New Horizons Detection of the Local Galactic Lyman-α Background

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Abstract

Since 2007 the Alice spectrograph on the New Horizons (NH) spacecraft has been used to periodically observe the Lyman-α (Lyα) emissions of the interplanetary medium (IPM), which mostly result from resonant scattering of solar Lyα emissions by interstellar hydrogen atoms passing through the solar system. Three observations of IPM Lyα along a single great circle were made during the NH cruise to Pluto, and these have been supplemented by observations along six great circles (spread over the sky at 30° intervals), acquired one month before and one day after the NH flyby of Pluto, and on a further five occasions since then, out to just over 47 au from the Sun. These data indicate a distant Lyα background of 43 ± 3 Rayleigh brightness (equivalent to 56 ± 4 nW m⁻² sr⁻¹), which is present in all directions (i.e., not only in the upstream direction, as previously reported). This result is found independently by: (1) the falloff with distance from the Sun of the IPM Lyα brightness observed by NH–Alice in several directions on the sky, and (2) the residual between the observed brightness and a model brightness accounting for the resonantly scattered solar Lyα component alone. The repeated observations show that this distant Lyα background is constant and uniform over the sky, and represents the local Galactic Lyα background. The observations show no strong correlation with the cloud structure of the local IPM. The observed brightness constrains the absorption coefficient of interstellar dust at Lyα to 0.2 ± 0.01 kpc⁻¹.

Unified Astronomy Thesaurus concepts: Interstellar medium (847); Interstellar scattering (854); Interstellar line emission (844); H I line emission (690)

1. Introduction

Hydrogen is the most abundant element, and its simplest electronic transition is a doublet from nl = 2p to nl = 1s at a wavelength of 121.567 nm, known as Lyman-α (Lyα). Since Lyα emissions are abundantly produced through the recombination of electrons and protons in H II regions, it is estimated that they carry a large fraction of the photon energy in the galaxy (Dijkstra 2019). Furthermore, studies of the extinction of light from high-z sources (e.g., quasars) due to scattering of Lyα photons by intervening hydrogen (i.e., the Lyα forest), have enabled observational cosmologists to map out the distribution of matter in the universe (e.g., Prochaska 2019). Owing to the importance of this emission to astrophysics, the local Galactic background of Lyα emission has been the subject of considerable interest for much of the space age (e.g., Münch 1962; Adams 1971; Fahr 1974). However, the near-Earth region of the solar system is dominated by resonantly scattered solar Lyα emissions, both in Earth’s geocorona (at brightnesses up to 35 kR, where 1 R = 1 Rayleigh = 10⁶ photons cm⁻² s⁻¹ (4πsr)⁻¹) and in the interplanetary medium (IPM); at brightnesses of 500–1000 R near 1 au; e.g., Meier 1977, 1991), which are considerably brighter than the expected Galactic background.

Thus, estimates of the Galactic Lyα background have varied widely over the last 60 years, from an early estimate of 500 R (Münch 1962) to a much lower recent determination of 3 R (Lallement et al. 2011). In this paper we present new results using the Alice ultraviolet spectrograph on the New Horizons (NH) spacecraft to detect the Galactic Lyα background at a brightness of 43 ± 3 R (equivalent to 56 ± 4 nW m⁻² sr⁻¹). Using an estimate for the production of Lyα photons from recombination in local H II regions, the observed brightness constrains a local dust absorption coefficient at Lyα wavelengths of 0.2 ± 0.01 kpc⁻¹.

2. Data

As with the Voyager spacecraft, the escape trajectory of NH from the solar system provides an excellent platform for observing the IPM Lyα background as a function of distance from the Sun. Figure 1 shows the NH and Voyager trajectories projected onto the plane of the ecliptic, with the flow direction of interstellar hydrogen atoms also indicated for comparison. The Alice ultraviolet spectrograph on the NH spacecraft consists of a telescope, a Rowland-circle spectograph, a double-delay-line microchannel plate (MCP) detector at the focal plane, and associated electronics and mechanisms (Stern et al. 2008). The entrance slit has two contiguous sections: a 2° × 2° “Box” and a 0°1° × 4° “Slot”. The bandpass is 52–187 nm with a filled-slit spectral resolution of 0.9 nm in the 0°1 wide slot. The box part of the slit is wide enough to...
permit off-axis IPM Lyα emissions to fall on a KBr or a CsI photocathode which coats the MCP on either side of the bare location on the detector where on-axis Lyα photons fall, giving the Alice spectrograph a high sensitivity to diffuse Lyα emissions (Gladstone et al. 2015). This sensitivity was initially estimated at 5.5 counts s$^{-1}$ R$^{-1}$ (Gladstone et al. 2015), but in comparing several long exposures of dark regions of the sky, we have determined an improved value for conversion of Alice count rates to Lyα brightness. The Lyα brightness measured in the Alice slot during eight different 1 hr observations of star-free regions near the IPM upstream and downstream directions were compared to the corresponding dark-corrected analog Alice count rates. The net result is a more exact revised value for the Alice Lyα sensitivity of 4.92 ± 0.09 counts s$^{-1}$ R$^{-1}$ (about 11% less than our initial estimate), which is used in this study. Note that this sensitivity is approximately 500× larger than the corresponding sensitivity of the Voyager UVS spectrometers (mostly due to the large solid angle of the box).

Beginning in late 2007, a single-great-circle scan observation of the IPM was performed during the first annual checkout (ACO-1) of the NH spacecraft (outside of ACOs, the spacecraft was in hibernation mode for much of the 9.5 yr transit from Earth to Pluto, and the Alice instrument was turned off). Similar observations were made during ACO-2 in 2008 and ACO-4 in 2010; for these single-great-circle observations, the +Z-axis of the NH spacecraft (i.e., the axis of rotation of the great circle) was pointed toward a Galactic longitude and latitude (l,b) direction of (129°8, −1°7). At Pluto flyby, near 33 au in 2015, the strategy for observing the IPM Lyα emissions was changed to provide denser coverage over the sky, using six great circles spaced 30° apart, with the NH +Z-axis pointed toward Galactic (l,b) directions of (190°3, −2°9), (179°8, −31°4), (159°8, −57°9), (91°5, −71°4), (37°0, −52°6), and (20°3, −25°1). The choice of great circles was constrained to avoid observing less than 10° from the Sun, and to avoid as many UV-bright stars as possible. Two six-great-circle IPM observations were executed during the flyby of Pluto, one month prior to closest approach and one day after; during both observations the scan rate was 1° s$^{-1}$. Following the Pluto encounter, another five nearly identical six-great-circle IPM observations have been performed; however, these most recent scans have all been made at a scan rate of 0.1° s$^{-1}$, which provides ~3× larger signal-to-noise ratio. The salient details of all the IPM scans are provided in Table 1, which includes the date, day of year, start and end in NH mission elapsed time (MET) and coordinated universal time (UTC), scan duration, scan rate, distance of NH from the Sun, NH ecliptic longitude and latitude (λ and β), Galactic longitude and latitude (l and b) as seen from the Sun, NH ecliptic coordinates, the angle between NH and Earth as seen from the Sun, the integrated, line-center, and 81 day average integrated Lyα fluxes at 1 au, the solar wind charge exchange, solar photoionization, and total lifetimes of H atoms at 1 au, and the ratio of radiation pressure to gravity on an H atom. The sky coverage of all the IPM scans are indicated in Figure 2.

The single great circles observed during ACOs 1, 2, and 4 overlap with the six-great-circle observations made at Pluto and since then at 11 locations, as indicated by the blue dots in Figure 2. These overlaps provide a record of the IPM brightness in these 11 specific directions as NH traveled outward from the Sun from 7.6 au to (most recently) 47.2 au. It is found that in each direction, the variation of the IPM Lyα background with NH distance from the Sun is remarkably well fit by this simple empirical function

$$4\pi I = A/r_{NH} + B$$

where 4πI is the IPM Lyα brightness (in Rayleighs), $r_{NH}$ is the distance of the NH spacecraft from the Sun, and A and B are constants. The falloff in the Lyα background brightness observed in one of the 11 overlap directions on the sky is shown in Figure 3. The data points are averages of all the count rate measurements made within 2° of the listed direction, and the error bars are their standard deviations. Along with the Alice measurements are plotted two simple least-squares fits of Equation (1) to the data, one with the value of B allowed to float and the other with B = 0. It is clear that a non-zero value of B provides an acceptable fit to the observations. Although Figure 3 only shows the falloff in the Lyα background brightness in one direction, the other 10 directions show similar results. These results are summarized in Table 2, which lists the 11 directions in ecliptic (λ, β) and Galactic coordinates (l, b), the angles between those directions and the upstream ($\Theta_{IPM}$) and solar ($\Theta_{Sun}$) directions, the simple model estimate of the IPM-scattered solar Lyα from Equation (2), and the least-squares fits to the Alice observations and associated $\chi^2_\nu$ values. In addition, Table 2 provides the average and standard deviation of the constant B$_{LSF}$ over all 11 directions, those directions at Galactic latitudes $|b| > 30°$, and those directions that are both at Galactic latitudes $|b| > 30°$ and at directions greater than 60° from the Sun (i.e., $\Theta_{Sun} > 60°$).

![Spacecraft Trajectories](image)
# Table 1

| IPM Observation | ACO-1 | ACO-2 | ACO-4 | P-28 | P-1 | KEM-1 | KEM-2 | KEM-3 | KEM-4 | KEM-5 |
|-----------------|------|------|------|------|-----|------|------|------|------|------|
| Date            | 2007 Oct 07 | 2008 Oct 18 | 2010 Jun 19 | 2015 Jun 16 | 2015 Jul 15 | 2017 Jan 28 | 2017 Sep 19 | 2019 Mar 03 | 2019 Aug 30 | 2020 Apr 27 |
| Day of year     | 280   | 292   | 170   | 167   | 196   | 028   | 262   | 062   | 242   | 118   |
| Start MET (s)   | 054029144 | 086636428 | 139244434 | 296789400 | 299293022 | 347914797 | 368113207 | 413932808 | 429514702 | 450294877 |
| End MET (s)     | 054032562 | 086643828 | 139251939 | 296792158 | 299295779 | 347937036 | 368135458 | 413955074 | 429536976 | 450317154 |
| Start UTC (hh:mm:ss) | 02:13:46 | 11:48:31 | 09:08:36 | 19:38:03 | 19:05:04 | 07:48:09 | 15:28:10 | 23:46:24 | 12:02:40 |
| End UTC (hh:mm:ss) | 03:10:44 | 13:51:51 | 11:13:41 | 20:24:01 | 19:51:01 | 19:18:37 | 13:59:00 | 21:39:16 | 29:57:38 |
| Scan duration (s) | 3418   | 7400   | 7505   | 2758   | 2757   | 22239  | 22251  | 22266  | 22274  |
| Scan rate (° s⁻¹) | 0.1    | 0.1    | 0.1    | 1.0    | 1.0    | 1.0    | 1.0    | 1.0    | 1.0    |
| nh (au)         | 7.624  | 11.337 | 16.991 | 32.679 | 32.919 | 37.561 | 43.775 | 45.229 | 47.161 |
| β NH (°)        | 259.32 | 269.33 | 276.56 | 284.02 | 284.09 | 285.15 | 285.52 | 286.25 | 286.73 |
| β NH (°)        | 1.17   | 1.50   | 1.72   | 1.91   | 1.91   | 1.91   | 1.93   | 1.94   | 1.96   |
| BSNH (°)        | 2.04   | 7.34   | 11.14  | 15.12  | 15.16  | 15.74  | 15.94  | 16.34  | 16.46  |
| BSNH (°)        | 9.86   | 1.35   | -4.81  | -11.14 | -11.20 | -12.10 | -12.41 | -13.02 | -13.43 |
| sNH (au)        | -1.41  | -0.13  | 1.94   | 7.91   | 8.01   | 9.81   | 10.56  | 12.24  | 12.81  |
| yNH (au)        | -7.49  | -11.33 | -16.87 | -31.69 | -31.91 | -36.23 | -38.01 | -42.00 | -45.35 |
| εNH (au)        | 0.16   | 0.30   | 0.51   | 1.09   | 1.10   | 1.26   | 1.34   | 1.50   | 1.55   |
| NH–Sun–Earth angle (°) | +114.00 | +116.00 | +88.88 | +18.99 | +8.88  | -156.56 | -156.56 | +70.77 | -123.73 |
| Ly/πF (photon cm⁻² s⁻¹) | 3.3 × 10¹⁰ | 3.1 × 10¹¹ | 3.6 × 10¹¹ | 4.1 × 10¹¹ | 3.9 × 10¹¹ | 2.9 × 10¹¹ | 3.1 × 10¹¹ | 3.3 × 10¹¹ | 2.9 × 10¹¹ |
| Ly/πF0 (photon cm⁻² s⁻¹ nm⁻¹) | 2.7 × 10¹² | 2.5 × 10¹² | 3.0 × 10¹² | 3.6 × 10¹² | 3.4 × 10¹² | 2.3 × 10¹² | 2.5 × 10¹² | 2.7 × 10¹² | 2.4 × 10¹² |
| <ΔLy/πF > std (photon cm⁻² s⁻¹) | 3.3 × 10¹¹ | 3.3 × 10¹¹ | 3.5 × 10¹¹ | 4.0 × 10¹¹ | 4.0 × 10¹¹ | 3.3 × 10¹¹ | 3.2 × 10¹¹ | 3.1 × 10¹¹ | 3.1 × 10¹¹ |
| H lifetime, solar wind (10⁶ s) | 2.5    | 2.8    | 2.6    | 2.0    | 2.0    | 2.1    | 2.2    | 2.2    | 2.3    |
| H lifetime, solar EUV (10⁶ s) | 12     | 12     | 12     | 6.2    | 6.2    | 7.9    | 7.9    | 8.5    | 8.6    |
| H lifetime, total (10⁶ s) | 2.1    | 2.3    | 2.1    | 1.5    | 1.5    | 1.7    | 1.7    | 1.8    | 1.8    |
| μ, H radiation pressure parameter | 0.89   | 0.85   | 0.88   | 1.2    | 1.2    | 0.99   | 0.92   | 0.85   | 0.84   |

Notes.

a Angles are negative from solar conjunction until opposition and positive from opposition until solar conjunction.

b Solar fluxes at 1 au from TIMED/SEE L3A line irradiances, corrected for relative ecliptic longitudes of Pluto and Earth as seen from the Sun, taken from http://lasp.colorado.edu/lisird/data/timed_see_lines_L3A/.

c At 1 au, averaged over the previous year.
The dependence found in the empirical fits to the data in different directions may be understood by the following heuristic argument. If the IPM \( \text{Ly}\alpha \) brightness were solely due to resonant scattering of solar \( \text{Ly}\alpha \) by a constant flux of optically thin interstellar H passing through the solar system, it would be well represented by the function

\[
p_{\text{IPM}} = -Q_{\text{Ig}} n_{\text{H}} \left( 4\pi \sin 2\Theta_{\text{EM}} \right) 
\]

where \( Q_{\text{Ig}} \) is the IPM \( \text{Ly}\alpha \) brightness (in Rayleighs) from resonantly scattered solar \( \text{Ly}\alpha \), \( g \) is the scattering rate of the solar \( \text{Ly}\alpha \) line at 1 au (commonly called the g-factor, equal to the integral over frequency of the solar \( \text{Ly}\alpha \) flux at 1 au multiplied by the resonant cross-section of the scattering hydrogen atoms), \( n_{\text{H}} \) is the density of H atoms, and \( \Theta_{\text{EM}} \) is the angle between the Sun direction and the look direction, as seen from NH. We use the line-integrated solar \( \text{Ly}\alpha \) fluxes from Figure 2.

\[
4\pi I_{\text{KEM}} = \frac{g n_{\text{H}} (\pi - \Theta_{\text{Sun}})}{r_{\text{NH}} \sin(\Theta_{\text{Sun}})} \quad (2)
\]

Figure 2. Orientation of the Alice slit and location on the sky of the three single-great-circle IPM observations made during cruise to Pluto (in yellowish colors), as well as all seven of the six-great-circle scan observations (in green and purple colors), which began in 2015, in Galactic coordinates. The overlap regions between early ACO and later six-great-circle scans, indicated by blue dots, provide a record of the IPM \( \text{Ly}\alpha \) brightness from \( r_{\text{NH}} = 8-47 \) au in 11 different directions. The directions labeled “IPM” indicate the upstream direction (at Galactic coordinates of \( l_U = 33.3^\circ \) and \( b_U = 15.9^\circ \)) and downstream direction (\( l_D = 183.3^\circ \) and \( b_D = -15.9^\circ \)) of the flow of interstellar hydrogen atoms through the solar system. The directions labeled “KEM” indicate where regular 1 hr spectral stares are performed in relatively star-free regions near the upstream and downstream directions; these spectra are used to calibrate count rate observations into \( \text{Ly}\alpha \) brightnesses. In Galactic coordinates, KEM upstream is at \( l_U = 348.6^\circ \) and \( b_U = 60.7^\circ \) and KEM downstream is at \( l_D = 167.3^\circ \) and \( b_D = -61.8^\circ \).

Figure 3. Alice IPM brightnesses shown as a function of the distance of the NH spacecraft from the Sun \( (r_{\text{NH}}) \) for one of the overlap directions of Figure 2, \( (l = 326.0^\circ, b = -85.8^\circ) \), with simple empirical model fits indicated. These brightnesses have been scaled by \( 2.4 \times 10^{12}/\pi F_0 \) (photons cm\(^{-2}\) s\(^{-1}\) nm\(^{-1}\) at 1 au), where \( F_0 \) values are from Table 1, in order to account for temporal variations of the line-center solar \( \text{Ly}\alpha \) flux. Both panels show the same data, plotted linearly (left) and logarithmically (right). The Alice \( \text{Ly}\alpha \) brightness data in this example are found to be reasonably fit by a \( 1/r_{\text{NH}} \) profile plus a constant 35.8 R background. A summary of the empirical model fits and background for the other overlap directions are provided in Table 2.
Now we investigate how more detailed models of the IPM Ly$\alpha$ compare with the Alice data. Interplanetary Ly$\alpha$ models for the locations of the NH spacecraft were run using a classical hot model (e.g., Thomas 1978) for the interstellar wind hydrogen density together with a full multiple-scattering radiative transfer model adapted from the code described in Hall (1992) and Hall et al. (1993); this will be referred to as the “Hall” code. In this cylindrically symmetric radiative transfer model, a single solar Ly$\alpha$ line profile is used from Lemaire et al. (1978). Photon scattering is handled using the complete frequency redistribution approximation, with Doppler profiles for absorption and emission. Doppler shifts and widths are calculated using bulk flow velocities and effective temperatures derived for each volume element. The radiative transfer equation is solved iteratively using an exponential integral formulation. Our implementation of the Hall code used 40 iterations and made calculations along $10^5$ steps in the angle $\theta$ between the upstream direction and a given point in space, as seen from the Sun. All-sky Ly$\alpha$ maps for the location of NH were generated for each of the great-circle observation periods on a $1^\circ \times 1^\circ$ ecliptic coordinate grid.

The hot hydrogen density model in the Hall code used here requires specification of three interstellar wind hydrogen parameters: hydrogen density, temperature, and velocity “at infinity”; these are the upstream values after processing and filtration at the outer heliospheric boundaries, but before solar wind charge-exchange and solar EUV photoionization have significantly further affected the densities. Based on the laboratory Cassini Ultraviolet Imaging Spectrograph (UVIS) calibration (Esposito et al. 2004) and fitting interplanetary Ly$\alpha$
UVIS data with our models (Pryor et al. 2008), we use a hydrogen density at infinity of $n_{\infty} = 0.12 \text{ cm}^{-3}$, consistent with the recent determination of $n_{\infty} = 0.127 \pm 0.015 \text{ cm}^{-3}$ by Swaczyna et al. (2020). Based on the Solar and Heliospheric Observatory (SOHO) Solar Wind Anisotropy Experiment (SWAN) hydrogen absorption cell measurements of Costa et al. (1999) we use $T_{\infty} = 12,000 \text{ K}$ and $v_{\infty} = 20 \text{ km s}^{-1}$ (note that these authors discuss a range of values for these parameters; $T_{\infty}$ in particular has substantial error bars). Spectrally-resolved measurements of Ly$\alpha$ from the Hubble Space Telescope (HST)/Goddard High Resolution Spectrograph confirmed that $v_{\infty}$ for hydrogen is in the range 18–21 $\text{ km s}^{-1}$ (Clarke et al. 1998). Additional velocity measurements and their trends have been discussed and modeled (Vincent et al. 2014). The interstellar wind hydrogen flow downwind direction is taken as ecliptic longitude $74^\circ.7$ and ecliptic latitude $-5^\circ.2$, based on Ulysses GAS measurements of the interstellar helium flow (Witte 2004), where we have neglected the $\sim 4^\circ$ offset between the hydrogen and helium flows detected using the SOHO/SWAN absorption cell (Lallement et al. 2005).

The Hall model used here also requires specification of several solar parameters. These include the solar Ly$\alpha$ flux at the sub-NH solar longitude available for scattering from interstellar wind hydrogen, the radiation pressure parameter ($\mu$), and the total expected hydrogen atom lifetime at 1 au. The daily Ly$\alpha$ fluxes were taken from the solar Ly$\alpha$ database at the University of Colorado Laboratory for Atmospheric and Space Physics (LASP; Woods et al. 2000). Radiation pressure from solar Ly$\alpha$ photons affects the trajectory of hydrogen atoms approaching the Sun. This effect is usually accounted for as $\mu$, the ratio of the radiation pressure to the solar gravity. When $\mu = 1$, radiation pressure and solar gravity cancel out. The radiation pressure used in our modeling is a one year average also derived from the LASP Ly$\alpha$ integrated flux database (Woods et al. 2000), and then corrected to the line-center Ly$\alpha$ value (Emerich et al. 2005). Two processes contribute to the hydrogen atom lifetime near the Sun: the loss of slow interstellar wind hydrogen able to scatter solar Ly$\alpha$ photons through charge-exchange of hydrogen atoms with solar wind protons, and the solar EUV photoionization rate. The one year average hydrogen atom charge exchange rate is calculated using the density and velocity of solar wind protons taken from the NASA/GSFC Space Physics Data Facility OMNIWeb solar wind database (http://omniweb.gsfc.nasa.gov/ow.html, King & Papitashvili 2005). The one year average solar UV photoionization rate of hydrogen is estimated with the Solar Irradiance Program code (Tobiska 2000; Tobiska & Bouwer 2006). The solar parameter values used in the runs described here are listed in Table 1.

Unlike our previous NH modeling efforts (e.g., Gladstone et al. 2013, 2018), these current model runs do not implement longitudinal or latitudinal asymmetries in Ly$\alpha$ (e.g., Pryor et al. 1992, 1996, 2013), or the latitude variations of the solar wind hydrogen lifetime due to asymmetries in the solar wind (e.g., Witt et al. 1979). For NH operating near the ecliptic plane at large distances upstream from the Sun, these solar wind and solar flux anisotropy effects are of minor importance.

Our previous Ly$\alpha$ studies (Pryor et al. 2013; Gladstone et al. 2013, 2018) calculated only single scattering of solar photons by interplanetary hydrogen, but with multiple scattering corrections taken from the Hall model (as described in Ajello et al. 1993, 1994). The Hall model produces multiple scattering results similar to the independently developed radiative transfer models of Quémerais & Bertaux (1993). A key result from the Hall et al. (1993) radiative transfer study is that intensities calculated looking radially outward in a uniform hydrogen medium fall approximately as $1/r_{\text{NH}}$ out to line center optical depth one, as expected for the optically thin case, then gradually assume an approximately $1/r_{\text{NH}}^2$ dependence. The unit optical depth path length for line-center Ly$\alpha$ photons is $\sim 12$ au for a uniform medium with hydrogen density of $0.12 \text{ cm}^{-3}$ at a temperature of 12000 K (Gladstone et al. 2013), indicating the need for a full radiative transfer study for NH observations in the outer solar system.

The Hall model also does not include the hydrogen wall in the outer heliosphere predicted by more sophisticated density codes (e.g., Baranov et al. 1991; Baranov & Malama 1993; Izmodenov et al. 2013; Quémerais et al. 2010, Quémerais et al. 2013, Katushkina et al. 2016, 2017). As briefly mentioned above, this hydrogen wall is thought to form from charge exchange between interstellar hydrogen and slow interstellar protons decelerated as they approached the heliopause. Quémerais et al. (2013) and Katushkina et al. (2017) modeled NH roll observations with their full radiative transfer model including a heliospheric wall. It would be a straightforward next step for us to superimpose a hydrogen wall in the Hall model specified by calculations from these other modeling codes, should future data call for it.

The count rate data during a typical six-great-circle scan are shown as a function of time in Figure 4 (KEM-4, which started on 2019 August 30). The Alice count rate data are quite “spiky” due to UV-bright stars (typically O, B, or A spectral types) passing through the slit. To avoid observing some particularly bright stars, the aperture door was closed and reopened, and these times are seen in the data where the count rate occasionally drops to near-zero values. It is generally straightforward to account for stars passing through the slit using a simple filter that looks for sudden jumps up and back down in count rate (either through the 0°1 wide slot or the 2°0 wide slot). This approach breaks down, however, where UV-bright stars are more numerous, as in the Galactic plane. When the Hall model expectation for the IPM Ly$\alpha$ brightness due to resonantly scattered sunlight is compared with the observed brightness (corrected for stars passing through the slit), it is clear that the model is too low by an approximately constant amount; for the KEM-4 observations of Figure 4 this difference is 50 R. However, since the large number of stars in the Galactic plane is not easily removed from the count rate measurements, we can get a better estimate of the difference by excluding observations at $|b| < 30^\circ$. These results are shown in Figure 5, and result in a difference between the data and the model of 43 R. Note that when Alice is pointing near the upstream direction (e.g., near 25.0, 26.0, 27.0, or 28.0 hr) the Galactic Ly$\alpha$ background is comparable to the modeled signal from resonantly scattered solar Ly$\alpha$, and already accounts for about half the observed upstream brightness at 45 au.

The results for all the six-great-circle observations are provided in Table 3, with the best-fit constant background Ly$\alpha$ brightnesses provided for three cases: (1) fitting the difference between all star-filtered count rates observed by Alice and the corresponding Hall model of resonantly scattered solar Ly$\alpha$; (2) the same, but restricted to observations at $|b| > 30^\circ$; and (3) the same, but restricted to observations at both $|b| > 30^\circ$ and...
In addition, for each case, Table 3 provides the average and standard deviation over all seven of the six-great-circle observations. We find there is very little difference between the second and third case, and adopt the third-case results \((43 \pm 3\text{ R})\) as the best estimate for the Galactic Ly\(\alpha\) background. Note that the standard deviation of the residual for the six-great-circle observation shown in Figure 5 is for a 1 s Alice measurement of the Galactic background, and the error of the mean of the 7747 residual points which remain after filtering is 0.1 R. However, the 3 R standard deviation of all seven six-great-circle observations performed to date provides a more robust estimate of the error in the Galactic background.

### Table 3

| IPM Observation | Date      | \(r_{NH}\) (au) | \(B_{LSF}\) (R) | \(\chi^2\) | \(B_{LSF}\) (R) \((|b| > 30^\circ)\) | \(\chi^2\) | \(B_{LSF}\) (R) \((|b| > 30^\circ \& \Theta_{Sun} > 60^\circ)\) | \(\chi^2\) |
|-----------------|-----------|-----------------|-----------------|----------|-------------------------------|----------|---------------------------------|----------|
| P-28            | 2015 Jun 6| 32.679          | 49.9            | 1.9      | 43.2                          | 0.7      | 44.2                            | 0.8      |
| P+1             | 2015 Jul 15| 32.561          | 43.8            | 1.6      | 38.1                          | 0.7      | 39.1                            | 0.8      |
| KEM-1           | 2017 Jan 28| 37.561          | 49.6            | 2.2      | 43.0                          | 0.8      | 43.0                            | 0.8      |
| KEM-2           | 2017 Sep 19| 39.472          | 53.5            | 2.2      | 46.8                          | 0.7      | 46.9                            | 0.8      |
| KEM-3           | 2019 Mar 3 | 43.775          | 44.0            | 2.7      | 37.4                          | 0.9      | 38.6                            | 0.9      |
| KEM-4           | 2019 Aug 30| 45.229          | 50.5            | 2.6      | 43.8                          | 0.8      | 44.2                            | 0.8      |
| KEM-5           | 2020 Apr 27| 47.161          | 54.2            | 2.7      | 47.2                          | 0.7      | 47.4                            | 0.8      |
| Average\(^a\)   |           | 49 ± 4          |                 |          | 43 ± 3                        |          | 43 ± 3                          |          |

Note.

\(^a\) Averages in this table were calculated to three significant figures, but are presented to two significant figures, in keeping with the limited spatial and temporal coverage of the data, and their variance.

\(\Theta_{Sun} > 60^\circ\). In addition, for each case, Table 3 provides the average and standard deviation over all seven of the six-great-circle observations. We find there is very little difference between the second and third case, and adopt the third-case results \((43 \pm 3\text{ R})\) as the best estimate for the Galactic Ly\(\alpha\) background. Note that the standard deviation of the residual for the six-great-circle observation shown in Figure 5 is for a 1 s Alice measurement of the Galactic background, and the error of the mean of the 7747 residual points which remain after filtering is 0.1 R. However, the 3 R standard deviation of all seven six-great-circle observations performed to date provides a more robust estimate of the error in the Galactic background.
We note that these results, from comparing the observations with a state-of-the-art model (which lacks a Galactic background component) are entirely consistent with the earlier result found by empirically fitting the observed falloff in brightness with distance from the Sun observed in various directions on the sky (i.e., $43 \pm 6$ R).

Finally, Figure 6 shows how the best-fit Galactic Ly$\alpha$ background, added to the Hall model, compares with the brightnesses measured by the NH–Alice spectrograph when plotted in Galactic coordinates, again for the KEM-4 six-great-circle observation. The agreement between the model plus background is seen to be very good at most locations away from the Galactic plane, even near the Sun. Also shown on this map are the outlines of four important local interstellar medium (LISM) clouds, as determined by Redfield & Linsky (2008). There does not seem to be any strong correlation between the cloud boundaries and the IPM Ly$\alpha$ brightness as measured by NH–Alice, with the possible exception of the LIC cloud boundaries and the IPM Ly$\alpha$ brightness data looking upstream, Hall et al. (1993) found that fits to radial trends were improved by adding a constant additive intensity, 25% as large as the signal observed at 15 au. A constant offset found in fitting Ly$\alpha$ data to models could be partially interpreted in terms of a weak Galactic background, Thomas & Blamont (1976) estimated that the Galactic Ly$\alpha$ contribution due to recombination of ionized hydrogen followed by cascade must be small, <10 R, based on Galactic H$\alpha$ observations and radiative transfer calculations of Ly$\alpha$ photon entrapment in the very optically thick ISM. Lallement et al. (1984) set an upper limit on Galactic Ly$\alpha$ of 15 R using Prognoz 5 and 6 absorption cell measurements. Clarke et al. (1998) did not detect any obvious signal from Galactic Ly$\alpha$ in spectrally resolved HST observations. Quémerais et al. (1996) modeled Voyager data from 1993 to 1994 (50–58 au) and found evidence for 10–15 R of external Galactic emission. Lallement et al. (2011) compared Voyager UVS Ly$\alpha$ data to H$\alpha$ sky maps and heliospheric models and detected 3–4 R of enhanced Ly$\alpha$ emission near the Galactic plane correlated with enhancements in H$\alpha$ which they attributed to Galactic Ly$\alpha$. Katushkina et al. (2016) argued that Galactic emission was affecting previous searches for the hydrogen wall in the upstream Voyager Ly$\alpha$ data, and excluded those directions with a Galactic signal from their study of Voyager data. Katushkina et al. (2017) made various models of the hydrogen wall in fitting Voyager 1 Ly$\alpha$ data obtained 90–130 au from the Sun, looking in a single direction roughly upstream (lines of sight with ecliptic latitudes $19^\circ$–$21^\circ$5 and longitudes $262^\circ$–$267^\circ$), and found an intriguing solution for fitting the Voyager Ly$\alpha$ trend was to add a 25 Rayleigh signal from outside the heliosphere. They further showed that fits to NH Ly$\alpha$ rolls (ACO-2 and ACO-4) from 11.3 au and 17.0 au from the Sun were improved by adding 20 R in the upstream direction. Build on this approach, Gladstone et al. (2018) examined NH–Alice maps from 2007 to 2017 (7.6–39.5 au) and found that 1/R$_{NH}$ fits to the upstream Ly$\alpha$ brightness data were improved by adding a constant $\sim$40 R source, probably from beyond the heliosphere. Now, having further analyzed the Alice data, we conclude that a similar background is seen in all directions on the sky, using the falloff in brightness with distance from the Sun present in the data alone, and by comparing the data with detailed modeling of the scattered solar Ly$\alpha$ brightness. The Galactic Ly$\alpha$ background is found to have an isotropic brightness of 43 $\pm$ 3 R (equivalent to 56 $\pm$ 4 nW m$^{-2}$ sr$^{-1}$). There is no strong indication of the expected extra Ly$\alpha$ brightness indicative of a hydrogen wall associated with the heliopause.

4. Discussion

Several papers have discussed the possibility of a contribution to the Ly$\alpha$ signal from outside the heliosphere. When applying their radiative transfer model to Voyager Ultraviolet Spectrometer (UVS) data looking upstream, Hall et al. (1993) found that fits to radial trends were improved by adding a constant additive intensity, 25% as large as the signal observed at 15 au. A constant offset found in fitting Ly$\alpha$ data to models could be partially interpreted in terms of a weak Galactic background, Thomas & Blamont (1976) estimated that the Galactic Ly$\alpha$ contribution due to recombination of ionized hydrogen followed by cascade must be small, <10 R, based on Galactic H$\alpha$ observations and radiative transfer calculations of Ly$\alpha$ photon entrapment in the very optically thick ISM. Lallement et al. (1984) set an upper limit on Galactic Ly$\alpha$ of 15 R using Prognoz 5 and 6 absorption cell measurements. Clarke et al. (1998) did not detect any obvious signal from Galactic Ly$\alpha$ in spectrally resolved HST observations. Quémerais et al. (1996) modeled Voyager data from 1993 to 1994 (50–58 au) and found evidence for 10–15 R of external Galactic emission. Lallement et al. (2011) compared Voyager UVS Ly$\alpha$ data to H$\alpha$ sky maps and heliospheric models and detected 3–4 R of enhanced Ly$\alpha$ emission near the Galactic plane correlated with enhancements in H$\alpha$ which they attributed to Galactic Ly$\alpha$. Katushkina et al. (2016) argued that Galactic emission was affecting previous searches for the hydrogen wall in the upstream Voyager Ly$\alpha$ data, and excluded those directions with a Galactic signal from their study of Voyager data. Katushkina et al. (2017) made various models of the hydrogen wall in fitting Voyager 1 Ly$\alpha$ data obtained 90–130 au from the Sun, looking in a single direction roughly upstream (lines of sight with ecliptic latitudes $19^\circ$–$21^\circ$5 and longitudes $262^\circ$–$267^\circ$), and found an intriguing solution for fitting the Voyager Ly$\alpha$ trend was to add a 25 Rayleigh signal from outside the heliosphere. They further showed that fits to NH Ly$\alpha$ rolls (ACO-2 and ACO-4) from 11.3 au and 17.0 au from the Sun were improved by adding 20 R in the upstream direction. Build on this approach, Gladstone et al. (2018) examined NH–Alice maps from 2007 to 2017 (7.6–39.5 au) and found that 1/R$_{NH}$ fits to the upstream Ly$\alpha$ brightness data were improved by adding a constant $\sim$40 R source, probably from beyond the heliosphere. Now, having further analyzed the Alice data, we conclude that a similar background is seen in all directions on the sky, using the falloff in brightness with distance from the Sun present in the data alone, and by comparing the data with detailed modeling of the scattered solar Ly$\alpha$ brightness. The Galactic Ly$\alpha$ background is found to have an isotropic brightness of 43 $\pm$ 3 R (equivalent to 56 $\pm$ 4 nW m$^{-2}$ sr$^{-1}$). There is no strong indication of the expected extra Ly$\alpha$ brightness indicative of a hydrogen wall associated with the heliopause.
and there is no strong correlation with known LISM clouds, although such features may begin to appear in future data.

The Galactic Lyα background may be used to estimate some properties of LISM dust. Since the Galactic Lyα background is found to be (as expected) largely isotropic, it is straightforward to estimate the average absorption coefficient of LISM dust at \( \lambda = 121.6 \text{ nm} \) as (see Thomas & Blamont 1976)

\[
k_{\text{abs}} = \frac{J}{4\pi} \tag{3}
\]

where \( J \) is the volume emission rate of Lyα photons in the LISM, and \( 4\pi \) is our measured Galactic background of 43 ± 3 R. For \( J \) we use the local ionizing photon volume emission rate, estimated by Vacca et al. (1996) as \( 7.0 \times 10^{51} \text{ photons s}^{-1} \) within 2.5 kpc of the Sun, or \( 3.6 \times 10^{15} \text{ photons cm}^{-3} \text{ s}^{-1} \), and convert this to a Lyα volume emission rate of \( 2.5 \times 10^{15} \text{ photons cm}^{-3} \text{ s}^{-1} \), based on the 0.68 fraction of recombinations that result in the emission of a Lyα photon (in a “Case B” medium that is optically thick to Lyman series emissions), as commonly recommended (e.g., Dijkstra 2019; Seon & Kim 2020). Using these values in Equation (3), we estimate \( k_{\text{abs}} = 5.8 \pm 0.42 \times 10^{-23} \text{ cm}^{-1} = 0.2 \pm 0.01 \text{ kpc}^{-1} \), where the error only includes our uncertainty in the measured Galactic Lyα background, and any uncertainty in the ionizing photon emission rate of Vacca et al. (1996), or if a substantial fraction of those photons escape the Milky Way without being absorbed, is not considered. Based on measurements of interstellar extinction at Lyα, Thomas & Blamont (1976) estimated \( k_{\text{abs}} = 2.81 \times 10^{-21} \text{NH}^{-1} (1−A) \text{ cm}^{-1} \), where \( A \) is the Lyα dust albedo. Taking \( n_H = 0.12 \text{ cm}^{-3} \), we find \( A = 0.83 \), very close to the “likely value” of Thomas & Blamont (1976).

However, a similar estimate, using Figure 7 of Draine & Lee (1984) for the total dust extinction at Lyα of \( k_{\text{ext}} = 1.68 \times 10^{-21} \text{NH}^{-1} \text{ cm}^{-1} \), leads to a somewhat lower albedo estimate of \( A = 0.71 \). These estimated dust albedo and absorption coefficients can be improved as estimates of the Lyα emission rate in the LISM are refined, e.g., through detailed modeling as in Seon & Kim (2020), and such models can now take advantage of the local Galactic Lyα brightness determined here.

5. Conclusions

Following up on indications of a distant Lyα background in Voyager UVS observations (e.g., Hall et al. 1993; Katsushika et al. 2016, 2017), we find that more sensitive recent observations by the NH–Alice UVS show clear evidence for an isotropic Lyα Galactic background (see Münch 1962) at an average brightness of \( 43 \pm 3 \text{ R} (56 \pm 4 \text{ nW m}^{-2} \text{ sr}^{-1}) \). Assuming the background is uniform, we estimate \( k_{\text{abs}} = 0.2 \pm 0.01 \text{ kpc}^{-1} \) for the local Lyα absorption coefficient due to dust. At the current >50 au distance of NH from the Sun, this background accounts for roughly half of the total Lyα brightness in the upstream direction, the other half being due to resonantly scattered solar Lyα by interplanetary H atoms. An expected brightness enhancement due to a hydrogen wall at the heliopause (e.g., Quémérais et al. 2010; Izmodenov et al. 2013) is not seen, but could be present at a ~10 Rayleigh level. Also, no strong correlations exist with the boundaries of the primary clouds of the LISM (e.g., Redfield & Linsky 2008); similarly, these could exist at a ~10 Rayleigh level. Further observations of the IPM background are planned, including more dense mapping to look for these and other structures in the Lyα background.

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