Optically Thick HI Does Not Dominate Dark Gas in the Local ISM

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Abstract

The local interstellar medium (ISM) is suffused with “dark” gas, identified by excess infrared and gamma-ray emission, yet undetected by standard ISM tracers such as neutral hydrogen (H I) or carbon monoxide emission. Based on observed dust properties from Planck, recent studies have argued that H I mixed with dust is strongly saturated and that dark gas is dominated by optically thick H I. We test this hypothesis by reproducing this model using data from Planck and new 21 cm emission maps from GALFA-H I—the first large-area 21 cm emission survey with comparable angular resolution to Planck. We compare the results with those from a large sample of H I column densities based on direct observations of H I optical depth, and find that the inferred column density corrections are significantly lower than those inferred by the Planck-based model. Further, we rule out the hypothesis that the pencil-beam H I absorption sight lines preferentially miss opaque “blobs” with small covering fraction, as these structures require densities and pressures that are incompatible with ISM conditions. Our results support the picture that excess dust emission in the local ISM is not dominated by optically thick H I, but is rather a combination of intrinsic changes in dust grain emissivities and H2 missed by CO observations.

Key words: ISM: atoms – ISM: clouds – ISM: molecules

1. Introduction

Galactic ecosystems rely on the conversion of the interstellar medium (ISM) into stars and then back again. Accounting for all components of the ISM is therefore crucial for building a self-consistent model of galaxy evolution. However, there is a significant ISM population that is not traced by standard neutral gas tracers. The prevalence of this “dark” gas is inferred via gamma-ray emission from cosmic-ray interactions with neutral gas (Grenier et al. 2005), excess far-infrared (FIR) emission (e.g., Planck Collaboration et al. 2011), dust extinction toward diffuse clouds (e.g., Paradis et al. 2012), and ionized carbon emission (e.g., Langer et al. 2014).

As for what dark gas is made of, one likely culprit is molecular hydrogen (H2), the most abundant interstellar molecule which cannot be observed directly in cold, dense environments. Carbon monoxide (CO) is a popular tracer for H2, as it has strong dipole-allowed rotational transitions that are easily excited at low temperatures. However, CO cannot be observed directly in cold, dense gas. In agreement, Reach et al. (2017a) found that optically thick H I measured toward lines of sight (LOS) in and around the Perseus molecular cloud accounts for at most ~20% of dark gas. In agreement, Reach et al. (2015) concluded that atypically high τH I is required to be consistent with F15 in high-latitude molecular clouds, which is not observed (Reach et al. 2017a).

These previous efforts either cover small regions around individual clouds, or have insufficient sample sizes to statistically constrain H I optical depth properties. We will expand these studies to a largely unbiased survey covering a fair fraction of the entire sky. We test the hypothesis that dark gas is optically thick H I by comparing direct measurements of τH I with those inferred by reproducing the F15 analysis at high angular resolution.

2. Data and Methods

In this work, we follow the procedures outlined by F15 to predict the contribution of optically thick H I to the total column density from all-sky maps of dust properties from Planck and 21 cm emission. All of the maps are converted to HEALPix® format (Górski et al. 2005) with Nside = 1024 (corresponding to 3/4 pixels), and smoothed with a Gaussian beam of full width at half maximum (FWHM) = 4′9 to match...
the all-sky dust maps from Planck\(^6\) (unless they have a lower native resolution). Next, we retrieve a large sample of \(\tau_{\text{H}}\) measurements from the literature for comparison.

### 2.1. Large-area Maps of 21 cm and Dust Emission

We gather 21 cm emission maps from the Galactic Arecibo L-band Feed Array Survey (GALFA-H\(\text{I}\); Peek et al. 2011a, 2018). GALFA-H\(\text{I}\) is the highest angular resolution (4\('))\), highest spectral resolution (0.18 km s\(^{-1}\)) large-area (13,000 deg\(^2\)) Galactic 21 cm emission survey to date, and the only large-area map with comparable angular resolution to Planck.

From the second GALFA-H\(\text{I}\) data release,\(^7\) we download the all-Arecibo-sky \((0 < \alpha_{\text{2000}} < 360\,^\circ, 0 < \delta_{\text{2000}} < 35^\circ)\) H\(\text{I}\) column density map at Galactic velocities \((-90 < v_{\text{LSR}} < 90\,\text{km s}^{-1};\) Peek et al. 2018). This map has been corrected for stray radiation, or radiation entering the main telescope beam from higher-order sidelobes, via comparison with the meticulously stray-corrected Leiden Argentine Bonn (LAB) survey (Kalberla et al. 2005). We download all GALFA-H\(\text{I}\) data cubes\(^8\) and construct a map of the peak brightness temperature \((T_{B,\text{peak}})\) within the same velocity range.

To estimate background radio continuum emission \((T_{\text{bg}})\), we use the all-sky map of 21 cm emission with 36\('\) resolution from the Stockert and Villa-Elisa telescopes (Reich & Reich 1986; Reich et al. 2001), downloaded from the Centre d’Analyse de Données Etendues.\(^9\)

To trace Galactic dust properties, we use the all-sky map of dust optical depth at 353 GHz \((\tau_{353})\) from the Planck Legacy Archive.\(^10\) This is the result of modeling dust emission from Planck at 353, 545, and 857 GHz, as well as emission at 100 \(\mu\)m from IRAS (Planck Collaboration et al. 2014a).

### 2.2. Masking

As our interest is the contribution of optically thick H\(\text{I}\) to the total gas column density, we mask regions with significant molecular gas emission. To construct the mask, we use the \(^{12}\)CO \(J = 1 - 0\) integrated intensity map of the Galactic plane at 8/7 angular resolution from Dame et al. (2001). We also include the all-sky Planck COMMANDER map of \(^{12}\)CO \(J = 1 - 0\). We mask all pixels with detected CO emission at \(>3\sigma\), based on an estimated \(\sigma_{\text{CO}} = 0.3 \, \text{K} \, \text{km s}^{-1}\) for the Dame et al. (2001) map and the all-sky error map from Planck.

Following F15, we mask regions with significant ultraviolet radiation which may affect the dust temperature and dust-to-gas ratio. To construct the mask, we use the all-sky map of H\(\alpha\) radiation at 6\('\) resolution from Finkbeiner (2003) and mask pixels with H\(\alpha\) emission \(>5\) Rayleighs.

Finally, all Galactic latitudes below \(|b| = 15^\circ\) are masked to avoid multiple components blended in velocity along the LOS. Following F15, we mask regions with significant extragalactic and intermediate-velocity emission for which the dust properties may be significantly different, defined by pixels with integrated H\(\text{I}\) brightness temperature \((W_{\text{H}})\) at \(|v_{\text{LSR}}| > 100 \, \text{km s}^{-1}\) greater than 10\% of \(W_{\text{H}}\) at \(|v_{\text{LSR}}| < 70 \, \text{km s}^{-1}\) and pixels with \(W_{\text{H}} > 50 \, \text{K} \, \text{km s}^{-1}\) at 35 \(< |v_{\text{LSR}}| < 70 \, \text{K} \, \text{km s}^{-1}\), respectively.

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\(\text{https://pla.esac.esa.int/pla/};\) Version 2.01.

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### 2.3. 21 cm Absorption

We gather available data from surveys of 21 cm absorption outside of the Galactic plane. The compiled catalog has 151 sight lines.

1. **21-SPONGE.** We include 57 interferometric \(\tau_{\text{H}}\) spectra from a large, high-sensitivity survey for Galactic H\(\text{I}\) absorption at the Karl G. Jansky Very Large Array: 21-SPONGE (Murray et al. 2015; Murray et al. 2018). 21-SPONGE achieved excellent rms noise in \(\tau_{\text{H}}\) (median \(\sigma_{\text{H}} = 0.001\) per 0.42 km s\(^{-1}\) channels), and includes matching expected emission profiles along the same LOS constructed by interpolating 21 cm emission from the Arecibo Observatory across each target position following the methods of Heiles & Troland (2003a).

2. Roy et al. (2013a). We include interferometric \(\tau_{\text{H}}\) data presented in Roy et al. (2013a) from the GMRT, WSRT, and ATCA, with matching 21 cm emission spectra from LAB. In the absence of publicly available spectra, we extract data from their Table 1, including H\(\text{I}\) column densities under the optical depth-corrected and optically thin approximations. We select the 22 LOS which are unique relative to 21-SPONGE.

3. **The Millennium Survey.** We include single-dish \(\tau_{\text{H}}\) spectra from the publicly available Millennium Arecibo 21 cm Absorption-Line Survey (Heiles & Troland 2003a, 2003b, hereafter HT03). The median sensitivity is \(\sigma_{\text{H}} = 0.01\) per 0.18 km s\(^{-1}\) channels. We select the 47 LOS unique in comparison with 21-SPONGE and Roy et al. (2013a), because HT03 is generally less sensitive and interferometric absorption measurements filter out contamination from 21 cm emission within the beam (however, we note excellent correspondence between SPONGE and HT03 where they overlap; Murray et al. 2015).

4. Stanimirović et al. (2014). We include single-dish \(\tau_{\text{H}}\) data from the Arecibo study of the Perseus cloud by Stanimirović et al. (2014), observed in the same manner as HT03. We gather data from Figure 5 of Lee et al. (2015), selecting the 25 LOS unique relative to 21-SPONGE, Roy et al. (2013a), and HT03.

### 3. Analysis

The total H\(\text{I}\) column density, \(N(\text{H})\), is given by

\[
N(\text{H}) = C_0 \int \tau_{\text{H}} T_B \, dv, \tag{1}
\]

where \(C_0 = 1.823 \times 10^{18} \, \text{cm}^{-2}/(\text{K} \, \text{km s}^{-1})\) (e.g., Draine 2011). Under the assumption that all gas along the LOS is a single temperature, \(N(\text{H})\) is given by

\[
N(\text{H})_\text{iso} = C_0 \int \frac{\tau_{\text{H}} T_B}{(1 - e^{-\tau_{\text{H}}})} \, dv, \tag{2}
\]

where the subscript “iso” denotes the isothermal approximation (e.g., Dickey & Benson 1982). In the optically thin limit \((\tau_{\text{H}} \ll 1)\), Equation (2) reduces to

\[
N(\text{H})_\text{thin} = C_0 \int T_B \, dv = C_0 \int W_{\text{H}} \, dv. \tag{3}
\]

Equation (3) is used to approximate \(N(\text{H})\) in the absence of optical depth information. The ratio of the total and optically
thin column densities, $\mathcal{R} = N(H I)/N(H I)_\text{thin}$, is a measure of the contribution of optically thick $H I$ to the $H I$ mass budget.

### 3.1. Inferring $\mathcal{R}$ via 21 cm Absorption

Observations of both 21 cm emission and absorption are required to constrain $\tau_{H I}$ and $T_s$ for measuring $N(H I)$. Furthermore, the complex velocity structure of Galactic 21 cm spectra implies that clouds along the LOS may have different properties, rendering the isothermal approximation in Equation (2) invalid. Significant efforts have been made to extract $\tau_{H I}$, $T_s$, and $N(H I)$ for individual clouds along the LOS (e.g., Dickey et al. 2003; Heiles & Troland 2003b; Mohan et al. 2004; Roy et al. 2013b; Murray et al. 2015, 2017).

Fortunately, $\mathcal{R}$ inferred from multicomponent analyses has been shown to be statistically indistinguishable from that inferred for the isothermal approximation (Equation (2); e.g., Lee et al. 2015; Nguyen et al. 2018; Murray et al. 2018). Lee et al. (2015) concluded that the estimates are equivalent as a result of low observed $\tau_{H I}$ by existing HI absorption studies. Via Monte Carlo simulations of the multiphase ISM, Chengalur et al. (2013) found that $N(H I)_\text{iso}$ traces the true $H I$ column density for $N(H I) < 5 \times 10^{22}$ cm$^{-2}$ regardless of the temperature distribution along the LOS. This indicates that $N(H I)_\text{iso}$ traces $\mathcal{R}$ accurately and with smaller uncertainty than from LOS decomposition. Therefore, for data sets where $\tau_{H I}$ is available, we compute $N(H I)_\text{iso}$ and $N(H I)_\text{thin}$ and gather published values where spectra are not available (e.g., Roy et al. 2013a). We define $\mathcal{R}_{H I}$ for each LOS via

$$\mathcal{R}_{H I} = N(H I)_\text{iso}/N(H I)_\text{thin}. \tag{4}$$

The uncertainty in $\mathcal{R}_{H I}$ is propagated from uncertainties in $N(H I)_\text{iso}$ and $N(H I)_\text{thin}$ estimated from the rms noise in offline channels of $T_B$ and $\tau_{H I}$.

In Figure 1 we display histograms of $N(H I)_\text{iso}$, $T_B$, and $\mathcal{R}_{H I}$, for all 151 $\tau_{H I}$ LOS (black, unfilled) and for the 72 LOS in the unmasked Arecibo sky (orange, filled). The LOS probe a wide range of column densities and dust temperatures. We note that for all LOS, $N(H I)_\text{iso} \ll 5 \times 10^{22}$, validating the use of $N(H I)_\text{iso}$ as a reasonable approximation of the total $H I$ column density (e.g., Chengalur et al. 2013).

### 3.2. Inferring $\mathcal{R}$ via Dust Properties

Unfortunately, $\mathcal{R}_{H I}$ measurements are limited by source availability and probe only the gas subtended by the angular size of the source (typically $\ll 1'$). To quantify the contribution of $\tau_{H I}$ to $N(H I)$ over large areas, indirect measures of the optical depth properties of gas are required.

In Figure 2 we plot integrated $H I$ intensity from GALFA-H I ($W_{H I}$) versus $\tau_{353}$ for the unmasked sky. The linear relation fitted to data points with the highest dust temperatures ($T_d > 22.5$ K) by F15 ($W_{H I} = 1.15 \times 10^6 \tau_{353}$) is overlaid as a blue dashed line.

$$N(H I)_{T_d,dust} = C_0 \cdot k \cdot \tau_{353} = 2.1 \times 10^{26} \cdot \tau_{353}, \tag{5}$$

where $k = 1.15 \times 10^6$ cm$^{-2}$ (F15).

Using this relation, we repeat the F15 procedure of solving coupled equations (their Equations (4) and (6)) to estimate $T_d$ and $\tau_{H I}$ from $\tau_{353}$, $N(H I)_\text{thin}$, $T_{bg}$, and $T_{d,peak}$ for each pixel via the least squares fit. As noted by F15, this method is valid for $\tau_{H I} \gtrsim 0.2$. We denote the resulting $\tau_{H I}$ and $T_s$ estimates, which represent average conditions, as $\tau_{H I,dust}$ and $T_{s,dust}$.
is estimated by propagating observational uncertainties in \( \tau_{\text{H I}} \) and \( N(\text{H I}) \) from Planck and GALFA-H I.

4. Results

In Figure 3 we display histograms of \( \tau_{\text{H I,dust}} \), \( T_s,dust \), and \( R_{\text{dust}} \). The results generally agree with F15 (c.f., their Figures 7 and 13). By eye, our distributions appear skewed toward smaller \( \tau_{\text{H I,dust}} \), larger \( T_s,dust \), and smaller \( R_{\text{dust}} \). With the inclusion of the all-sky Planck CO map, we mask larger areas of sky with significant CO emission, and therefore the F15 results are likely contaminated at some level by CO-bright gas.

We display a map of \( R \) in Figure 4. The map is colored by \( R_{\text{dust}} \), with \( R_{\text{H I}} \) for the 121 LOS within the GALFA-H I field of view (FOV) overlaid. Large regions feature \( R_{\text{dust}} > 1.5 \), corresponding to \( \tau_{\text{H I,dust}} > 1 \). However, even at low latitudes, within the masked regions of the \( R_{\text{dust}} \) map (Figure 4), the correction inferred from H I is \( R_{\text{H I}} \lesssim 1.3 \).11

In Figure 5 we compare \( R_{\text{dust}} \) and \( R_{\text{H I}} \) for the 72 LOS in the unmasked sky. Although \( R_{\text{H I}} \) and \( R_{\text{dust}} \) are consistent for some LOS below \( R_{\text{dust}} = 1.3 \), above this value we have \( R_{\text{dust}} > R_{\text{H I}} \). To be consistent with F15, we repeat the analysis for the same data sets at LAB resolution (\( N_{\text{side}} = 128 \), corresponding to 27.5 pixels) and with 21 cm emission from LAB, and include the results in Figure 5 (gray crosses). We include an all-sky map of \( R_{\text{dust}} \) from our analysis of LAB data in the Appendix in Figure 7. We find consistent \( R_{\text{dust}} \) from LAB as from GALFA-H I, indicating that our results are not biased by the Arecibo FOV. Considering the difference in angular resolution between GALFA-H I (4') and LAB (36'), the coherence between results in Figure 5 suggests that H I is largely diffuse at high latitudes down to 4' scales and the lower angular resolution observations are not missing significant unresolved H I contrast.

11 We note that saturated \( \tau_{\text{H I}} \) was measured toward one Stanimirović et al. (2014) source (4C + 32.14) and two 21-SPONGE sources (PKS1944 + 251, J2021 + 3731, excluded from their catalog). For these LOS, \( R_{\text{H I}} \gtrsim 2 \). However, these LOS are masked due to significant CO emission or low latitude (Section 2.2).
Furthermore, although accurately measuring the column density of dark gas requires careful modeling of both gamma-ray and FIR emission (e.g., Planck Collaboration et al. 2015), and an all-sky map is not yet available to our knowledge, we find that where dark gas maps are available (Remy et al. 2017), specifically in the anticenter and Chameleon molecular cloud regions, regions of $R_{\text{dust}} \sim 2–3$ correspond to significant dark gas column densities ($N(\text{H})_{\text{dark}} \gtrsim 10^{20–21}$). Figure 7, in Galactic coordinates, may be compared with existing dark gas maps (e.g., Grenier et al. 2005).

5. Discussion

We observe that LOS with significant H I saturation inferred from dust (i.e., $R_{\text{dust}} \sim 2$) feature H I optical depth corrections ranging from $R_{\text{HI}} = 1.0$ to $\sim1.3$. If these LOS are indicative of the average $R_{\text{HI}}$, then we have ruled out the F15 hypothesis that optically thick H I comprises the majority of dark gas in the local ISM probed by our high-latitude LOS.

But what if our $\tau_{\text{H I}}$ LOS miss optically thick gas with small covering fraction? For example, Fukui et al. (2018) asserted that the solid angle coverage of H I absorption observations is too small to sample highly filamentary, cold H I. For $R_{\text{dust}} < 1.3$, $R_{\text{HI}}$ and $R_{\text{dust}}$ are often consistent within uncertainties and are therefore not useful discriminants. However, we find that all 51 LOS with $R_{\text{dust}} > 1.3$ have $R_{\text{HI}} < 1.3$.

In the following, we compute what the properties of missing optically thick H I structures—“blobs” for want of a more descriptive term—must be to account for the discrepancy between $R_{\text{dust}}$ and $R_{\text{HI}}$. From Poisson statistics, the probability of observing $R_{\text{HI}} > 1.3$ zero times in 51 LOS is $<10\%$ with 99% certainty. We conservatively assume that this value (10%) is the maximum blob covering fraction. A Planck 355 GHz pixel is 4.9\arcsec across, and therefore a blob covering 10% of a pixel area is at most 1.5\arcsec across. Each blob must account for the missing $N(\text{H I})$ in 10% of the area, and therefore the column density through a blob must be 10 times higher than for the 100% covering factor. For the 51 LOS with $R_{\text{dust}} > 1.3$, these blobs have necessary column densities from $8 \times 10^{20}$ to $8 \times 10^{22}$ cm$^{-2}$ with a mean value of $8 \times 10^{21}$ cm$^{-2}$. As distances are difficult to determine, we use a conservative estimate of the H I scale height of 200 pc (Dickey & Lockman 1990) to compute a typical blob distance of 200/sin[42°] = 300 pc, where 42° is the median blob latitude. Assuming the blobs have no preferred orientation and that they are no deeper than they are across, their diameters are 0.13 pc with an average proton density of 19,000 cm$^{-3}$ and a volume filling fraction of $<4 \times 10^{-4}$. To estimate the minimum pressure of these blobs, we assume the coldest known temperature for Galactic H I-only clouds, 17 K (Heiles & Troland 2003b; Peek et al. 2011b, the Local Leo Cold Cloud). Assuming an ideal gas in local thermodynamic equilibrium, this temperature yields a minimum blob pressure of $P/k_B = 3.2 \times 10^7$ K cm$^{-3}$.

In Figure 6 we display a histogram of the minimum inferred pressures for blobs along all 51 LOS following the same reasoning as above. The observed mass fraction of H I at these high pressures (i.e., $\gtrsim10^5$) is exceedingly small ($\sim 0.05\%$) and typical pressures are orders of magnitude lower, $\sim 3800$ K cm$^{-3}$ (Jenkins & Tripp 2011). So, the blobs should expand to reach pressure equilibrium with their surroundings within a sound-crossing time, $\sim 20,000$ years, without some containment mechanism.

Although tiny scale atomic structures (TSAS) have been inferred from opacity variations on tens of au scales with $\Delta \tau_{\text{H I}} < 0.5$ (e.g., Brogan et al. 2005; Lazio et al. 2009), the required blob column densities to explain $R_{\text{dust}} > 1.3$ are orders of magnitude higher than observed for TSAS, and these structures must be short-lived with a small overall mass fraction (e.g., $<10\%$; Dickey & Lockman 1990). Furthermore, although geometrical arguments—for example, the end-on alignment of curved filaments or sheets—may explain anomalous inferred properties of TSAS (e.g., Heiles 1997), the same arguments break down under the requirement that blob column densities are $100\times$ larger than for typical TSAS and $\sim 10\times$ larger than for cold neutral H I (typically $\sim 10^{20}$ cm$^{-2}$).

So, how do we account for the discrepancy between $R_{\text{HI}}$ and $R_{\text{dust}}$? It is highly likely that significant variations in dust grain properties render the F15 assumption of uniform dust opacity invalid. On the one hand, the dust opacity assumed by F15 ($\tau_{353}/N(\text{H I}) = 4.8 \times 10^{-27}$, e.g., Equation (5)) is $\sim30\%$ smaller than that found by Planck for high-latitude cirrus (7.1 $\pm 0.6 \times 10^{-27}$; Planck Collaboration et al. 2014b), corresponding to a $\sim 30\%$ increase in their inferred $R_{\text{dust}}$. Although F15 found that allowing $\tau_{353}$ to vary as $N(\text{H I})^{3.28}$ based on Herschel observations of Orion A (Roy et al. 2013b) did not affect their conclusions, it is unclear that this relation should hold for the diffuse ISM. From a careful selection of optical depth-corrected H I sight lines with no molecular gas (defined by the nondetection of CO or OH emission at high sensitivity), Nguyen et al. (2018) found that the specific dust opacity varies by up to $\sim 40\%$, likely as a result of dust grain evolution. In support, from detailed studies of the total gas column densities ($N(\text{H})$) traced by gamma-ray and dust emission, Planck Collaboration et al. (2015) and Remy et al. (2017) observed a systematic increase in dust opacity as $N(\text{H})$ increases between the diffuse atomic, dark, and CO-bright phases in the Chameleon and anticentre clouds. This has been predicted theoretically (e.g., Ysard et al. 2015) and inferred by Planck dust models (e.g., Planck Collaboration et al. 2016), which demonstrated that variations between FIR and optical dust grain properties are incompatible with standard models and require both varying radiation fields and optical grain properties (Fanciullo et al. 2015; Köhler et al. 2015).

In addition, $\text{H}_2$ undetected by CO should be prevalent. First of all, the F15 mask threshold of $I(\text{CO}) \lesssim 1$ K km s$^{-1}$ does not guarantee that gas is $\text{H}_2$-free. In the diffuse ISM, CO has been detected in emission ($I(\text{CO}) < 1$ K km s$^{-1}$; Liszt & Pety 2012)
and via UV and millimeter absorption (e.g., Sonnentrucker et al. 2007; Sheffer et al. 2008). Furthermore, in massive high-latitude clouds, neither optically thick H I nor variations in dust grain emissivity are sufficient to explain the observed wide range of dust emission per unit gas column density, indicating that H2 must contribute. In addition, Liszt (2014) observed significant flattening of $N$(H I)/$E(B - V)$ at $E(B - V) > 0.1$ mag, which cannot be accounted for by $\tau_{HI}$ effects, but can be explained easily by H2 formation. That CO-faint H2 should be a significant component of the ISM is further supported by theoretical models (e.g., Wolfire et al. 2010). Our results support these conclusions as well.

6. Summary

To quantify the contribution of optically thick gas to the ISM mass budget over large areas, we reproduce the F15 model for H I properties ($\tau_{HI}$ and $T_{b}$) based on dust emission from Planck and 21 cm emission from GALFA-H I. We include additional masking for regions dominated by molecular gas based on $^{12}$CO $J = 1 - 0$ maps from Planck. Using this model, we compute the inferred correction to the H I column density in the optically thin limit (R_{dust}). For comparison, we compute the correction to the optically thin column density based on direct measurements of $\tau_{HI}$ (R_{HI}) for a large sample of $\tau_{HI}$ observations (151 LOS), 72 of which are within the unmasked GALFA-H I FOV. Our results are as follows.

1. Although $R_{dust}$ and $R_{HI}$ are consistent at low values, for all 51 LOS with $R_{dust} > 1.3$ we find significantly lower $R_{HI}$ (1.0 $< R_{HI} < 1.3$).
2. We rule out the possibility that our $\tau_{HI}$ LOS miss high optical-depth blobs with a small covering fraction, as these structures must have properties that are significantly incompatible with ISM conditions.
3. We conclude that the discrepancy between $R_{HI}$ and $R_{dust}$ rules out the F15 hypothesis that optically thick H I dominates the dark gas in the local ISM. Although we cannot distinguish here between intrinsic variations in dust grain emissivity and H2 undetected by CO, both likely contribute significantly to the inferred dark gas mass budget.

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Appendix

To compare our results with those of F15, who used H I data from the LAB survey (Kalberla et al. 2005), and to ensure that our analysis is not biased by the GALFA-H I FOV (i.e., $0 < \alpha_{2000} < 360^\circ$, $0 < \delta_{2000} < 35^\circ$), we repeat our analysis using 21 cm emission maps from the LAB survey, with all other maps at LAB survey resolution ($N_{side} = 128$, corresponding to 27.5 pixels). An all-sky map of $R_{dust}$ (Equation (6)) is shown in Figure 7, with the positions of all 151 $\tau_{HI}$ LOS overlaid as crosses, colored by $R_{HI}$ (Equation (4)). We find...
excellent agreement with F15 (their Figure 12, lower panel), indicating that we are successfully reproducing their analysis method here. We note that in comparison with F15, we have included additional masking at intermediate latitudes due to CO detected by Planck, and we have not applied by-hand masking of the Magellanic System resulting in less masking at the highest Galactic latitudes.

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