positive values of $A$ (e.g., Witt et al. 1979). A secondary loss process for hydrogen atoms is time-dependent EUV photoionization, which is estimated using the Space Environment Technologies (SET) Solar Irradiance Program (SIP; Tobiska et al. 2000; Tobiska & Bouwer 2006). The ionization rates were averaged over periods of a year or longer, as discussed in Pryor et al. (2013). The radiative transfer model used is fundamentally a single-scattering model. However, a correction is made for multiple scattering enhancement of signal in the downwind direction based on the angle from upwind, as discussed in Quémerais & Bertaux (1993) and in Ajello et al. (1994) and calculated using multiple scattering codes (Hall 1992; Hall et al. 1993).

This paper fits the Cassini Ly$\alpha$ data with a representation of the form

$$\text{Data} = \text{scale factor} \times \text{heliospheric Lyman} - \alpha \text{model} + \text{galactic Lyman} - \alpha \text{background}.$$

The scale factors for a particular data set are found by subtracting the galactic Ly$\alpha$ value to be tested from the data and dividing by the standard heliospheric model:

$$\text{scale factor} = \frac{\sum(\text{Data} - \text{galactic Lyman} - \alpha \text{background})}{\sum(\text{heliospheric model})},$$

where the $\sum$ represents a sum over the data points being studied. We compared the success of the various model values $M_N$ in fitting the $N$ data values $D_N$ by using an rms fit percentage, defined by

$$\text{rms} = 100 \times \sqrt{(1/N) \times \sum((D_N - M_N)/D_N)^2)},$$

where the $\sum$ again represents a sum over the $N$ data points being studied. Figure 2 shows two models compared to the data, which have been binned to represent the average of seventy 25 s measurements. A scaled heliospheric Ly$\alpha$ model with no galactic background fits the data reasonably well upwind (6.8% rms fit), but produces too much time variability when compared to the downwind data (9.7% rms fit); fitting the peaks in the data (black dots) with the scaled model (red dots) leaves several model dips that drop significantly below the
data. A second fit applied to both the upwind and downwind data applying a slightly different scale factor to the heliospheric model and a constant galactic background of 43 R found by Gladstone et al. (2021) provides reasonable agreement in the upwind (6.7% rms fit) and somewhat improved agreement (9.3% rms fit) in the downwind look directions. The second fit in particular (yellow dots) reduces the peak-to-peak amplitude of the modulations sufficiently to better fit the data in both the upwind and downwind directions, although the effect is larger downwind where the overall signal is lower. Adding an even larger galactic background further shrinks the modulation. We find a broad minimum in the rms fits for a Lyα galactic background with the minimum best fit downwind of 9.2% near 90°. However, a solution with an 86° background (twice the value expected from the New Horizons observations) has a low upwind scale factor of 0.83, which would correspond to an improbably low hydrogen density upwind of 0.085 \pm 0.083 = 0.071 cm^{-3}, well below recent estimates (e.g., Swaczyna et al. 2020 found n = 0.127 \pm 0.015 cm^{-3}). The linear least-squares fitting routine LINFIT in the software package IDL applied to the binned data and heliospheric model in Figure 2 finds an upwind constant background term of 67.3 \pm 1.0 R and a downwind constant background of 93.9 \pm 9.8 R, which we interpret as additional estimates of the galactic Lyα background.

The Cassini UVIS data and the models used here all show “27 day” waves in both the upwind and downwind directions. The peaks upwind and downwind in Figure 2 are out of phase, representing rotation of active regions on the Sun, which are generally well captured in the model. Not all 27 day waves are equally well fit, as expected. Sunspot evolution during a rotation is not included in the model; we use the values measured at the Earth and rotate those values by an appropriate amount. For example, the far side of the Sun is assumed to have a far-side solar-wind lifetime using data from the Solar and Heliospheric Observatory (SOHO) Solar Wind Anisotropy Experiment (SWAN) are found in Koutroumoupa et al. (2019), Katushkina et al. (2019), and Pryor et al. (2020). The first two more detailed studies determine the detailed hydrogen-lifetime latitude dependence unconstrained by the A parameterization, while the Pryor et al. study uses the A parameter to characterize SOHO SWAN all-sky Lyα maps from 2008 to 2019 and finds that A = 0.4–0.5 is often a useful approximation, at least away from solar maximum when a lower A value is preferred. Figure 3 does not provide additional constraints on the galactic background because only a single day of data is represented, and our model uses daily Lyα values, so this roll data does not contain significant 27 day modulation effects.
4. Discussion

The present study was motivated by our desire to test the idea of a substantial isotropic galactic Lyα signal. The 43 ± 3 R of galactic signal indicated by New Horizons data (Gladstone et al. 2018, 2021) represents about 20% of the downwind signal seen from a downwind spacecraft at ∼10 au. Twenty-seven day variations measured from the Sun at Earth due to solar rotation of Lyα producing active regions are also seen in the downwind Lyα signal. As shown in Figure 2, using just a multiplicative scaling on the model and matching the peaks in the data leads to dips in the model downwind with significantly lower brightness than are seen in the data. Using both a constant 43 R background and a multiplier applied to the model better matches both the peaks and the dips downwind, as well as upwind. In fact, both the upwind and downwind are now fit by applying roughly the same scaling factor of 1.00 to the heliospheric Lyα model and adding the 43 R galactic Lyα background expected from New Horizons work (Gladstone et al. 2021). The final scaling factor of 1.01 upwind could be interpreted as determining the model hydrogen density upwind inside the heliospheric boundaries to be 0.086 cm$^{-3}$. The uncertainties in our density estimate are dominated by the Cassini UVIS calibration uncertainties. Estimating a calibration uncertainty of 20% leads to a formal hydrogen density estimate for this study of $n = 0.086 ± 0.017$ cm$^{-3}$, somewhat lower than the recent Swaczyna et al. (2020) estimate from New Horizons pickup ion observations that found $n = 0.127 ± 0.015$ cm$^{-3}$ near the termination shock. If instead there is no significant galactic contribution, our upwind model scale factor of 1.18 to fit the UVIS data in Figure 2 yields a higher hydrogen density estimate of $0.085 * 1.18 = 0.10 ± 0.020$ cm$^{-3}$. In other words, the presence of a galactic Lyα background tends to reduce the derived interplanetary hydrogen density.

Past studies of Lyα modulation (Shemansky et al. 1984; Quémerais et al. 1996; Pryor et al. 2008) have included multiple scattering in the outer heliosphere. They found that in the outer heliosphere interplanetary Lyα 27 day waves are damped in amplitude compared to the solar 27 day waves because of multiple scattering effects spreading initial Lyα anisotropies around the Sun. At 10 au, since the upwind data are fit by the model without obvious damping at Cassini, this indicates we are still in or near the single-scattering regime. Our current modeling does not rule out that the upwind–downwind differences in modulation are due to enhanced multiple scattering looking downwind from downwind.

![Figure 3](image-url)

**Figure 3.** Top panel: Cassini UVIS low-resolution slit Lyα roll brightness (black dots) from 2004 day 78 is plotted as a function of ecliptic latitude. Each dot is an average of five 25 s measurements. A model for the brightness using a hydrogen-lifetime asymmetry parameter of A = 0.4 is also shown, scaled by a factor of 1.03 and with an added background of 43 R (yellow dots). Data–model is also shown (+ symbols). A 5σ statistical error bar is shown on one data point. Bottom panel: Cassini UVIS low-resolution slit Lyα roll brightness (black dots) from 2004 day 78 is plotted as a function of ecliptic latitude. A model for the brightness using an isotropic hydrogen-lifetime asymmetry parameter of A = 0.0 is also shown, scaled by a factor of 1.07 and with an added background of 43 R (yellow dots). The differences between the data and the model values are also shown (+ symbols). A 5σ statistical error bar is shown on one data point.
However, at low optical depths, scattering around the Sun is limited in angular extent, as detailed in Quémerais et al. (1996) so the expected damping is limited. Their Figure 6 shows, using Monte Carlo calculations at 10 au downwind of the Sun, that the expected modulation damping is similar in three different view directions, looking upwind, downwind, and sideward, within 10%. The differences seen in the modulation of the UVIS data looking upwind and downwind are larger than in those Monte Carlo multiple scattering calculations, with the observed upwind modulation almost twice as large as the downwind modulation, suggesting a different explanation besides multiple scattering effects is needed. We conclude that the fact that our simple model improves the fits to both the upwind and downwind modulations when a 43 Rayleigh signal isotropic galactic signal is added provides some additional evidence for such a source, already identified in New Horizons data by Gladstone et al. (2018, 2021).

An alternative way of thinking about the data is to estimate the size of isotropic galactic background required to produce the observed upwind and downwind Lyα brightness modulations, neglecting multiple scattering effects that would tend to dilute the modulations by distributing the photons in ecliptic longitude. The Appendix shows a way to estimate the background from the observed upwind and downwind brightness and the observed upwind and downwind modulation. Using that algebra, and taking a few estimates from Figure 2, an upwind mean brightness \( u \sim 295 \, R \), a downwind mean brightness \( d \sim 190 \, R \), an upwind modulation amplitude of \( \Delta u \sim 45 \, R \), and a downwind modulation amplitude of \( \Delta d \sim 25 \, R \) can be explained by an isotropic galactic background of \( \Delta R \sim 60 \, R \). Examining other waves will give somewhat different values. This estimate is no replacement for drawing conclusions from the full model but does clarify what is shown in Figure 2.

The question of an isotropic galactic Lyα source merits some discussion. Lallement et al. (2011) looked for Lyα signal correlations with H II regions expected to produce Lyα based on their hydrogen Hα emission line production and set a limit on the galactic Lyα of 3 \( \alpha \), with the limited observed galactic Lyα seen in a location with enhanced Hα. However, Dijkstra (2019) emphasized the extremely complicated radiative transfer involved in the very optically thick galactic hydrogen. Isotropy may be reasonable based on the fact that scattering from a hydrogen atom is much more likely than absorption by a dust grain and there are very large hydrogen optical depths in the galaxy, creating a fog-like effect. Hayes (2019) found that Hα and Lyα are often uncorrelated in galaxies, and that many galaxies have extended Hα emitting regions (see especially their Figure 4.26). A good follow-up project would be to look at spectrally resolved Lyα data sets obtained outside the geocorona, for example from the Mars Atmosphere and Volatile Evolution (MAVEN) orbiter Imaging Ultraviolet Spectrograph (IUVS; McClointock et al. 2015) cruise data, to see if galactic Lyα can be spectrally identified or constrained. This issue of a possible large isotropic galactic Lyα signal should be resolved as a necessary first step before detailed Lyα studies of the proposed upwind hydrogen wall (e.g., Izmodenov et al. 2013; Katushkina et al. 2016) can reach firm conclusions.

5. Conclusions

Modeling the modulation of interplanetary hydrogen Lyα data obtained by the Cassini UVIS from 2003–2004 at \( \sim 10 \, au \) from the Sun on the downwind to sidewind side provides an opportunity to test for a large unmodulated galactic isotropic signal. While other models are certainly possible, we found that adding the \( 43 \, R \) isotropic signal proposed by Gladstone et al. (2021) from studying New Horizons Lyα data to our fundamentally single-scattering model provided improved fits to the 27 day modulations seen in the data, particularly when observing in the downwind direction. This suggests that previous heliospheric Lyα studies have been missing an important element, the galactic Lyα background. The fact that this improvement is seen from the downwind Cassini spacecraft looking downwind, even though the New Horizons results were for an upwind spacecraft, suggests the galactic emission may be somewhat uniform and isotropic, although further study is needed from New Horizons and other spacecraft. Cassini, for example, obtained InterPlanetary Hydrogen survey (IPHsurvey) Lyα data throughout the Saturn orbital phase from 2004 to 2017, which merits future detailed study. Looking at the UVIS data as a whole would allow us to assess instrument sensitivity changes since launch in 1997 by comparison with the standard model and may revise the estimates of hydrogen density in this paper.

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Appendix

How to Find an Isotropic Background from the Upwind and Downwind Modulation in the Single-scattering Limit

We measure the quantities \( u = \text{mean upwind signal} \), \( d = \text{mean downwind signal} \), \( \Delta u = \text{amplitude of upwind waves} \), and \( \Delta d = \text{amplitude of downwind waves} \). The upwind and downwind signals \( u \) and \( d \) can be broken down into solar and isotropic galactic background components:

\[
    u = u_s + b,
\]

where \( u_s \) is the solar part of the mean upwind signal and \( b \) is the isotropic galactic background component.

\[
    d = d_s + b,
\]

where \( d_s \) is the solar part of the downwind signal and \( b \) is the isotropic galactic background. A third relationship is

\[
    \Delta u / u_s = \Delta d / d_s,
\]

that is, we expect the modulated fraction to be the same upwind and downwind from a linear response to a solar flux increase, neglecting multiple scattering effects. Then by rearranging

\[
    d_s = u_s \Delta d / \Delta u + b,
\]

Then, substituting for \( d_s \) in the second equation, we have two equations in the two unknowns \( u_s \) and \( b \):

\[
    d = u_s \Delta d / \Delta u + b,
\]

\[
    u = u_s + b,
\]
\[ u = u_s + b. \]

Now subtract the second of these two equations from the first:

\[ d - u = u_s((\Delta d/\Delta u) - 1), \]

and solve for \( u_s \) in terms of known quantities:

\[ u_s = (d - u)/(\Delta d/\Delta u) - 1), \]

then the background \( b \) is found from

\[ b = u - u_s = u - (d - u)/(\Delta d/\Delta u) - 1). \]

Inspection of Figure 2 gives sample values. We picked a time on the plot between Saturn orbit insertion and the next Saturn periapse with fairly steady Ly\( \alpha \) waves, suggesting slow solar variations. If \( u = 295 \) \( R \), \( d = 190 \) \( R \), \( \Delta u = 45 \) \( R \), and \( \Delta d = 25 \) \( R \), then the crudely estimated galactic background \( b \) is

\[ b = 295 - (190 - 295)/(25/45) - 1) \sim 60 \text{ Rayleighs}. \]

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